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SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

APRIL 2020

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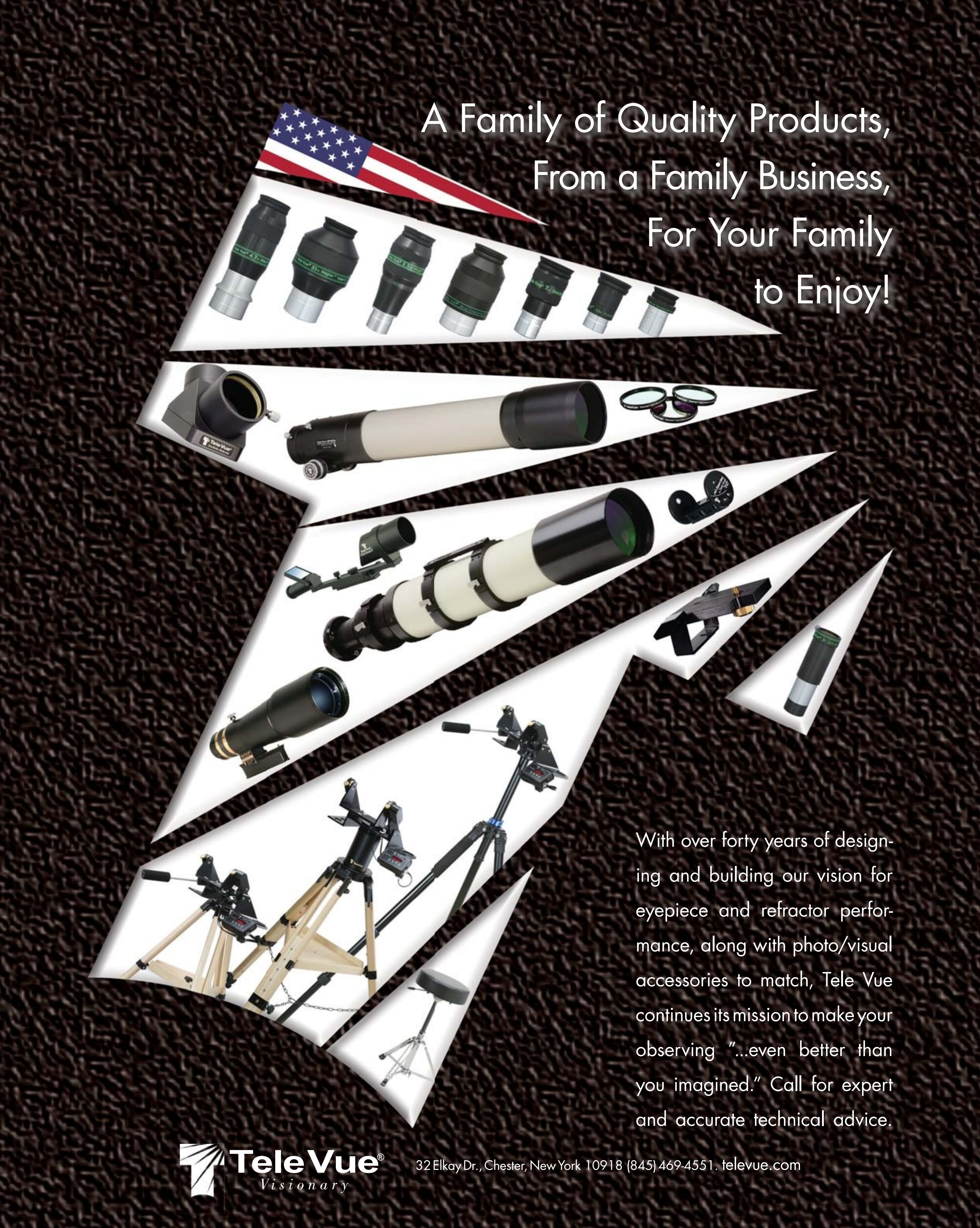
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THE ESSENTIAL GUIDE TO ASTRONOMY

April 2020 VOL. 139, NO. 4

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J. U. GUNTER / *SKY & TELESCOPE* ARCHIVES

ON THE COVER

A newly found image of NGC 6946 from Hubble's archives

PHOTO: NASA / ESA / L. HO (PEKING UNIV.), PROCESSING: GLADYS KOBER (NASA / CUA)

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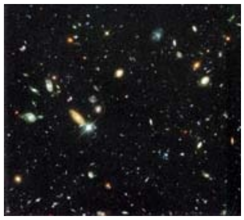
SKY & TELESCOPE (ISSN 0037-6604) is published monthly by AAS Sky Publishing, LLC, owned by the American Astronomical Society, 1667 K Street NW, Suite 800, Washington, DC 20006, USA. Phone: 800-253-0245 (customer service/subscriptions), 617-500-6793 (all other calls). Website: skyandtelescope.org. Store website: shopatsky.com. ©2020 AAS Sky Publishing, LLC. All rights reserved. Periodicals postage paid at Washington, DC, and at additional mailing offices. Canada Post Publications Mail sales agreement #40029823. Canadian return address: 2744 Edna St., Windsor, ON, Canada N8Y 1V2. Canadian GST Reg. #R128921855. POSTMASTER: Send address changes to Sky & Telescope, PO Box 420235, Palm Coast, FL 32142-0235. Printed in the USA.

A Discerning Eye

EVERYONE HAS A FAVORITE HUBBLE IMAGE. Maybe it's the iconic Pillars of Creation. Or the Helix Nebula, that giant, blue-pupiled eye in the night sky. Or the bruises in Jupiter's atmosphere left by the shards of Comet Shoemaker-Levy 9. The latter is one of the selections Vanessa Thomas includes in her breathtaking photo essay celebrating the Hubble Space Telescope's 30th anniversary (page 14).

My own favorite has always been the first Hubble Deep Field image from 1995. Seeing it for the first time blew my mind. In an instant, that galaxy-studded view became my new frame of reference for contemplating our place in the universe. Perhaps Edwin Hubble had a similar feeling when he first confirmed the Milky Way was not the whole universe.

The Hubble Deep Field epitomizes the space telescope's talent for opening entirely new vistas onto the cosmos. In no particular order and far from comprehensively, consider these achievements:



A portion of the 1995 Hubble Deep Field

R. WILLIAMS (STSCI) / THE HUBBLE DEEP FIELD TEAM / NASA

Hubble found evidence of oxygen and hydrogen — the elements of water — erupting from Jupiter's moon Europa, supporting notions of a subsurface ocean. It discovered four of Pluto's moons ahead of the 2015 New Horizons flyby, then pinpointed the spacecraft's next target in tiny, bilobed Arrokoth — 4 billion miles distant. Just recently, it took the first time-lapse of an interstellar object.

In other solar systems, Hubble has witnessed the births of some stars and the death throes of others, in jaw-dropping detail. It imaged the first exoplanet around a Sun-like star and has since helped astronomers measure the atmospheric composition of multiple other distant worlds. The telescope also provided key evidence that the cores of most galaxies harbor gargantuan black holes, which contain the mass of millions or even billions of Suns.

On the cosmology front, Hubble observations have aided researchers in grappling with dark energy, a mysterious form of energy that they hadn't even envisaged when the telescope went into orbit in 1990. The telescope helped astrophysicists reveal that the universe is not only expanding, but that the expansion rate is accelerating — a Nobel Prize-winning discovery. It played an essential part in constraining the universe's estimated age: Before Hubble, calculations ranged from 10 to 20 billion years; now we agree on about 13.8 billion years.

Most astonishingly, at least for me, Hubble has allowed us to peer back through 97% of all time that has ever transpired. Emblematic of that deep dive: the galaxy GN-z11, an indistinct blob Hubble imaged as it appeared just 400 million years after the Big Bang.

Bravo, Hubble. Keep on wowing us.

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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U.S. and possessions: $54.95 per year (12 issues)
Canada: $69.95 (including GST)
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Photo: Philipp Keltenich Taken with: Pro APO 71/450 Quadruplet

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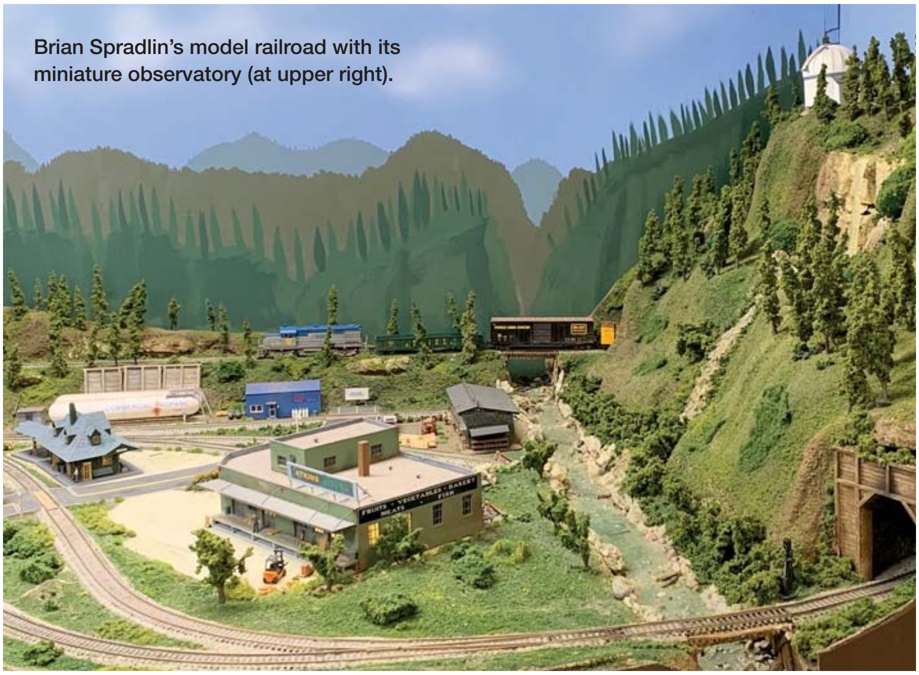

Brian Spradlin's model railroad with its miniature observatory (at upper right).

Fond Memories of First Telescopes

As I read Jerry Oltion's attempt to improve an old reflector (*S&T:* Dec. 2019, p. 72), I had to laugh when he mentioned frustrated would-be amateur astronomers turning to model railroading after they couldn't get their new scopes to work. You see, model railroading is another hobby of mine.

Earlier this year, I finished a small layout in my garage (in the traditional HO scale of 3.5 mm to 1 foot) and incorporated astronomy into my design. I built a small observatory, complete with a 1-meter telescope using the barrel of a Sharpie pen as my scope's tube. On the layout's background, I used glow-in-the-dark paint to add constellations and a ribbon covered in stars for the Milky Way. I referred to a star map from a June issue of *S&T,* as well as *Sky Safari* to make the stars accurate.

For a dramatic effect in a darkened room, I added an LED blacklight overhead. I love running my trains "at night," enjoying the glow of stars in my simulated summer sky.

It turned out better than I'd hoped. I'm glad I combined both of my hobbies in this layout.

Brian Spradlin
Harbor City, California

I have owned, at age 71, at least 20 telescopes in my lifetime. The earliest was a 40-mm Sears refractor that could have killed the hobby for me. But the optics were not bad, and I stuck with it until I was able to purchase a Unitron 60-mm. Then I began grinding mirrors with varying success, culminating in a superb 8-inch f/5 Newtonian.

I find, as Jerry Oltion's articles stress, that the mount is of prime importance. The optics today are superb, but long focal lengths require massive support.

And I still get the most satisfaction with low-power eyepieces and wide fields of view. Anyone seeking to buy a telescope should not fall for the high-magnification ads.

The ancient "Richest Field Telescope" articles in the *Amateur Telescope Making* trilogy published by *Scientific American* are still worth perusal.

My most satisfying observations have been the ones that followed those guidelines.

Robert Miller
Berlin, Vermont

I thoroughly enjoyed Jerry Oltion's "Hobby Killer" articles in the December 2019 issue. It's infuriating that most low-cost telescopes, even from manufacturers with good reputations, are destined to disappoint. Our local society typically offers a program in the fall aimed at first-time telescope buyers and a post-holiday workshop to assist new telescope owners in using their scopes.

I have a suggestion for an improvement to the "Revive a Hobby Killer" telescope. The mount shown on page 72 is tall compared to its base diameter, which causes instability. If a small weight is added near the bottom of the tube, it'll move the center of gravity closer to the mirror and allow the base to be shorter. The weight of the tube will increase, but the weight of the mount and its size will be reduced. I made just such a weight for one of my scopes out of lead scuba weights.

Jeff Delmas
Huntsville, Alabama

James Hannon's letter (*S&T:* Oct. 2019, p. 6) brought back fond memories of my start in amateur astronomy and telescope-making many years ago. It all started when a young kid was gracious enough to show me, an even younger kid, his homemade telescope. That encouraged me to grind a mirror and make a telescope.

It didn't turn out great, but thanks to some reconfiguring and advice from Thomas Cave and Cave Optical Company, all ended well. Years later, I tried my hand at a 12½-inch mirror with a far better outcome. That telescope saw first light in August 1957 when I focused it on Jupiter. The picture of the cover of the July 1959 issue of *S&T,* reproduced next to Hannon's letter, shows a photo of the Moon taken with my 12½-inch. I still have that telescope. It was totally rebuilt in 2017.

Jack Eastman
Sheridan, Colorado

◀ Jack Eastman stands next to his homemade 12.5-inch Newtonian in 2017.

TRAIN SET: BRIAN SPRADLIN; NEWTONIAN: JACK EASTMAN

My Thrilling "Discovery"

Matt Wedel's belief that any discovery is thrilling, even if many others have made the discovery before (*S&T:* Nov. 2019, p. 43) rings very true. So I wondered if his third "homework assignment," concerning the proper motion of 61 Cygni, could be detected on images taken with a standard 50-mm camera lens over a few decades. I remembered that in August 1977, at age 15, I had taken a photo of this area of the sky whilst staying at Patrick Moore's house, with a camera attached to one of his telescopes.

Although Moore's drive wasn't tracking well that night, I scanned the resulting print from my treasured old photo album and compared it with a digital image I took 38 years later in August 2015. After careful measurements of the apparent separation of 61 Cygni from two nearby reference stars, I concluded that the annual proper motion was 5.8 ± 1.2 arcseconds in the direction of position angle 65 ± 22°. This calculation tallies, within the limits of its uncertainty, with the values of 5.22 arcseconds and 52° in *Burnham's Celestial Handbook*. Indeed, flipping between the 1977 and 2015 images on the computer showed this star's tiny displacement. Thank you, Matt, for inspiring me to make this "discovery"!

Peter J. Garbett
Sharnbrook, England

New Horizons and Parallaxes

NASA's New Horizons spacecraft is now almost 50 astronomical units away as it leaves the solar system. At its current location, the nearest stars will have noticeably shifted from where they are seen from Earth. On April 22, 2020, New Horizons and several Earth-based observatories will simultaneously image the fields around Proxima Centauri and Wolf 359 to demonstrate two stars' relative shifts or "parallaxes" between the two vantage points. For those who would enjoy obtaining their own images, both stars can be observed with electronic cameras on 8-inch or larger telescopes.

The New Horizons project will combine the spacecraft and observatory images into stereo pairs to demonstrate the large parallaxes of the targeted stars. The stereo images and the results of the demonstration will be released in May. Check the *S&T* website page **https://is.gd/nhepo** for further details.

Tod Lauer
Tucson, Arizona

FOR THE RECORD

● J. Wesley Simpson photographed Kordylewski's clouds aboard NASA's Convair 990 laboratory aircraft in 1966, not aboard its Kuiper Airborne Observatory in 1967 (*S&T:* Jan. 2020, p. 53).

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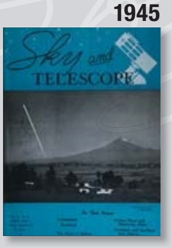
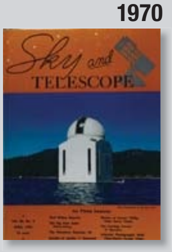
75, 50 & 25 YEARS AGO by Roger W. Sinnott

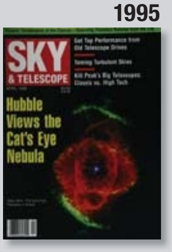
1945



1970



1995



◖ **April 1945**

White Dwarf Twins "Seventy white dwarfs have been discovered to date. In 11 cases, a white dwarf has been found as one component in a binary system. Until Dr. W. J. Luyten's recent discovery [at Steward Observatory], however, no twin white dwarfs were known. The twins are in Antlia, about 50 degrees south of Regulus. They are of 14th magnitude . . .

"Probably the twins are each intrinsically 1,600 times less luminous than the sun, and have diameters smaller than the earth's. If their masses are typical for such stars (about the mass of the sun), they have densities of about 25 tons per cubic inch."

More such twins are now known, including an extreme case found last year in Boötes with an orbital period under 7 minutes. It is expected to be emitting gravitational waves.

◖ **April 1970**

Gunfire in the Dome "The third largest telescope in the world — the 107-inch reflector at McDonald Observatory in Texas — escaped serious damage during an unusual incident on the evening of February 6th. Shortly before midnight, a newly hired employee fired seven point-blank shots with a 9-mm. pistol into the front surface of the 4-ton primary mirror. . . . [He] has since been committed by local authorities to a state mental institution.

"Harlan J. Smith, director of McDonald Observatory, reported that the damage to the fused silica mirror was very slight. It is limited to small craters, ranging from about 2½ to four inches in diameter, which reduce the telescope's light-collecting efficiency by only one percent . . ."

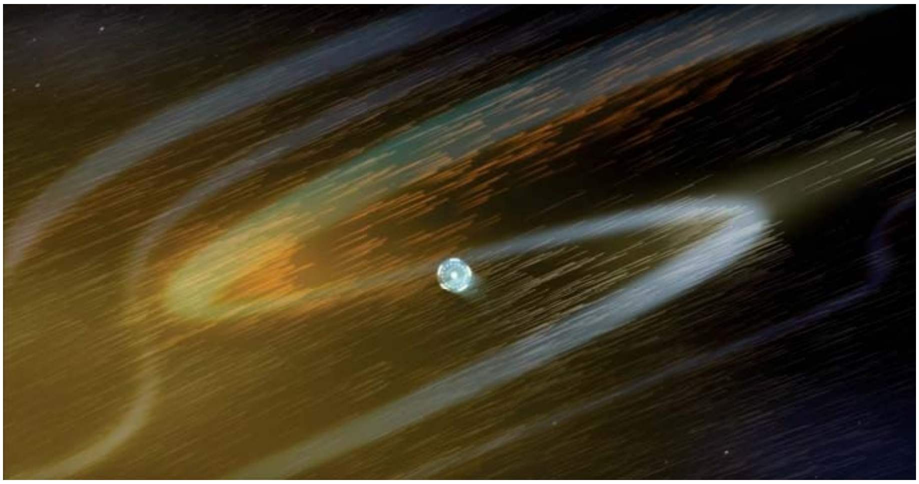
Optical tests showed no change in the mirror's figure, and research with the 107-inch never stopped. It has recently taken part in cutting-edge exoplanet studies.

◖ **April 1995**

Cat's Eye "Even before the refurbished Hubble Space Telescope pointed at NGC 6543 in Draco, this planetary nebula was among the most complex known. Recently dubbed the Cat's Eye, it had presented ground-based observers with a confusing tangle of bright bubbles, loops, and knots. . . .

"Located some 3,000 light-years away, NGC 6543 consists of gas gently cast off by its parent star about 1,000 years ago. . . .

"[The] inner bubble, ring, and outer lobes resulted from successively earlier episodes of mass loss from the central star. Yet the most intriguing features resolved by Hubble lie beyond the outer cocoon . . . Two small clouds called fast, low-ionization emission-line regions, or FLIERs, were ejected from the star and escaped through the outer lobes to depart the system at a hasty 25 kilometers per second or more."



▲ The Parker Solar Probe flew through many *switchbacks*, where the magnetic field swiftly reversed by 180°. View an animation of such a fly-through at **https://is.gd/switchbacks**.

NASA / GSFC / CIL / ADRIANA MANRIQUE GUTIERREZ

SUN

First Science from Parker Solar Probe

THE PARKER SOLAR PROBE TEAM has announced key findings from the spacecraft's first two perihelion passes in November 2018 and April 2019. These results, published in the December 12th *Nature*, mark the first public release of data from NASA's flagship heliophysics mission, which aims to understand the Sun's outer atmosphere, or *corona*, and the solar wind that emanates from it.

During its first two passes Parker already swooped within 24 million kilometers (15 million miles) of the Sun's visible surface, equivalent to just over half of Mercury's distance from the Sun at perihelion, or 35 times the Sun's radius. Parker carries a host of instruments into this hostile territory: The SWEAP instrument suite measures properties of the plasma, the FIELDS package measures magnetic and electric fields, and ISΘIS characterizes high-energy particles. The Wide-Field Imager for Solar Probe (WISPR) also obtains white-light images of the corona.

Researchers had hoped to use Parker to take a closer look at *Alfvén waves*, which are thought to transfer energy from the Sun's visible surface to its hot corona. These waves travel along magnetic field lines loaded with plasma, like vibrations traveling along strings of beads. Researchers were expecting to see stronger waves as the probe neared the Sun, but the number of so-called "rogue" waves that swept over the spacecraft took them aback.

"The speed of the [solar] wind could jump by more than 500,000 kilometers per hour within seconds," says SWEAP principal investigator Justin Kasper (University of Michigan). *Switchbacks*, 180° reversals in the magnetic field, often accompanied these velocity spikes.

Parker has seen thousands of these events already, each one lasting anywhere from a few seconds to a few minutes. The team is confident that the rogue waves originate closer to the Sun's surface but awaits data from future close passes to determine their source.

Parker is also helping scientists understand how charged particles emanating from the Sun escape its gravity and flow into the solar system. As the Sun spins, its magnetic field grips the corona, forcing it to rotate like a rider on a merry-go-round. Yet near Earth, the solar wind flows directly away from the Sun, as if riders had jumped off the carousel. Parker's path near the Sun enables it to see the transition.

STARS

Betelgeuse "Faints"

BETELGEUSE, THE RED SUPERGIANT star that marks Orion's western shoulder, has faded markedly in a behavior termed "fainting." The star typically varies in brightness between magnitudes 0.3 and 1.2, but observations in December and January indicate a steep drop in brightness to magnitude 1.5, a historic low.

Betelgeuse is a semiregular variable, its brightness varying as the star expands and contracts on a roughly 425-day period. Betelgeuse also shows changes on a longer, roughly 6-year cycle due to other internal forces. At its largest and coolest, the star would balloon out to Jupiter's orbit if put in place of the Sun (*S&T:* May 2019, p. 34).

Ultimately, Betelgeuse will run out of fuel and explode as a core-collapse supernova. Cosmically speaking, this event is just around the corner: Astronomers have predicted that the star will explode within 100,000 years or so. For this reason, the current drop in brightness provoked much discussion. However, while the supergiant's current behavior is certainly out of the ordinary, it doesn't necessarily mean an eruption is imminent.

Edward Guinan (Villanova University), who has been monitoring the star for more than 25 years with Richard Wasatonic (also at Villanova) and amateur Thomas Calderwood, suggests that the star happens to be near the minimum of its 5.9-year cycle at the same time as it's reaching a deeper than usual minimum of its 425-day cycle. Guinan encourages observers to monitor the star while it's in this unusually faint and cool state.

■ **BOB KING**

Find out how to keep tabs on Betelgeuse yourself at https://is.gd/Betelgeuse.

▶ Amateur Tim Wetherell used the same telescope, camera, and exposure time to capture the striking difference in Betelgeuse's brightness between February 2019, when it was in mid-cycle, and January 2020, when the star "fainted" to a historic low.

To the scientists' surprise, at Parker's closest point, SWEAP was already recording the solar wind whipping around the Sun at 35 to 50 km/s — 15 to 25 times faster than some theoretical models predicted. Why it's moving so fast remains a mystery.

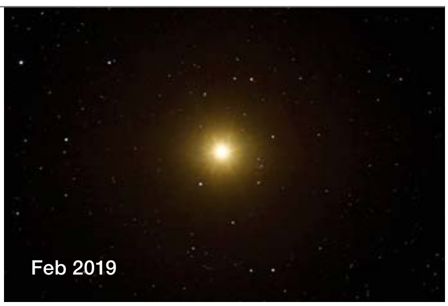
"Our standard models of the Sun are missing some very fundamental physics, and this mission has a great chance of revealing what is really happening," Kasper says.

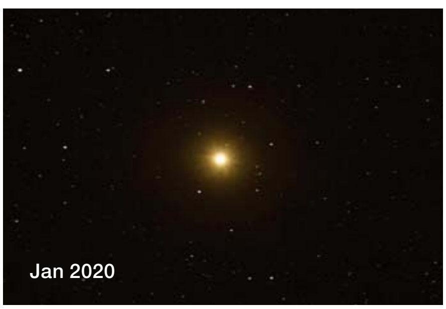
Other findings the Parker team announced include a wide-field image by WISPR documenting preliminary evidence of a dust-free region close to the Sun. This region is expected, as the Sun's heat should break down dust grains that come too close, but until now no mission had seen it. Future passes nearer the Sun could take Parker inside the dust-free zone for definitive measurements.

The Parker Solar Probe also made the second of seven Venus flybys on December 26, 2019, passing about 3,000 km from the planet's surface. While Parker's instruments were turned off during much of the first Venus pass, they were on during the second pass, and the team is eager to analyze data on the Venusian atmosphere.

■ DAVID DICKINSON

See more Parker Solar Probe results at https://is.gd/Parkerfirstresults.

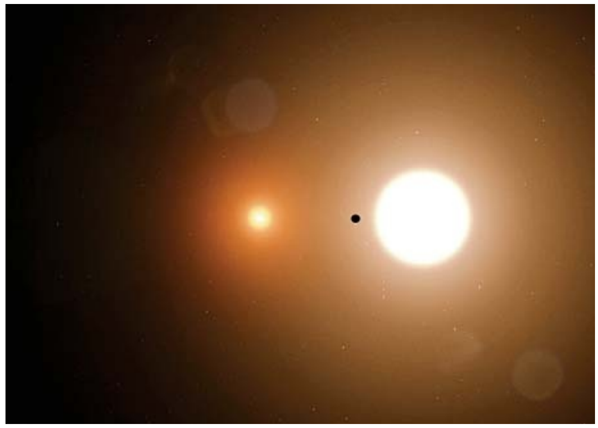




TESS: NASA'S GODDARD SPACE FLIGHT CENTER / CHRIS SMITH

EXOPLANETS

NASA's TESS Announces First-Year Roundup



▲ This artist's illustration shows one of the TESS mission's confirmed planets, TOI 1338b. The world is 6.9 times Earth's radius and stably orbits two stars in a system 1,300 light-years away.

SCIENTISTS WORKING with NASA's Transiting Exoplanet Survey Satellite (TESS) announced the official catalog that summarizes the mission's first year of exoplanet-hunting results at a meeting of the American Astronomical Society in Honolulu.

From July 2018 to July 2019, TESS searched for planets in the southern sky, revealing more than 1,100 planet candidates. Of these, 37 — so far — have been confirmed via follow-up observations and published in peer-reviewed journals. The catalog will be available in an upcoming issue of *Astrophysical Journal Supplements*, according to catalog manager Natalia Guerrero (MIT).

Like its predecessor, NASA's Kepler mission, TESS finds planets by watching for dips in starlight caused when a planet transits across the face of its star. But unlike Kepler, TESS watches stars close to Earth. By design, all of the planets it finds are within about 3,000 light-years, and some are much closer. With these discoveries, astronomers can do more than tally an exoplanet census — they can get to know our planetary neighbors one by one.

Perhaps the most famous discovery within the first-year catalog is TOI 700d. This Earth-size world is the outermost known planet in its system. It circles the cool, red star every 37 days, putting it in the star's *habitable zone*, the region where (under the right conditions) liquid water could exist on its surface. TOI 700d is one of only a few Earth-size planets found in their stars' habitable zones so far and the first one that TESS has discovered.

■ MONICA YOUNG

Read about more TESS-discovered planets at https://is.gd/TESSfirstyear.

IN BRIEF

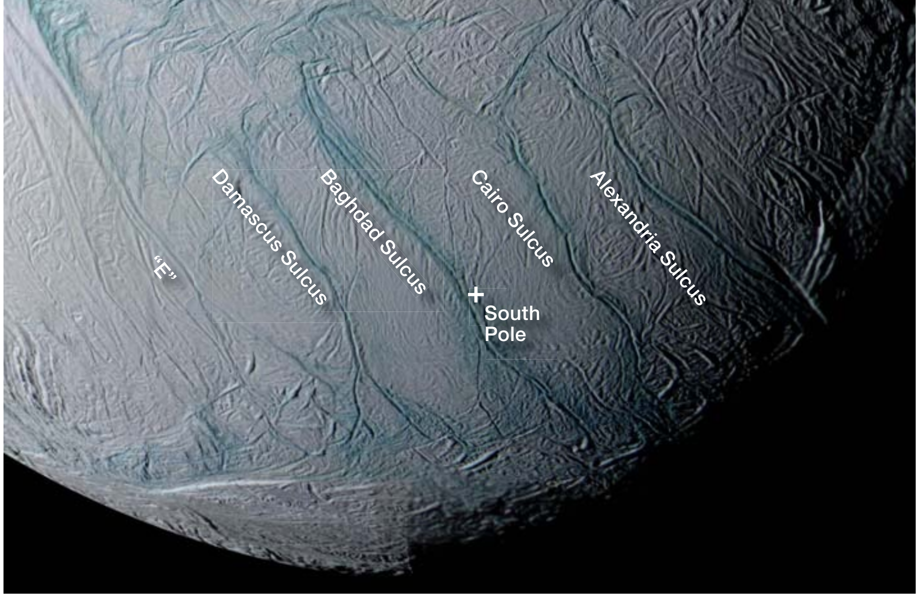
Meade Files for Bankruptcy

Meade Instruments, based in Irvine, California, filed for bankruptcy protection on December 4, 2019. The action follows the loss of a multimillion-dollar antitrust lawsuit brought by Orion Telescopes & Binoculars. The court found that the Chinese manufacturer Ningbo Sunny Electronic Co. Ltd, which purchased Meade in 2013, had colluded with other Chinese manufacturers in a price-fixing scheme. According to the filing, Meade has debts of up to $50 million. Founded in 1972, Meade rose from humble beginnings in the amateur astronomy market, eventually becoming the world's largest telescope manufacturer, with distribution in more than 30 countries. In 1997, it became the first amateur telescope manufacturer to go public. Meade has clashed with competition several times in the past, settling lawsuits with longtime rival Celestron and with Star Instruments and RC Optical. After the filing, Meade announced that it would continue supporting its products, customers, and network of dealers throughout the bankruptcy process.

■ SEAN WALKER

SOLAR SYSTEM

How Enceladus Got Its Tiger Stripes



▲ In this false-color closeup, four rifts, dubbed *tiger stripes*, cross near Enceladus's south pole (white cross). These are the source of the moon's plumes, made mostly of water vapor.

ASTRONOMERS HAVE STRUGGLED to understand the origin of several parallel fractures on Saturn's moon Enceladus, dubbed *tiger stripes*. They are about 35 kilometers (22 miles) apart and located only at the moon's south pole. What's more, they're unlike any features found on the other icy moons.

Now, in the December 9th *Nature Astronomy*, Douglas Hemingway (Carnegie Institution for Science) and colleagues outline a scenario that can simultaneously explain all of the stripes' characteristics.

The idea is simple in concept: After global pressure opens a first crack in Enceladus's icy crust, a cascade of fractures form next to it.

The moon is known to go through cooling periods, which create global pressure as the moon's underground ocean begins to freeze and expand, pressing on the icy crust from the inside. The crust is thinnest at its poles, where Saturn's gravitational pull creates the most heat, so that's where it breaks.

Hemingway and colleagues suggest that Baghdad Sulcus, a crack that cuts directly through the geographic south pole, formed in this way. Baghdad Sulcus relieved the global pressure, explaining why there are no similar fractures at the north pole. But once the crack cut through the ice, it filled with water, which boils off at the top in geyser-like fashion. Water ice "snows" down, building up a ridge on either side of the groove over time. Eventually, the ridges became heavy enough to bend the icy crust, creating additional cracks at a specific distance — 35 km — from the first one. Symmetric pairs of stripes formed around Baghdad Sulcus: first Cairo and Damascus, then Alexandria and a feature informally named "E."

Ultimately, the fracturing cascade ended, either because not enough "snow" built up along the ridges or because the ice crust became thick enough to not bend and break.

In this scenario, Hemingway explains, other icy moons don't host similar features because they have enough gravity to prevent cracks from ripping open in the first place. Only on tiny Enceladus can the fissures break all the way through the icy crust.

Other scientists commend this all-encompassing scenario. "I think this is another important 'milestone' paper," says Frank Postberg (Free University of Berlin), "one that solves one of the long-standing riddles with which Enceladus has been puzzling us."

■ MONICA YOUNG

TIGER STRIPES: NASA / JPL / SPACE SCIENCE INSTITUTE; JUPITER'S SOUTH POLE: NASA / JPL-CALTECH / SWRI / ASI / INAF / JIRAM

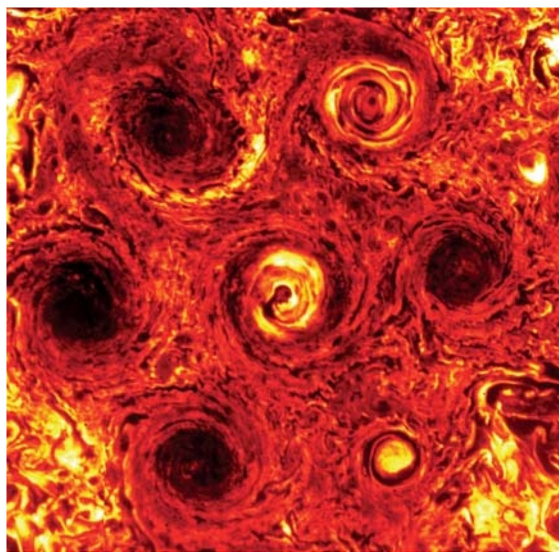
SOLAR SYSTEM

New Cyclone for Jupiter's South Pole

IMAGES FROM NASA'S Juno mission have revealed a new cyclone that has pushed its way into the grouping at Jupiter's south pole.

Scientists have been wanting to watch a new polar cyclone form ever since Juno revealed the symmetrical and seemingly stable pentagon of cyclones at Jupiter's south pole in 2018. Jupiter almost seemed to tease researchers over the following months as Juno saw gaps in the pentagon open and close again; meanwhile, smaller cyclones kept forming and dissipating just outside the shifting pentagon.

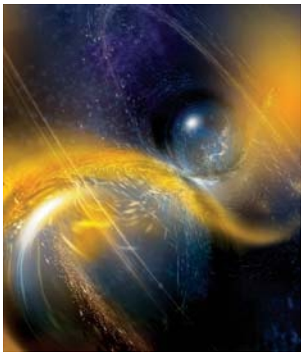
Finally, in November, researchers got what they were waiting for: A new storm had formed and edged its way into a gap, creating a stable hexagon. Alessandro Mura (National Institute for Astrophysics, Rome), a coinvestigator on the Juno team, presented the discovery at a meeting of the American Geophysical Union in San Francisco. The newest



▶ Juno's infrared imager caught the appearance of a new cyclone (lower right) that joined the exclusive club at Jupiter's south pole. The darker regions contain ammonia crystals and are 10 to 20 kilometers higher up than the brighter regions rich in hydrogen sulfide.

GRAVITATIONAL WAVES

Second Neutron Star Merger Detected



▲ Artist's rendition of two neutron stars merging

SCIENTISTS WITH THE LIGO and Virgo collaborations have detected a second pair of neutron stars that went bump in the night, scientists announced at a meeting of the American Astronomical Society in Honolulu. Results will appear in an upcoming issue of *Astrophysical Journal Letters*.

The merger, designated GW190425, is the first official event of the gravitational-wave detectors' third observing run, which started April 1, 2019, and continues until April 30, 2020.

Unlike the first detection of a neutron star merger, known as GW170817 (*S&T:* Feb. 2018, p. 32), follow-up observations looking for a light wave counterpart to the gravitational-wave event turned up empty, and not for a lack of trying. That's partly because the event was spotted with only a single detector, which made the source difficult to triangulate. The second merger also occurred at least twice as far away as the first one, between 290 million and 744 million light-years from Earth.

Astronomers determined the objects' masses from the gravitational-wave signal: The first was between 1.1 and 1.7 times the Sun's mass; the other was heavier, between 1.6 and 2.5 solar masses. The second object is therefore within black hole range, which would make this the first merger of a neutron star and a black hole.

However, the LIGO team argues that the involvement of a black hole is a less likely scenario. While a black hole can theoretically have a little more than double the Sun's mass, no such black hole has ever been observed. Due to the range of estimated masses, a neutron star collision remains a more straightforward explanation.

Still, even if the event involves only neutron stars, the pair is strange. Unlike GW170817, the sum of the masses involved in GW190425 is greater than any other known neutron star pair in our galaxy.

"No matter what the source of this signal is," says Katerina Chatziioannou (Flatiron Institute), "it challenges our understanding of how these systems form and merge."

■ MONICA YOUNG

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cyclone whips around at 100 m/s (225 mph), comparable in speed to the others, but it's still the runt of the crew. It spans the width of Texas, whereas the central cyclone would cross the continental United States.

The new storm has allowed theorist Cheng Li (University of California, Berkeley) to test his ideas on how such storms are able to maintain stable configurations. Li's simulations play with the parameters of cyclone-encircling *buffer zones*, where gas flows in the direction opposite the vortex. The buffer zones repel other cyclones, preventing them from merging. They are thus vital to maintaining a stable symmetry in the presence of multiple storms. However, as turbulence erodes buffer zones, even apparently stable configurations will evolve.

Li cautions that his model is limited because it's two-dimensional. Vertical winds, for example, may play a role in shaping the dynamics at the pole. Incorporating such 3D aspects will require additional Juno observations that delve deeper into Jupiter's atmosphere. Juno will continue collecting data until at least 2021.

■ MONICA YOUNG

NEUTRON STAR MERGER: NSF / LIGO / SONOMA STATE UNIVERSITY / A. SIMONNET; NIGHTINGALE: NASA / GODDARD / UNIVERSITY OF ARIZONA

IN BRIEF

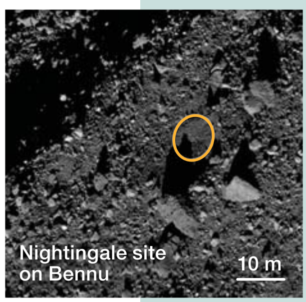
Europe Launches Exoplanet Mission

On December 18th, a Russian Soyuz rocket launched the first European space mission dedicated to studying exoplanets. Unlike NASA's Kepler and TESS missions, the Characterising Exoplanets Satellite (Cheops) won't hunt for new planets. Instead, it will conduct detailed studies of known exoplanets transiting bright stars, including the super-Earth 55 Cancri e and the hottest known gas giant, KELT-9b. Cheops will measure the brightness of stars every 30 to 60 seconds to a precision of 20 parts per million. Such precise observations of the planetary transits will yield exact values for the planets' sizes. Mass determinations from ground-based radial-velocity observations will then help astronomers understand the planets' compositions. Precise light curves throughout a transit can also show whether an atmosphere exists.

■ GOVERT SCHILLING

NASA Selects "Nightingale" Site on Bennu

NASA has selected the site on asteroid 101955 Bennu for next year's sampling maneuver by the Osiris-REX spacecraft. The site, nicknamed "Nightingale," is located within a 10-m (33-ft) crater in the northern region of Bennu. Its selection minimizes risk to the spacecraft while providing the best opportunity for interesting science, as the site contains the most fine-grained material for sampling, is subject to a lower level of sunlight (and therefore lower temperatures), and should contain pristine material. The area isn't without its risks, though. The mission originally called for a sample site 50 meters wide, but the sampling area at the Nightingale site is only 16 meters wide; the touchdown maneuver will have to be nearly spot on. There's also a boulder the size of a 2- to 3-story building on the nearby crater rim, which the spacecraft will have to avoid as it backs away. The "Osprey" site, inside a small crater in Bennu's equatorial region, serves as a backup. Osiris-REX's touch-and-go maneuver is set for August 2020.



Nightingale site on Bennu

■ DAVID DICKINSON

The Universe Through Hubble's Eye

Amateurs celebrate the venerable space telescope's 30th anniversary with a look at some of its most mesmerizing images.

For 30 years, the Hubble Space Telescope has been a powerhouse of discovery for professional astronomers. But behind the scenes are some amateur astronomers, too. We are among the hundreds of dedicated scientists, engineers, managers, and others who have kept the venerable spacecraft operating and its cosmic revelations flowing over the past three decades. And to share Hubble's sharp vision from space, we sometimes rely upon insights gained from stargazing on Earth.

I was in junior high when Hubble launched aboard Space Shuttle *Discovery*. Back then, the many nights I spent stargazing during family camping trips in northern Michigan had just begun to develop into a deeper curiosity about the universe. It wasn't long before I decided that I wanted to be an astronomer. The summer before heading to MIT for college, I was awestruck by Hubble's images of the giant, black scars Comet Shoemaker-Levy 9 left on Jupiter. Never would I have imagined that, decades later, Hubble would still be wowing me and that I'd be at NASA, telling the ongoing story of the telescope and its discoveries.

But I never became a professional astronomer. Midway through college, I loved astronomy more than ever, but I feared that I had neither the stamina nor the finances to spend several more years obtaining a PhD. Instead, I paired my passion for astronomy with a knack for writing and became a science writer. I've been with the Hubble team since 2006, involved in crafting articles, videos, social media posts, handouts, books, media campaigns, public events, and anything else NASA's Hubble outreach team creates to share the telescope's accomplishments with the world.

I've sustained my bond with the universe as an amateur astronomer, though — shivering in remote fields while counting streaks cast by the latest meteor shower, camping out at star parties around the country to marvel at the dark skies, and hunting down every Messier object with my trusty Dobsonian. I've held positions in local astronomy clubs, and I share views of the night sky with everyone I can at outreach events.

My experience as an amateur occasionally comes in handy at work, too. When Hubble is releasing a new image of a celestial object that's visible in the night sky, for instance, the communication team frequently

Specs

The Hubble Space Telescope is 13.2 meters (43.5 ft) long, the length of a large school bus. Its primary mirror is 2.4 m in diameter and weighs 828 kg (1,825 lb).

NASA / ESA / HUBBLE HERITAGE TEAM (STSCI / AURA)

▲ **GALAXY MERGER** In this Hubble image of Arp 194, stars appear to be "leaking" from galaxy to galaxy like water dripping from a faucet. In reality, the giant clusters of blue stars probably formed as a result of the interactions between the merging galaxies at the top, which would have compressed gas and spurred starbirth. Fellow amateur Kevin Hartnett and I have picked some of our favorite Hubble images from the last 30 years to share with you on the following pages.

turns to me to find out if and when amateurs could spot the object, what equipment is needed to see it, and what it might look like from a suburban backyard, so we can share that information with the public. And when NASA provided telescopes for Astronomy Night at the White House in 2009 and again in 2015, my colleagues selected me to attend because I could operate a telescope and locate interesting targets, even in the light-polluted skies of Washington, DC.

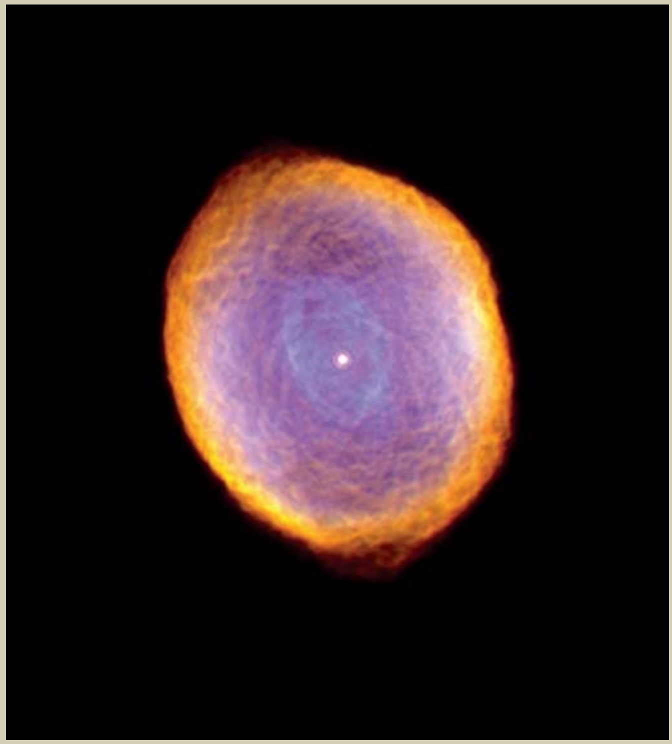
I've been fortunate to find other amateur astronomers on the Hubble team — kindred spirits who know the night sky and appreciate what some of the celestial objects in Hubble's remarkable images look like through ordinary telescopes on the ground. One of them is Kevin Hartnett, who oversees the mission's science operations conducted by the Space Telescope Science Institute (STScI). Kevin was hooked by astronomy as a kid, too — in his case by a friend who was grinding a 6-inch telescope mirror. The two of them joined the Junior Astronomical Society of Harrisburg, staying out all night in sleeping bags to soak in the dark Pennsylvania skies.

Kevin caught the astrophotography bug early and continued to develop his skills while studying physics and astronomy at the University of Delaware, completing a project to image Comet Kohoutek. Like me, Kevin opted out of the PhD route, instead working in private industry after graduation. He made his way to NASA's Goddard Space Flight Center as a mission operations contractor before being offered a job as a NASA employee the day before Hubble's launch in 1990. He joined the Hubble team in 1997, right about the time I was shifting my aspirations from becoming a professional astronomer to writing about astronomy.

Kevin spends many hours teaching others about the heavens, hosting star parties, and photographing the sky. Since purchasing a DSLR camera five years ago, he has contracted astrophotography fever. At Goddard, Kevin's images of the night sky hang alongside Hubble's grand views on conference room and cafeteria walls. We've even compared Kevin's photos of some celestial objects to those targeted by Hubble so we could assess the view from his Maryland backyard relative to Hubble's view from orbit, 540 km (335 miles) up.

Repairs

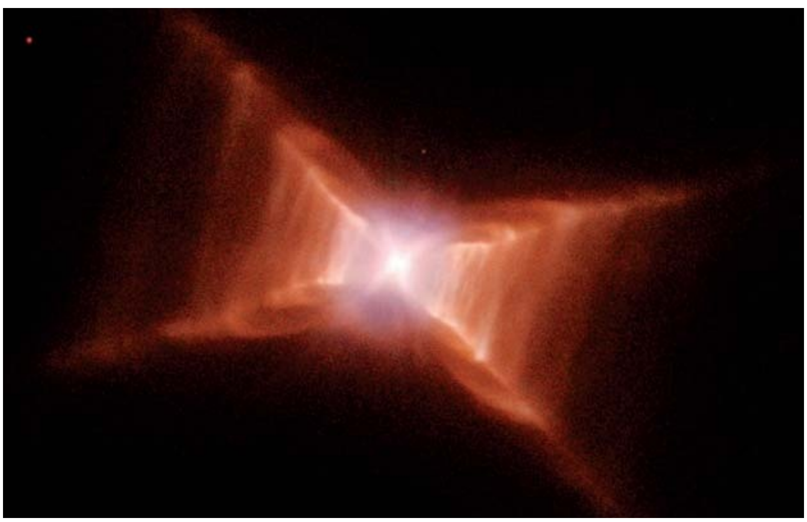
Hubble launched in April 1990 but with a primary mirror aberration that blurred images. It wasn't until after the first servicing mission in 1993 that astronomers could capture the pristine images the space telescope is famous for. Astronauts completed five Hubble servicing missions between 1993 and 2009.



▲▲ **M94** This visible-ultraviolet composite image of M94 highlights the stunning starburst ring encircling the spiral galaxy's core.

▲ **IC 418** This image of the Spirograph Nebula (IC 418) is an old classic of Hubble's that has fascinated me for years. I never get over how much complex detail there is in this planetary nebula.

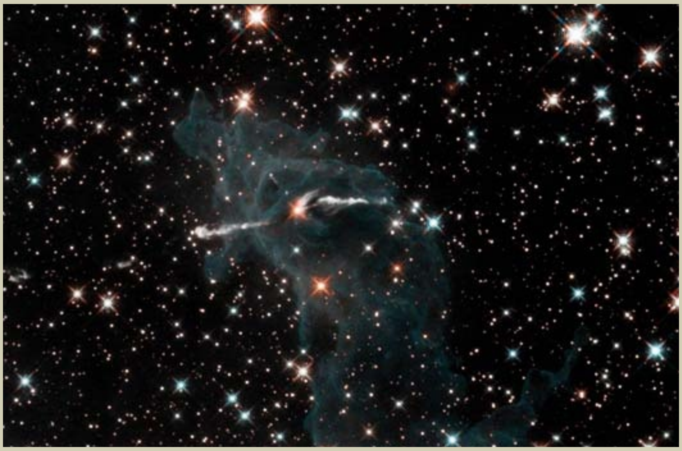
M94: ESA / HUBBLE & NASA; IC 418: NASA / HUBBLE HERITAGE TEAM (STSCI / AURA)



NGC 1999: NASA / ESA / HUBBLE HERITAGE TEAM (STSCI / AURA); HD 44179: NASA / ESA / HANS VAN WINCKEL (CATHOLIC UNIV. OF LEUVEN, BELGIUM) / MARTIN COHEN (UNIV. OF CALIFORNIA, BERKELEY)

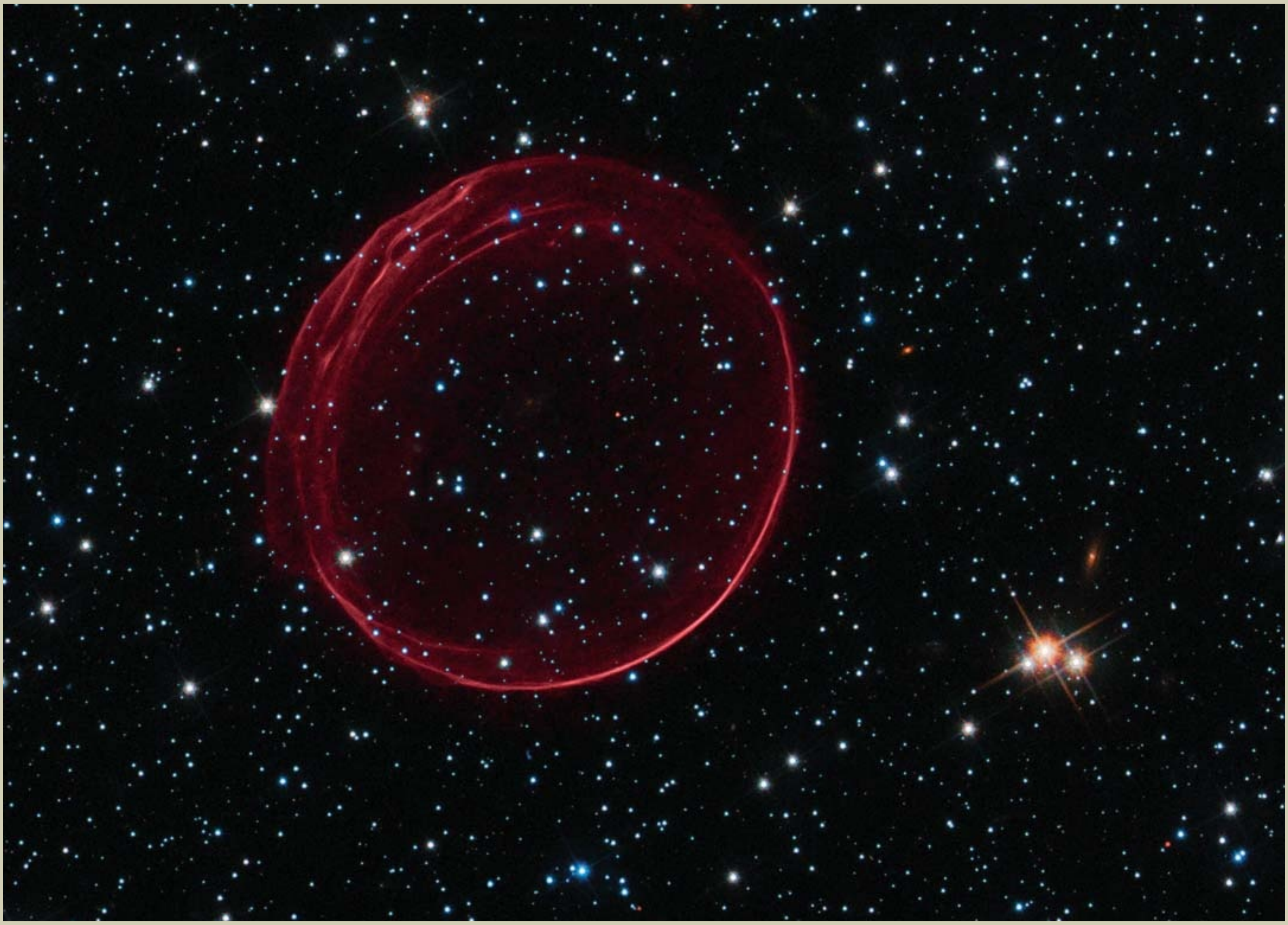
▲ **DARK HOLE** I love the dramatic contrast in this Hubble image of reflection nebula NGC 1999. Infrared observations suggest that the dark region is not a dense cloud, as once thought, but an actual hole in the nebula.

◀ **HD 44179**
I always feel taken aback when I look at this image of the Red Rectangle protoplanetary nebula, produced by the dying star HD 44179. I am so used to seeing curves in nebulae that it's striking to see such straight lines and angles.



▲ **COSMIC TAPIR** Forming stars shoot pairs of jets. Mostly hidden in the visible image *(left)*, the jets of a protostar in Carina become clear in infrared *(seen at right)*.

▼ **SUPERNOVA REMNANT** This red bubble, SNR 0509-67.5, looks serene. But it's the result of gas being shocked by a violent supernova explosion in the Large Magellanic Cloud dwarf galaxy.



CARINA JET (2): NASA / ESA / HUBBLE SM4 ERO TEAM; SNR 0509-67.5: NASA / ESA / HUBBLE HERITAGE TEAM (STSCI / AURA)

Kevin and I are both active members of the Goddard Astronomy Club, a small but enthusiastic group of amateur astronomers who work or once worked for NASA in a variety of roles — from engineers and scientists (including a couple of professional astronomers) to programmers, IT specialists, managers, and outreach professionals. Kevin and I have even recruited other members to help us out with projects at times. For example, we've put our amateur hats on to assemble online collections of Hubble images taken of objects from the Messier and Caldwell catalogs, so that other backyard astronomers could compare their views to Hubble's. We've used our observational knowledge to explain when and how others can see these objects themselves and to create basic star charts to accompany Hubble's images. I believe our experience as amateurs provides perspective, helping us better explain why Hubble's crisp views from above the atmosphere are so vital to astronomy and advancing our understanding of the universe.

(continued on page 22)

▲ **DRAMATIC DEATH** Of all the planetary nebulae Hubble has observed, this one, NGC 5189, must be one of the most visibly dynamic. What events transpired during the central star's death to create all these interesting shapes?

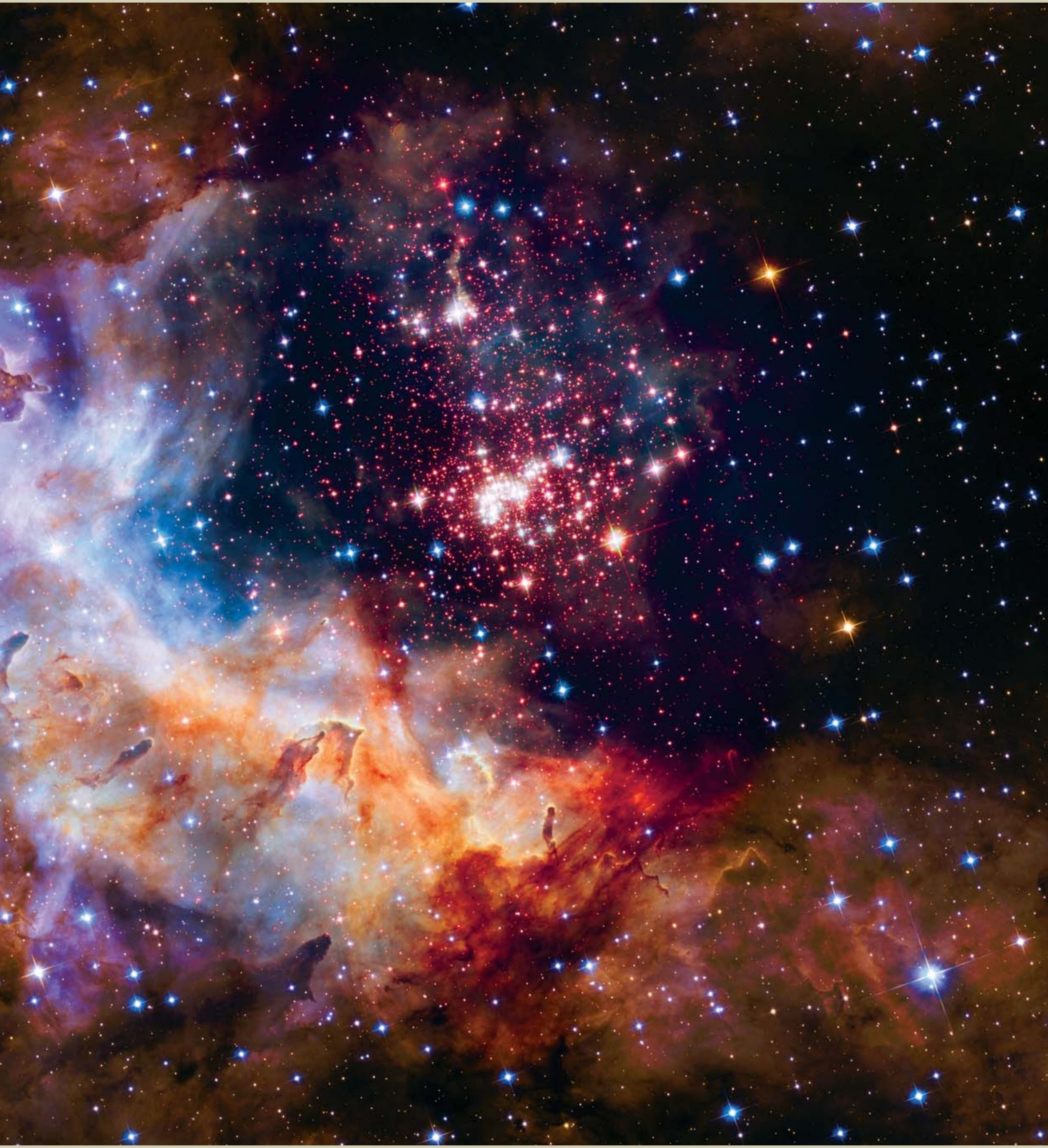
▲ **BARRED SPIRAL** *Left:* Hubble studied this "hidden gem" of a galaxy to help astronomers improve the precision of the universe's expansion rate. Astronomers identified dozens of Cepheid variables and a Type Ia supernova (both of which are used as cosmic distance markers) in this barred spiral, called NGC 1015 and located 118 million light-years away. **M64** *Right:* I must have a thing for galaxies with prominent dust lanes, because while Hubble's Sombrero Galaxy image is my favorite, I adore this picture of the Black Eye Galaxy (M64) almost as much. This spiral galaxy clearly has a story to tell — probably that it tore apart and cannibalized a smaller galaxy. This is an object that I particularly love to look at through my telescope and compare to the Hubble image to dig into the details.

NGC 5189: NASA / ESA / HUBBLE HERITAGE TEAM (STSCI / AURA); NGC 1015: NASA / ESA / A. RIESS (STSCI / JHU); M64: NASA / HUBBLE HERITAGE TEAM (AURA / STSCI)

◀ **PRO AND AM** Hubble's portrait of the "Pillars of Creation" in the Eagle Nebula, taken with its Wide Field and Planetary Camera 2 back in 1995, is arguably its most famous image ever. In 2014, Hubble revisited these towers of star formation with its Wide Field Camera 3 to capture a wider, more detailed view in both visible *(top)* and infrared *(center)*, revealing stars inside and beyond the nebula's clouds of gas and dust. We often use this powerful side-by-side demonstration to help explain why so many of us are excited for Hubble to work alongside the upcoming James Webb Space Telescope. It's also a perfect target for comparisons with backyard astronomers' images *(bottom)* — in this case, one by Kevin using an 8-inch SCT with a Canon EOS 600D camera and total exposure of 0.7 hour.

▶ **RAMPANT STARBIRTH** Released for Hubble's 25th anniversary, this image features the 3,000-member-strong star cluster Westerlund 2 alongside clouds of gas and dust in the Gum 29 nebula that are giving birth to even more stars. The picture combines visible-light observations from the Advanced Camera for Surveys with infrared exposures from the Wide Field Camera 3.

PILLARS OF CREATION: HUBBLE IMAGES: NASA / ESA / HUBBLE HERITAGE TEAM (STSCI / AURA); AMATEUR IMAGE: KEVIN HARTNETT; STAR CLUSTER: NASA / ESA / HUBBLE HERITAGE TEAM (STSCI / AURA) / A. NOTA (ESA / STSCI) / WESTERLUND 2 SCIENCE TEAM



▲ **COMET PUNCHES** In July 1994, about six weeks before heading off to college to study astronomy, I was awed by Hubble for the very first time when I saw its shots of the Comet Shoemaker-Levy 9 impacts on Jupiter. The black scars created by the comet fragments were far bigger than I'd imagined they'd be — some were the size of Earth. Who knew we could watch the universe change in real time?

▲ **SLICING THROUGH SPACE** This Hubble image of M102 fascinates me. There is so much to take in, from the tendrils of dust that curl above and below the galaxy's disk and the blue line of stars that extend farther out from the ends of the dusty part of the disk, to the white elliptical halo of stars enveloping the disk and the faraway galaxies embedded in the background.

JUPITER: HUBBLE SPACE TELESCOPE COMET TEAM / NASA; GALAXY: NASA / ESA / HUBBLE HERITAGE TEAM (STSCI / AURA)

(continued from page 19)

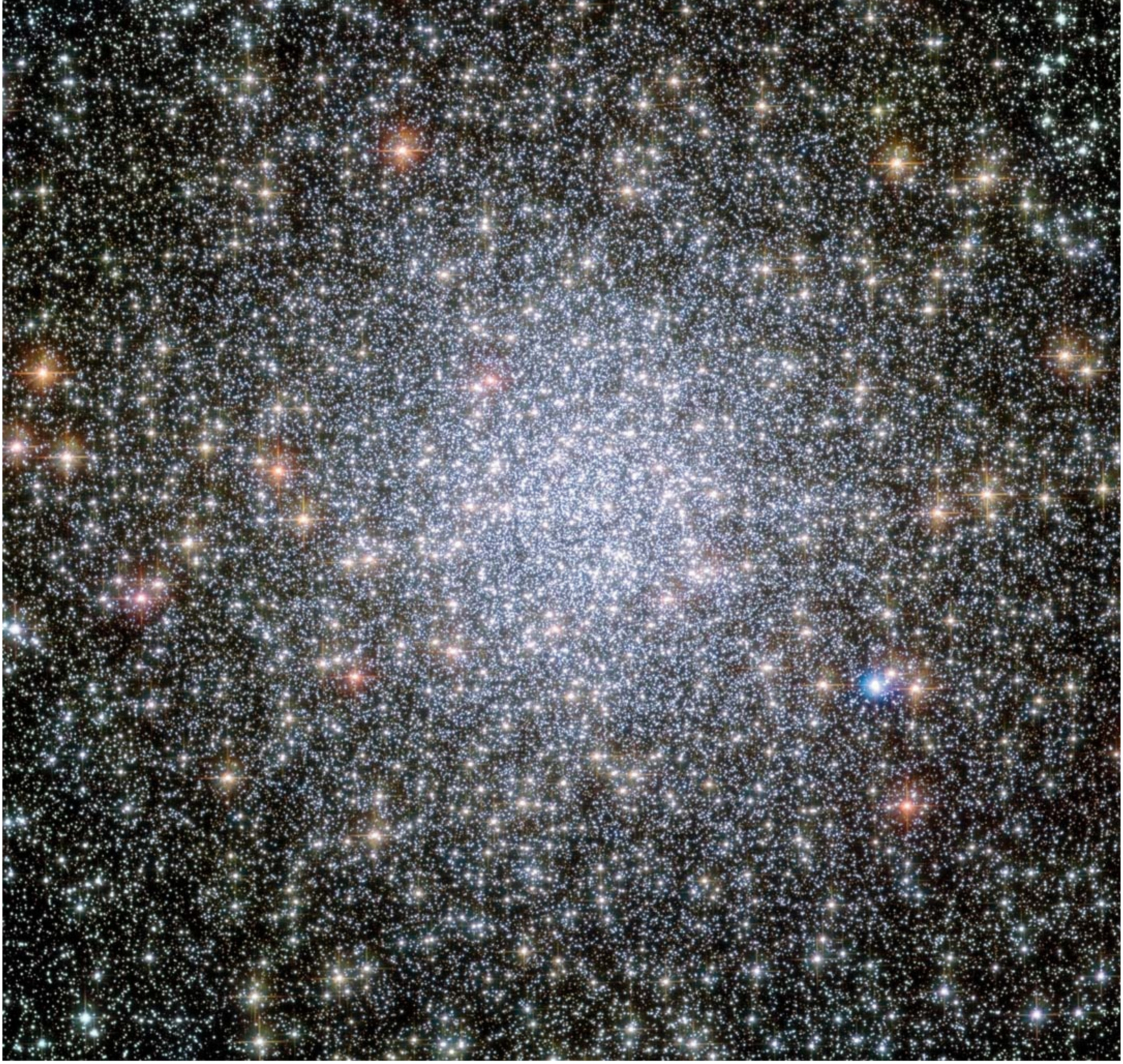
When Kevin gives tours of Hubble's control center and describes Hubble's images, for example, he often shares his own photos of the same objects imaged by Hubble and tells visitors when they could view these things in the night sky. We've both found that when members of the public find out that they can see some of the same objects Hubble has, it heightens their interest in the telescope and its observations. Reviewing some of Hubble's images has also inspired us to venture outside to revisit these objects or view them for the first time with our own eyes.

Fuelless Pointing

The space telescope has no thrusters. To change angles, it uses Newton's third law of motion: It spins its four reaction wheels in the opposite direction it wants to go, and the combined torques point it at any location on the sky. The telescope takes 15 minutes to turn 90° — the speed of the minute hand on a clock.

Kevin attests that much of what he's learned as an amateur astronomer — from names and nomenclatures to facts and figures to general astronomy concepts — aids him in his daily work. This includes understanding and evaluating decisions made by STScI in matters ranging from scheduling the telescope to calibrating its instruments. In one instance, Kevin's familiarity with Messier objects helped when the calibration group needed to find a large open cluster in the spring sky after their go-to cluster for calibration, M35, slipped into Hubble's *solar avoidance zone*. (This is a region of sky 54° in radius around our star that the space telescope can't observe, lest its optical tube heat up dangerously.) Kevin was able to quickly recommend M44 or M67. He says that a firsthand knowledge and familiarity with CCD astrophotography has also taught him the importance of the calibration frames that STScI uses to process Hubble's images.

Looking back at Hubble's 30 years (and onward to the future), I can't help but feel that Hubble's story and mine have been intertwined, and not just because I work on the team. Hubble has had an effect on us all. It has revolutionized the



NASA / ESA / HUBBLE HERITAGE (STSCI / AURA)-ESA / HUBBLE COLLABORATION

▲ **DIAMONDS GALORE** Globular star clusters are my favorite objects to look at through a telescope. On a trip to Chile last year to experience my fifth total solar eclipse, I made a point to seek out this cluster, 47 Tucanae, in the night sky because I'd heard so much about it. I wanted to measure it up against Omega Centauri, which I'd previously seen only from the Florida Keys during the Winter Star Party, and compare the view with my own eyes to this one from Hubble. I wasn't disappointed.

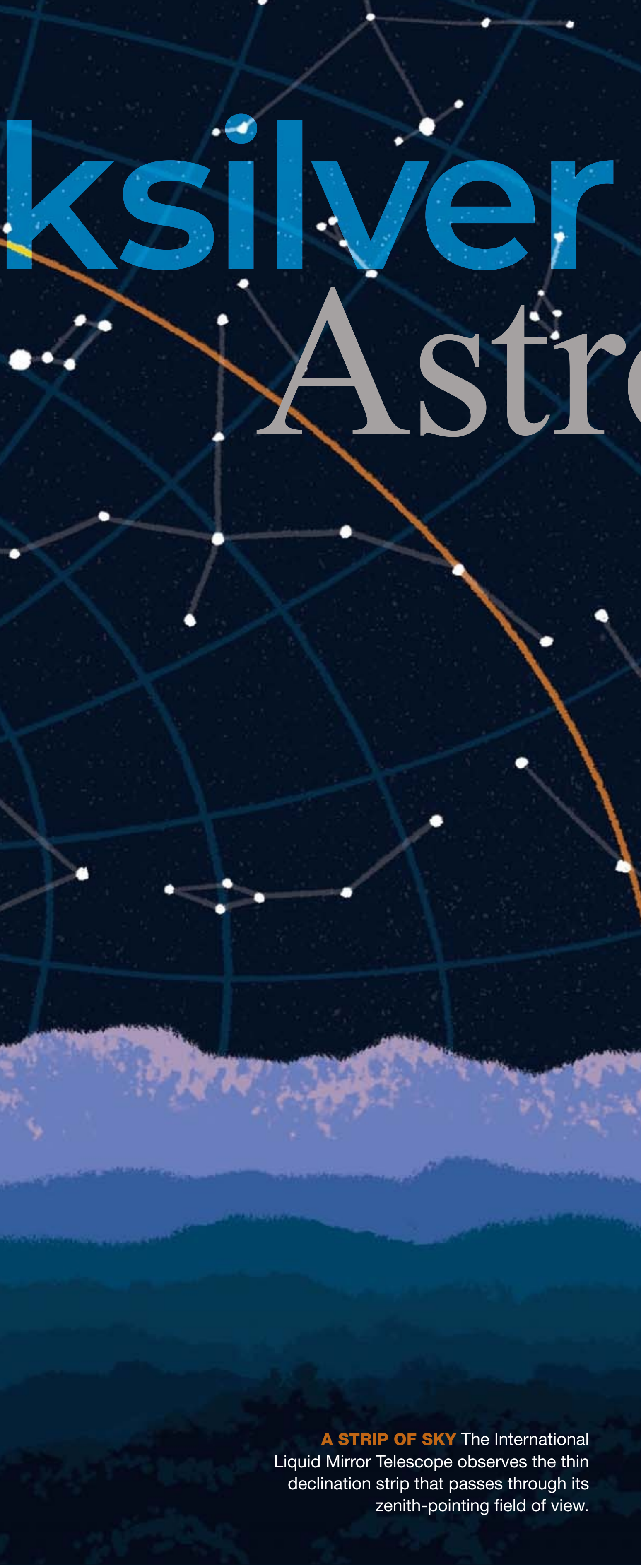
way we understand the universe, permeated our culture, and even changed the way we think about the cosmos. I know when I think of the Crab Nebula, for example, I don't immediately think of the small, oval fuzz of light in my eyepiece — I visualize Hubble's fantastic, colorful visage of tangled threads of glowing gas. I see the universe through Hubble's eye. And from views of the universe in sci-fi movies to imaginative works of art, it's clear that others do, too. I'd be surprised if Hubble hasn't made some kind of impact in the life of every astronomy enthusiast around the planet it orbits.

We hope you enjoy the images we've shared with you on these pages as much as we do, and that they might inspire you to go outside and observe the night sky, too.

■ **VANESSA THOMAS** got her start in science writing as an intern at *Sky & Telescope* many years ago. She's delighted to contribute a few words about a little NASA project she's been involved with lately.

Dive into Hubble's treasures: hubblesite.org/resource-gallery


Quic



A STRIP OF SKY The International Liquid Mirror Telescope observes the thin declination strip that passes through its zenith-pointing field of view.

LEAH TISCIONE / S&T

ksilver Astronomy

Forget lenses and silvering — astronomers are turning to whirling dishes of mercury to study the universe.

It's not the largest telescope in the world. It's not at the best possible site. And it can only look straight up, towards the zenith. But at just over $2 million, the nearly completed 4-meter International Liquid Mirror Telescope (ILMT) in northern India is cheap. So cheap, in fact, that it may usher in a new era of observational astronomy. As the very first liquid mirror telescope that will actually be used for regular astronomical research, the ILMT could pave the way for a slate of successors — maybe even on the farside of the Moon.

The principle is simple. Fill a basin with mercury (also known as quicksilver) and set it spinning. Due to the combination of gravity and the *centrifugal pseudo force*, the shiny liquid metal will adopt a paraboloidal surface — the ideal shape to focus the light of distant stars. Place a camera at the focal point, and there's your zenith-pointing telescope.

However, building the ILMT has turned out to be anything but simple. The project has a checkered history, marked by endless delays. "We just never wanted to give up," says principal investigator Jean Surdej (University of Liège, Belgium).

Fits and Starts

People have been thinking about liquid mirror telescopes for more than 150 years (see sidebar, page 26), but Surdej hadn't paid any attention to the concept until 1996. At that time, he worked at the Space Telescope Science Institute in Baltimore, studying quasars and gravitational lenses. One day, astrophysicist Ermanno Borra (Laval University, Canada) approached him. "Ermanno was developing mercury mirrors and asked me if research on gravitational lenses might benefit from the construction of a large liquid mirror telescope," he recounts. "I said no. After all, we only knew of a handful of lensed quasars back then, so a non-steerable telescope seemed pretty useless."

In the 1980s, Borra — the pioneer of the field — had already developed the necessary technologies to build small liquid mirrors. These included the use of a pressurized air bearing below the mercury container to prevent unwanted vibrations, and precise control of the rotational speed (eventually with 0.00001% accuracy) to maintain the perfect paraboloidal shape. In the late 1980s, Borra teamed up with astrophysicist

What Came Before

Isaac Newton realized that the surface of a spinning liquid forms a paraboloid — the ideal shape to focus parallel rays of light into one single point. In 1850, well over a century after Newton's death, Ernesto Capocci (Naples Observatory, Italy) was the first to suggest the use of a spinning liquid-mercury mirror to construct telescopes. However, there is no evidence that he built one. In 1868, English amateur astronomer Richard Carrington (famous for his observations of spots and flares on the Sun) also dabbled with the idea, but again, it's unclear whether or not he put it into practice.

The first documented liquid mirror was a 35-centimeter one, made in 1872 by astronomer Henry Skey in New Zealand. In 1909, Robert Wood (Johns Hopkins University) built a larger, 51-centimeter mercury mirror. However, after Skey's and Wood's early work, astronomers didn't pursue the technology again until the 1980s, when pioneer Ermanno Borra (Laval University, Canada) revived the topic. After he wrote a landmark paper on the technique in 1982, Borra kept developing the technology for many years, eventually together with Paul Hickson (University of British Columbia, Canada).

Year	Size	Milestone	Builder / Location
1850	**Concept only**		E. CAPOCCI / ITALY (NAPLES)
pre-1857	**Concept only**		BUCHAN (FULL NAME UNKNOWN) / U.S.
late 1850s	**Unspecified size**		H. SKEY / ENGLAND
1868	**Unspecified size**		R. C. CARRINGTON / ENGLAND (FRENSHAM)
1872	**0.35 m (lab)**	First published account of a working LMT	H. SKEY / NEW ZEALAND (DUNEDIN)
1908	**0.18 m (lab)**		R. W. WOOD / U.S. (BALTIMORE)
1908	**0.51 m, f/1.7 to f/3 (lab)** **0.51 m, f/9 (field)**	First astronomical observations	R. W. WOOD / U.S. (EAST HAMPTON)
1922	**15.2 m, f/5.6 to f/12 (concept)**		B. A. MCA. (FULL NAME UNKNOWN) / CHILE (CHANARAL)
1982	**Concept only**	Landmark paper	E. F. BORRA / CANADA (QUEBEC CITY)
1983	**1 m, f/0.72 (lab)**		V. P. VASIL'EV / USSR (KHAR'KOV)
1983–1986	**1 m, f/1.6 (lab)** **1 m, f/4.7 (field)**		E. F. BORRA / CANADA (QUEBEC CITY)
1983–1984	**1.7 m, f/0.89 (lab)**		E. F. BORRA / CANADA (QUEBEC CITY)
1987	**1.2 m, f/4.58 (field)**	First scientific paper based solely on LMT observations	E. F. BORRA / CANADA (QUEBEC CITY)
1987–1989	**1.5 m, f/2 (lab)**		E. F. BORRA / CANADA (QUEBEC CITY)
1989–1994	**2.7 m, f/1.89 (field)**		P. HICKSON / CANADA (VANCOUVER)
1991–present	**2.7 m, f/1.89 (field)**		PURPLE CROW / CANADA (ILDERTON)
1992–1994	**3.0 m, f/1.7 (lab)**		NODO / U.S. (HOUSTON)
1994–1995	**2.7 m, f/1.89 (field)**		P. HICKSON / CANADA (MAPLE RIDGE)
1995–2002	**3.0 m, f/1.7 (field)**		NODO / U.S. (CLOUDCROFT)
1995–2009	**2.7 m, f/1.89 (field)**		HIPAS / U.S. (FAIRBANKS)
2003–2014	**6.0 m, f/1.50 (field)**		LZT / CANADA (MAPLE RIDGE)
2006–present	**4.0 m, f/2 (field)**	First to be dedicated to astrophysical observations	ILMT / INDIA (DEVASTHAL)
2008	**20 m to 100 m (concept only)**		R. ANGEL / THE MOON (NORTH POLE)
2011	**8 m (concept only)**		ALPACA / CHILE (CERRO TOLOLO)

◀ **A HISTORY OF LIQUID MIRROR TELESCOPES** LMTs have experienced three periods of activity in the last 170 years, the current one beginning with Borra's paper in 1982. Developments in gray have limited or anecdotal evidence. Dates and focal lengths are approximate. Except for the ILMT, all telescopes built in the 1990s or 2000s were dedicated to space debris (NODO) or lidar and atmospheric studies.

Paul Hickson (University of British Columbia, Canada), who had more experience in building telescopes and who subsequently designed and engineered larger mercury mirrors.

"In 1994, my students and I had built a prototype instrument with a 2.7-meter mirror," says Hickson. "I set it up for testing in my own backyard in White Rock," a small coastal community just south of Vancouver. Just a few weeks after regular observations began, he presented the design and performance results at a conference on astronomical telescopes and instrumentation in Hawai'i. *Science* magazine reported on it, the dean of his university read the story, and before long, Hickson got money to build a permanent home for the instrument in Maple Ridge, some 60 kilometers east of Vancouver.

The UBC/Laval 2.7-meter Liquid Mirror Telescope, as it was officially known, was really a technology demonstrator — it has never been used for regular observing. But Hickson also built a 3-meter mirror for NASA's Orbital Debris Observatory (NODO) near Cloudcroft, New Mexico. NODO, largely developed under the leadership of project scientist Mark Mulrooney, operated from 1995 to 2002 and looked for small pieces of space junk passing overhead.

So by the time Borra sought collaborators for a really big mercury telescope in 1996, he and others already had quite a bit of experience with the new technology. Too bad that Surdej didn't seem to be interested.

That all changed in 1997, at an astronomy conference in Marseille, France, says Surdej. A liquid mirror telescope can only observe a narrow strip of the sky, but Surdej and his colleagues realized that a deep survey in such a narrow strip might detect some 50,000 new quasars. "About one in every 1,000 quasars should show multiple images due to gravitational lensing by a foreground galaxy," he says, "so this could yield 50 new multiply imaged quasars." That would constitute a treasure trove for cosmologists, who can use these systems to study the distribution of dark matter and the geometry and expansion history of the universe. Observing time on a "conventional" large optical telescope is much too precious to carry out such a time-consuming survey, but a cheap, dedicated instrument would be ideal.

At the Marseille conference, French and British astronomers also expressed interest, and together with Borra and Liège colleague Jean-Pierre Swings, Surdej developed the first plans for what would become the 4-meter International Liquid Mirror Telescope. However, securing the necessary funds wasn't easy. "In my naïveté, I thought that wealthy industrialists might want to sponsor the project," he says. Surdej and Swings even approached the foundation of King Baudouin I of Belgium for money. Alas, royal money failed to materialize.

TERRI DUBÉ / S&T, SOURCES: B. K. GIBSON / *JOURNAL OF THE ROYAL ASTRONOMICAL SOCIETY OF CANADA* 1991, PAUL HICKSON

Of course, building a large, unconventional telescope presented many technological hurdles, too. Right from the start, it was clear that the Belgian company AMOS (Advanced Mechanical & Optical Systems), also based in Liège, would be the main contractor for the ILMT. AMOS knew all about constructing professional telescopes (it built the four 1.8-meter auxiliary telescopes for the Very Large Telescope Interferometer in Chile), but the company had no experience with liquid mirror technology. Luckily, while visiting the NODO facility in New Mexico in 2000, Surdej ran into Hickson and convinced him to join the project. "The man is a genius," Surdej says. "Without him, the ILMT would never have been possible."

One complicated component of the future telescope was the corrector in front of the CCD camera. Because a quicksilver telescope has a fixed orientation, stellar images move across the CCD as a result of Earth's rotation. They do so in slightly curved paths, dependent on the telescope's geographic latitude. Apart from compensating for off-axis optical aberrations, the corrector — an intricate set of special-purpose lenses — also needs to rectify these curved tracks into straight lines. As a result, each stellar image moves across a straight row of pixels at a constant pace, enabling longer exposures by reading out the CCD in a "co-moving" way — a process known as *time-delayed integration*.

Initially, Surdej and his team were eying the European La Silla Observatory in Chile as the site for the new telescope. After all, back in the 1960s Belgium had been one of the founding members of the European Southern Observatory (ESO). Moreover, Riccardo Giacconi, ESO's director general from 1993 to 1999, was enthusiastic about the project. By the late 1990s, following a design proposed by Hickson and optical engineer Harvey Richardson, a British company was already constructing the ILMT corrector for La Silla's latitude of 29° south. But it never panned out, says Surdej. "We didn't develop a good personal relationship with La Silla's director, Jorge Melnick, and he wasn't very supportive. We would have had to pay €70,000 [about US$78,000] per year, just for the site, water, and electricity."

Another setback came in 2002, when the United Kingdom joined ESO. Just a few years earlier, the British research council PPARC had ranked UK participation in the ILMT project as one of their top priorities, but now they decided that all their astronomy funding should go to ESO. Around the same time, the French funding agency CNRS gave priority to the 378-megapixel MegaCam instrument on the Canada-France-Hawai'i Telescope on Mauna Kea. Suddenly, the ILMT's future started to look bleak.

> "We had the most powerful lidar facility in the world."
> —PAUL HICKSON

Himalayan Home

Meanwhile, back in Vancouver, Hickson had secured funds for the construction and operation of a larger, 6-meter liquid mirror telescope. Building on the experience with the earlier 2.7-meter prototype and using parts of the decommissioned NODO instrument, this Large Zenith Telescope (LZT) was erected between 2003 and 2005 for less than $1 million (*S&T:* Apr. 2013, p. 26).

"It took us about a year to get it working properly," says Hickson. "The main problem was that the fast rotation of the mirror — one meter per second at the rim — was causing air flows that resulted in tiny ripples on the mercury surface." Eventually, the researchers solved the problem by suspending an ultra-thin, transparent sheet of Mylar just above the mirror's surface to damp any unwanted turbulence.

However, the Maple Ridge site suffered from light pollution and bad weather. "It proved to be a good place to develop the technology, but not such a good location for astronomy," says Hickson. Instead, starting in 2008 the LZT was mainly used in combination with a lidar facility to precisely study the variable properties of the sodium layer in Earth's mesosphere. Large telescopes fire laser beams into the sky to excite sodium atoms in this 90-kilometer-high layer; the resulting *laser guide stars* enable the use of adaptive optics to compensate for the effects of atmospheric turbulence.

▼ **TEAM EFFORT** (From left to right) Jean Surdej, Paul Hickson, Stefan Denis, and Tatyana Sadibekowa prepare for the basin's spin casting.

▼ **SPIN CASTING** (From left to right) Team members Denis Defrère, Paul Hickson, Arnaud Magette, and Stefan Denis pour polyurethane over the spinning mirror basin, which is made of sheets of carbon fiber.

▼ **SMOOTHER THAN SILK** Surdej checks the smoothness of the mirror basin's polyurethane surface during the first spin casting in 2010.

ANNA AND JEAN SURDEJ (3)

"We had the most powerful lidar facility in the world," says Hickson, who is also the project scientist for the adaptive optics system of the future Thirty Meter Telescope. "Our results are of great value for the next generation of extremely large telescopes."

The LZT funding ended in 2014, and the telescope was taken apart. "We removed everything," says Hickson. "The building is now empty. Yes, it's a bit sad, but the LZT served its purpose. The experience we gained can now be used for the ILMT."

◀ **DEVASTHAL** The ILMT perches at 2,450 meters (8,040 ft) in the northern Indian state of Uttarakhand, just south of the Himalaya Mountains.

During the LZT's construction phase, Surdej and Swings had approached many other potential funders, such as the Belgian National Fund for Scientific Research (FNRS), the University of Liège, the Royal Observatory of Belgium, and the regional Wallonian government. Slowly but surely, the project got back on track. "It went slice by slice," says Swings, who, together with his colleague Serge Habraken, had become an ILMT project manager.

Then, in 2006, when the Belgian company AMOS had already started preliminary construction work, the decision was made to move the new telescope to India. As it happened, AMOS was also building a "conventional" 3.6-meter telescope for the Devasthal Observatory of the Aryabhatta Research Institute of Observational Sciences (ARIES) in Nainital, in the northern state of Uttarakhand. The institute's director at the time, astrophysicist Ram Sagar, was visiting the plant in Liège, and AMOS arranged a meeting with Surdej and Swings. Before long, an enthusiastic Sagar offered the Devasthal site free of charge, in return for a share of ILMT observing time.

Devasthal Observatory is located at an altitude of 2,450 meters (8,040 ft) in the foothills of the Himalaya. It is home to a small 1.3-meter telescope and, since March 2016, to the new 3.6-meter Devasthal Optical Telescope (DOT) — the largest one in India. "The view of the Himalayan peaks is just incredible," says Surdej. Moreover, as luck would have it, the site is almost exactly as far north of the equator as La Silla is south, at a latitude of 29°. Says Surdej: "We were able to use the same corrector that had been developed for La Silla — we just had to flip it by 180°."

So was this the end for the many troubles the project had been facing so far? Unfortunately, no. "We have experienced so many delays," laments Surdej. "I could write a book about it. I could write two."

At ARIES, construction of the 3.6-meter DOT took precedence over work on the ILMT, especially when Sagar's tenure ended in January 2014. One of his successors, astrophysicist Anil Pandey, never showed much interest in the ILMT, despite being the project's local principal investigator. Because of all the delays, the large, box-like enclosure for the ILMT wasn't completed until the spring of 2017, a full five years after AMOS had shipped the parts of the telescope to the site.

It took until early 2019 before everything appeared to be ready. With the telescope (basically a simple vertical tower to hold the corrector and the CCD camera) finally completed, it was now time to fill the 4-meter-diameter bowl with 35 liters of mercury. Upon rotating the mirror at the appropriate speed (approximately 8 r.p.m.), the mercury would distribute itself over the surface in a perfect paraboloidal film of some 3.5 millimeters.

Alas, says Hickson, who traveled all the way to northern India to witness this milestone, there was another setback. Apparently, AMOS had underestimated the amount of mercury needed to "close the surface," as it's called — 35 liters turned out not to be enough to form a perfect mirror. In mid-January, when this issue went to press, Surdej was still unable to say when the problem would be solved.

MAP: GREGG DINDERMAN / S&T; BASIN ON CRANE: RAM SAGAR; ALIGNMENT: ANNA AND JEAN SURDEJ

▶ **ARRIVAL** A transporter team lifts the ILMT basin off its truck upon its arrival at Devasthal Observatory in March 2012.

▶▶ **ALIGNMENT** ARIES electronic technical engineer Khushal Singh aligns the asymmetric optical corrector in the north-south direction at local noon. The line he's using for reference is the projected shadow of a pendulum (hanging at right).

▶▶▶ **NEARLY DONE** The ILMT appears here fully assembled, except for its mercury and the Mylar cover.

"Because of health risks, mercury may not be imported or exported from Europe," he says. "The additional mercury will now have to be imported from Ukraine, but right now I have no idea when it may arrive."

In the best-case scenario, the ILMT may see first light in the second half of April.

Mercurial Prospects

Even though it can only observe a narrow strip of sky at a fixed declination, the ILMT is the ideal instrument for two types of research. Astronomers can co-add the images taken on different nights in order to detect and study the faintest possible galaxies and quasars and to learn about the evolution and large-scale structure of the universe. They can also subtract subsequent images to search for transient phenomena such as distant supernovae, asteroids, Kuiper Belt objects, and space debris.

In fact, these are broadly the same scientific goals of the future 8.4-meter Large Synoptic Survey Telescope (LSST) — now named the National Science Foundation Vera C. Rubin Observatory. Of course, compared with the Rubin Observatory, the ILMT has a much smaller (16-megapixel) camera, a much smaller field of view (27 arcminutes across), and thus a more limited view of the night sky. But it is also roughly 300 times less expensive.

However, despite the bright prospects, the immediate future of mercury astronomy is uncertain. Years ago, together with astronomers from three other universities, Hickson's team developed the design of a large 8-meter liquid mirror telescope for the Cerro Tololo Inter-American Observatory in Chile. That would have been a pathfinder for an envisioned Large Aperture Mirror Array (LAMA) — an optical interferometer consisting of 18 similar instruments.

Such an array would yield a huge sensitivity and an unprecedented angular resolution for a reasonable price. "However, we were unable to raise funding to continue the project," he says.

Other ambitious plans also failed to materialize. Both the NASA Innovative Advanced Concepts (NIAC) Program — an initiative to explore controversial ideas and risky endeavors — and the Canadian Space Agency have funded feasibility studies for a large liquid mirror telescope on the surface of the Moon. Because of the lack of atmosphere, a liquid mirror telescope on the Moon could not use mercury: It would immediately evaporate. Instead, engineers considered molten salts, a type of compound known as ionic liquids. The NIAC study, led by famous telescope pioneer Roger Angel (University of Arizona), focused on a 20-meter instrument, but thanks to the Moon's low gravity, even a gigantic 100-meter successor might be a serious possibility. Unfortunately, these studies have never been followed up.

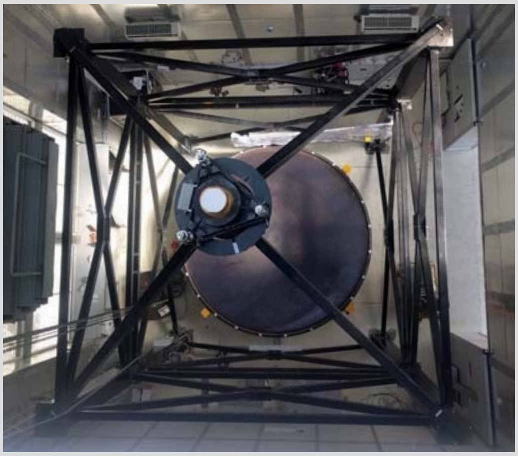
Hopefully, when the ILMT starts to yield its first scientific results, the tide may turn again in favor of quicksilver astronomy. "We have found solutions to all of the potential problems in the construction of large liquid mirror telescopes," says Hickson. "From now on, it just requires willpower to realize them."

As for Surdej, he says he's "too pragmatic" to consider futuristic projects like a large liquid mirror telescope on the Moon. "Right now, I'm happy enough that the ILMT has finally been completed."

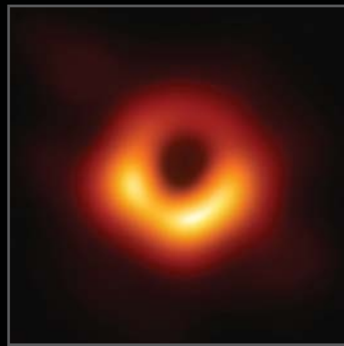
■ *S&T* Contributing Editor **GOVERT SCHILLING** is an astronomy writer in the Netherlands. When he first read about liquid mirror telescopes some 30 years ago, he thought it was an April Fools' Day joke.

ANNA AND JEAN SURDEJ (2)

▶ **OBSERVATORY** This aerial view shows the liquid mirror's "dome" (lower left) as well as the 3.6-meter Devasthal Optical Telescope (background) and the 1.3-meter Fast Optical Telescope (foreground, right). The Himalayan foothills are behind the camera.



 by Howard Banich



A Curious Straight Ray

Join the author on his endeavor to observe and sketch the relativistic jet in Messier 87.

Imagine a close-up view of M87's central regions, with its raging accretion disk distorted by the extreme gravity of the 6.5-billion-solar-mass black hole within. Now envision two tightly collimated, relativistic jets screaming out for thousands of light-years in opposite directions, perpendicular to the accretion disk. Visually detecting any trace of the blazing jet would be an extraordinary observation from 54 million light-years away, yet incredibly it's quite possible for an observer with the proper equipment and observing conditions to succeed.

M87 and Its Jet

M87, a supergiant elliptical galaxy (classified as type-cD in the Yerkes system), is located deep in the heart of the Virgo Galaxy Cluster. M87 weighs in at around 200 times the mass of the Milky Way Galaxy. More impressively, its supermassive black hole was the first to have its shadow imaged by the Event Horizon Telescope, an astonishing and historic achievement (*S&T:* Sept. 2019, p. 18).

M87's visual jet that's aimed roughly in our direction is about 5,000 light-years long and may be pointed only 15° or so away from beaming directly at us. This makes it a likely "misaligned blazar" — if the jet were pointed directly at us, M87 would have all the characteristics of a blazar.

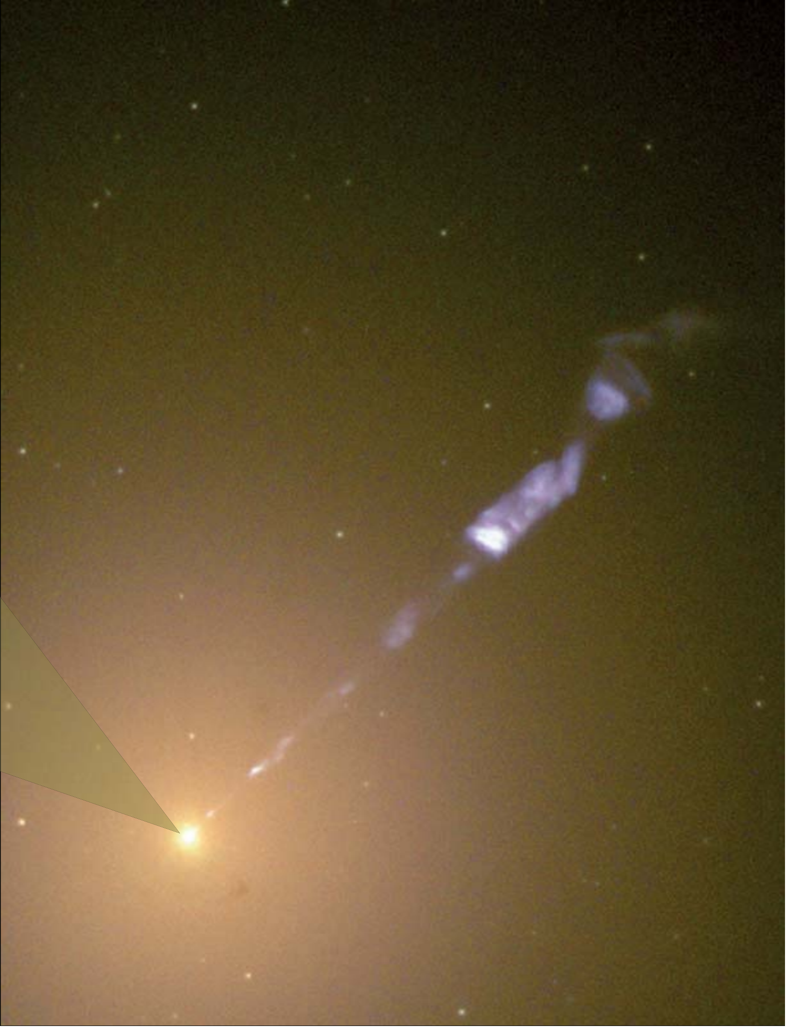
Highly energetic conditions in the black hole's accretion disk can give rise to jets, such as the one we see in M87. The interplay between matter (or plasma) in the accretion disk, the strong gravitational potential of the supermassive black hole,

Discovery of the Jet

Heber Doust Curtis, astronomer at the Lick Observatory, discovered M87's jet in photographs obtained with the 36-inch Crossley Reflector and published this in 1918 in *Publications of the Lick Observatory, Vol. XIII, Part I*:

◀ **AT LICK OBSERVATORY** Heber Doust Curtis poses with the 36-inch Crossley Reflector. Curtis first noted M87's jet in a photograph taken through this very telescope.

BLACK HOLE: EVENT HORIZON TELESCOPE COLLABORATION; CURTIS: COURTESY SPECIAL COLLECTIONS / UNIVERSITY LIBRARY / UNIVERSITY OF CALIFORNIA SANTA CRUZ / LICK OBSERVATORY RECORDS



▲ **JET POWER** Matter pours out of M87 at relativistic velocities in a highly collimated outflow. Note that this Hubble image shows only the central portion of M87, creating the impression that the jet extends to the visible edge of the galaxy. In reality, the jet is mostly within the brightest part of the core, one of the reasons it's difficult to see visually. All the slightly fuzzy starlike objects in the image are actually globular clusters. The inset is the Event Horizon Telescope image of M87's supermassive black hole's shadow surrounded by a ring of light.

M87: THE HUBBLE HERITAGE TEAM / STSCI / AURA / NASA / ESA

and the magnetic field locked in the accretion disk generates the jets. Radiating shock waves along the path of the expelled matter contribute to the knotty nature of the jets. The jets are quickly accelerated to relativistic speeds, creating the perfect setup for the illusion of *superluminal motion*, making this an even more fantastic object. (See the sidebar on page 33 for a brief explanation of this non-intuitive phenomenon.)

Another relativistic factor, *Doppler boosting*, makes M87's approaching jet appear brighter. This phenomenon is a combination of seeing the jet's concentrated light pointed nearly at us, and movement of matter within the jet approaching us at relativistic speeds. Due to a combination of geometry and the relativistic beaming effects of matter traveling at speeds close to that of light, the *counterjet* (or the jet that's ejected in the opposite direction to the one we see) is less readily detectable.

How to See the Jet

In spite of these superlatives, M87 itself is a bit of a telescopic letdown. Visually, it appears as a nearly featureless round glow that's bright at its center and gradually fades away into intergalactic space. That's it. A casual, low-power look shows no obvious sign of the incredible jet blasting from its core. By definition M87 doesn't have spiral arms, or dark lanes of gas and dust to break up its uniform shape, so depending on the size of your telescope and observing conditions it's usually a rather uninspiring sight.

But with a little luck, and when the atmosphere is exceptionally steady, the view through a large amateur — or small professional — telescope will show the jet, transforming this galaxy into a spine-tingling, unforgettable object. Here are some tips on how to see it:

Step 1: Find a big telescope located somewhere that regularly has steady seeing.

This is by far the easiest way to see the jet. M87 is bright and large enough to observe in just about any size telescope, but seeing the jet well requires both a big telescope and steady seeing conditions. In my experience, you're practically guaranteed a good view of the jet when you use a big (48-inch or larger) scope, even when conditions aren't at their best.

Alternate Step 1: Sighting the jet is also possible with scopes in the 12- to 16-inch range.

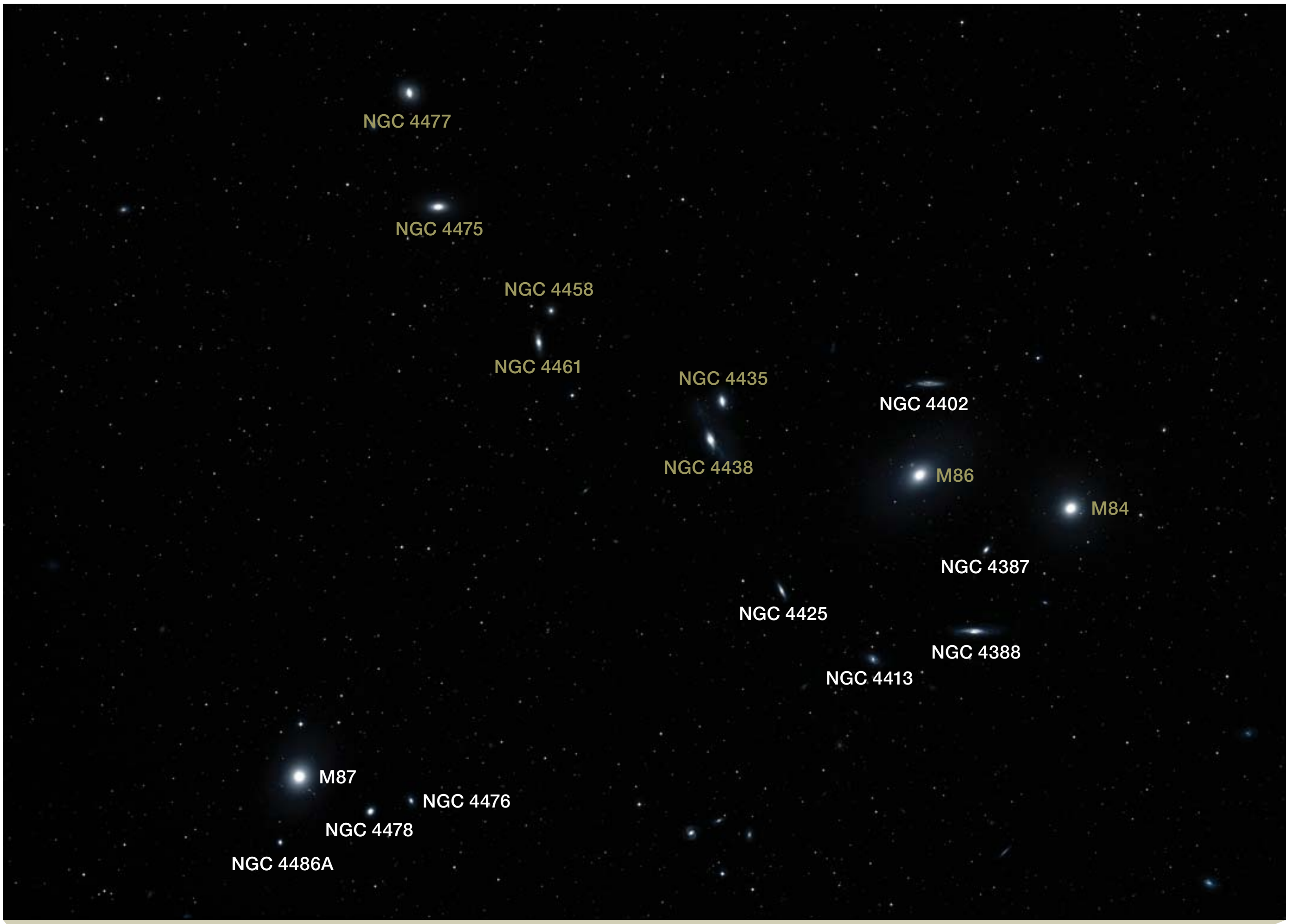
Again, steady seeing is absolutely essential for a successful observation with scopes in this size range. You'll need

Exceedingly bright; the sharp nucleus shows well in the 5^m exposure. The brighter central portion is about 0′.5 in diameter, and the total diameter about 2′; nearly round. No spiral structure is discernible. A curious straight ray lies in a gap in the nebulosity in p.a. 20°, apparently connected with the nucleus by a thin line of matter. The ray is brightest at its inner end, which is 11″ from the nucleus. 20 s.n.

(The final notation refers to the fact that Curtis also identified "20 small nebulae," which we now understand to be galaxies, on the same plate.)

As it happened, Curtis discovered M87's jet a little more than a decade after Albert Einstein published his paper on special relativity in 1905. Curtis and his colleagues had no idea at the time what M87's "straight ray" was. It wasn't until the early 1950s that our current understanding of it as a relativistic jet streaming out from the center of M87 began to take shape.

By the way, Curtis is almost always referred to as H. D. Curtis in the literature, and I'm unaccountably pleased to have finally come across his full name.



A CURIOUS GALAXY AMONG MANY OTHERS You'll find M87 deep inside the Virgo Cluster, with Markarian's Chain (members are labeled in gold) arcing gracefully to its north.

sharp optics, and be prepared to pile on more magnification than you might think is required. The reward is worth your effort and patience.

Step 2: Know where to look, what to look for, and how to maximize your chances of seeing it.

Knowing the orientation of the jet relative to the center of M87 is helpful, as is having a good idea of how short the jet is compared to the rest of the galaxy. My sketches on pages 34 and 35 show the orientation and length of the jet, so check them carefully if you plan to go after it. For best results, especially in smaller scopes, be sure to place the location of the jet in the *averted vision sweet spot* of your observing eye to improve your odds at seeing it.

What is the averted vision sweet spot? It's the place in your eye where your averted vision is most sensitive, and knowing exactly where it's located is a valuable tool for detecting small objects like M87's jet. It's usually about a third of the way

POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY across your field of vision away from your nose, but it varies from person to person. The only way to find yours is by noting where dim objects consistently appear brightest in your field of view.

Step 3: Steady seeing is the hard part.

The contrast between the galaxy's fuzzy core and the thin, sharply delineated jet makes it seem like this shouldn't be such a tough observation. That's how this cookie crumbles, though, and the jet can be seen only when the air is steady, unless you're using a really large scope. A trembling atmosphere blurs the jet into the overall fuzziness of M87, and unfortunately there are few places that have consistently steady seeing.

For many of us in the Northern Hemisphere M87 is never high enough to get the most out of a steady night. Sometimes it happens anyway, though, and depending on your observing site it may take many nights before the atmosphere gets out of the way enough for a successful observation.

Visual Observations

My experience trying to see the jet certainly followed that pattern. Before even suspecting that I'd seen the jet, my notebooks are filled with observations that boil down to "tried to see M87's jet, no luck again." I first tried throughout the 1980s with my homemade 12.5-inch f/7.8 Dob, and continued trying when I replaced the Dob with a 20-inch f/5 Obsession in 1991. I had one observation with the 20-inch that gave brief but repeated suggestions of the jet, but I can't say that I really saw it. Frustrating.

In 2007 I had my first taste of the jet with my 28-inch f/4 Dob, but I couldn't convince myself I'd really detected it. While hints of the jet are enticing, they're also disappointing.

Three years later all that changed on a memorable night at Kitt Peak.

Capturing the Jet

You don't need a large telescope or digital detector to image the jet. For this 90-minute exposure captured on Fuji Provia 400F slide film, amateur astronomer John Boudreau used a 12-inch Meade SCT scope at f/11 and an Olympus OM1n camera. He took the photo on March 20, 2001, at Myles Standish State Forest near Plymouth, MA.

Want to see M87's jet in a big scope?

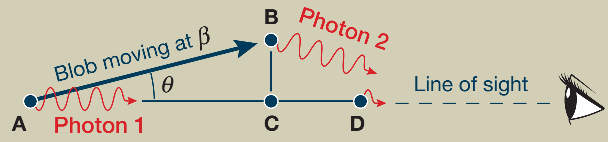
Here are links for public viewing reservations at the three largest publicly available telescopes in the U.S.:

- 82-inch Otto Struve scope at McDonald Observatory: **https://is.gd/mcdonald_visitors**
- 100-inch Hooker telescope on Mt. Wilson: **https://is.gd/mtwilson100_visitors**
- 60-inch telescope on Mt. Wilson: **https://is.gd/mtwilson60_visitors**
- Note: The 90-inch Bok telescope at Kitt Peak doesn't accept reservations for public viewing.

SUPERLUMINAL MOTION: GREGG DINDERMAN / *S&T*

How Apparent Superluminal Motion Works

M87's jet has the perfect setup for the appearance of superluminal motion, but the concept itself can be a slippery one to grasp at first. A little math and a simple diagram of the geometry will help you understand what's going on. Bear in mind that the diagram below isn't to scale, but it gives you a general idea of the layout.



Point A in the diagram is the stationary source of the jet that's expelling matter — a blob, say, or a shock wave — at a velocity that's a significant fraction of the speed of light, which we'll call β (= v / *c*). The blob travels at an angle θ to our line of sight. The blob emits a photon at A, and then some time later, when it has arrived at Point B, it emits another photon. During that time (the photons will take a long time to arrive at the detectors at Point D, though!), the blob appears to have covered the transverse distance BC.

Making simplifications, we have the following formula for the blob's transverse velocity (its speed across our line of sight):

$$\text{v\_transverse} = \frac{\beta \sin \theta}{(1 - \beta \cos \theta)}$$

This is where the fun part begins: Grab your favorite calculating device and start plugging in numbers.

Let's start with a blob traveling at 90% the speed of light (so, $\beta = 0.9$) at an angle of 15° to our line of sight. Substituting for those numbers:

$$\text{v\_transverse} = \frac{0.9 \sin 15°}{(1 - 0.9 \cos 15°)} = 1.8c$$

The blob appears to travel at nearly twice the speed of light!

What happens if we slow the blob down to 60% the speed of light? Substituting 0.6 for β gives us:

$$\text{v\_transverse} = 0.4c$$

And 25% the speed of light? We get,

$$\text{v\_transverse} = 0.09c$$

Notice how the actual speed of the blob, v, has to be close to the speed of light for the superluminal effect to occur?

First Success: The 90-inch Bok Telescope

The view through the 90-inch Bok telescope at Kitt Peak in 2010 was a dramatically different story altogether, made even more special because it was a once-in-a-lifetime opportunity to observe through this tremendous instrument. Here's an excerpt from my notes:

> *"By golly, there it is, big as life! AV* [averted vision] *brings it out best along with two bright knots in the jet — how cool is that! Words are failing me at this point because everything is superlative — a jet of relativistically accelerated matter by a supermassive black hole — woohoo! The jet appears cooler / bluer than M87 . . . 668×, 21.52 SQM* [sky quality meter]."

This was an electrifying sight! I had given no thought to the jet's color beforehand and seeing it so well was thrilling. Afterward, I wondered if this stunning vision of the jet would spoil future observations. Fortunately, no.

Second Success: My 28-inch Telescope

The first time I definitely saw the jet in my own scope was in 2012. Through the 28-inch I saw the two knots on the end of the jet blurred into a single stubby, fuzzy knob pointing outward from the core of M87. It was diffuse and appeared much wider than expected — the knots had looked stellar in the 90-inch — but that did nothing to dull my excitement. Hey, I'd finally seen part of the jet in my own scope! Assuming it's possible (which I am), seeing it extend all the way to the core in the 28-inch will take a night with much steadier seeing conditions. My notes from that night's observing read:

> *"Not quite a jet sighting, but I did see the brightest knots in the jet! I should have given this a shot last night when the seeing was steadier. 695×, 21.68 SQM."*

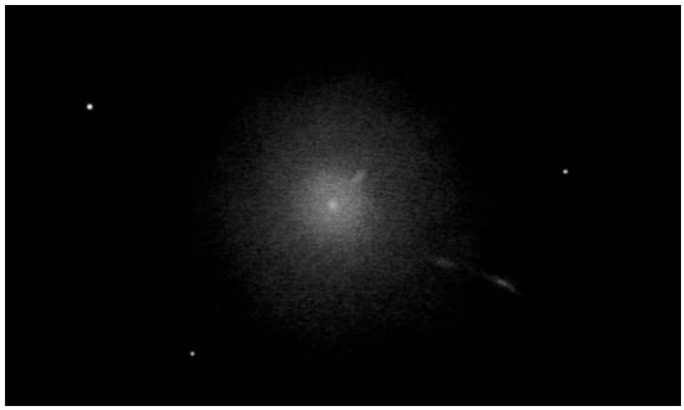
Third Success: Jimi Lowrey's 48-inch Telescope

I've seen the jet in Jimi Lowrey's 48-inch each time we've looked. The best views show the jet coming from the central core, and the two brightest knots toward the end look like beads on a string. This is what I noted regarding my best view in 2017:

> *"Holy cow, this is nearly as good a view as in the 90-inch Bok!! The jet is thin and long, coming directly out of the core and has two knots, the brightest on the end. They're stellar during the steadiest moments of seeing. SPECTACULAR! 690× gave the best view — an unforgettable sight — wow! 21.74 SQM."*

Interestingly, the jet has always looked wider in the 48-inch than in the 90-inch. Or in the 82-inch for that matter, which is just a short drive up Texas Highway 118 at McDonald Observatory.

▲**THROUGH THE 90-INCH BOK TELESCOPE** The view was pretty much the same through the 82-inch and 90-inch scopes, so this 90-inch sketch represents them both. M87's outer reaches had no obvious edge and filled the field of view. The relativistic jet was a knockout direct-vision object, especially when the light blue color of the jet was seen — look carefully at the sketch, the color is subtle just like through the big scopes. Wow for both! North is up in all sketches featured here.



▲**THROUGH MY 28-INCH SCOPE** This sketch shows how I perceived M87 and the knots at the end of its jet in my 28-inch f/4 scope. Compare with the other sketches and note that the jet isn't portrayed as a thin ray all the way to the core. See also how wide the knots are — they blended into one fuzzy blob during this observation.

▲**THROUGH JIMI LOWREY'S 48-INCH SCOPE** I call this a "kick-butt view," though I didn't perceive any color in this observation.

HOWARD BANICH (3)

Fourth Success: The 82-inch Otto Struve Telescope

The jet was a wondrous sight in the 82-inch even on a so-so night that coincided with the 2019 Texas Star Party. I described my experience thus:

> *"A fantastic view! The jet is an exceedingly thin ray shooting from the center of M87, and has two star-like knots along its length. The jet also has an unsaturated light blue hue, just like in the 90-inch Bok scope. Interesting that the jet looks so thin in the 82-inch and 90-inch scopes but is (by comparison) a stubby finger in Jimi's 48-inch and (even stubbier in) my 28-inch. 617×. (no SQM)."*

You've probably noticed these observations were made with magnifications between 617× and 695×. I'm not suggesting this is the optimal magnification range in every telescope on every night, but it does point out that significant magnification is needed. The jet is quite small at only 20″ long and 2″ wide.

Orientation of the Jet within M87 and Nearby Galaxies

The small size of the jet isn't the only reason it's difficult to see. It's nearly hidden in the bright core of M87, and only the two brightest knots extend into its fainter, outer reaches. Even on a steady night the contrast between the jet and the core is rather low, so it's helpful to know how the jet fits within M87 and in which direction it's pointing.

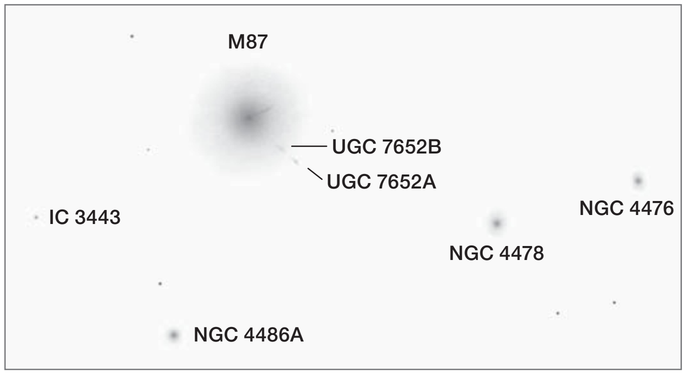
Perhaps the quickest way to find the orientation of the jet is to start by locating the two faint galaxies closest to M87, UGC 7652B (magnitude 16.6) and UGC 7652A (magnitude 16.8). Don't confuse them with the much brighter and farther away NGC 4478 (magnitude 11.4) and NGC 4476 (magnitude 12.2). A line drawn approximately between the two fainter galaxies toward M87 forms an angle of about 80° with the direction of the jet.

If you can't see these two faint galaxies, a line drawn through the two NGC galaxies and NGC 4486A points in nearly the same northwest direction as the jet.

Visual Size of M87 and its Jet

M87's apparent size is hard to pin down because it becomes fainter so gradually away from the core that there's nothing to suggest an outer edge. As such, its size can change quite a bit depending on observing conditions. As I've noted, steady seeing is the most important factor in glimpsing the jet. Don't let sub-optimal darkness and transparency conditions slow you down — approach the jet in much the same way as observing the planets. Your best view of M87 isn't necessarily your best chance to see the jet.

For example, I've seen the jet in Jimi Lowrey's 48-inch scope on a night with essentially perfect darkness and transparency, and on another night that was much brighter and less transparent. The view of the jet on the brighter, less transparent night was sharper and more detailed simply because the seeing was steadier.



HOWARD BANICH

▲ **JET ORIENTATION HELPER** The small galaxies UGC 7652A and UGC 7652B are seemingly embedded in M87's glow. The two bright knots near the end of the jet are right on the edge of the bright core, and the jet is pointing toward about 2 o'clock. This sketch is a combination of low- and high-magnification observations.

Interestingly, the larger the aperture, the thinner the jet looks. As a general rule, elongated deep-sky objects tend to look wider in smaller scopes than they do in larger ones, and especially as compared to images. I'm not sure why they look wider rather than just fainter in smaller scopes, but it's a common theme in deep-sky observing.

Color

I first thought the cause of the jet's light-blue color through the 82- and 90-inch scopes was the jet's blueshifted light due to its relativistic speed in our direction. The actual origin for the blue glow is synchrotron radiation arising from electrons spiraling in the helical magnetic fields of the jet. I can't decide which is more astounding — the monumental physical processes creating the color, or being able to see it in the eyepiece from 54 million light-years away.

Observing through professional instruments like the 82-inch telescope at McDonald Observatory or the 60- and 100-inch scopes on Mt. Wilson is a rare treat and is your only chance to see the color of the jet. It's also one of the best reasons to pay for the opportunity. For the cost of a decent eyepiece, you'll get to see — along with many other great objects — a superluminal, blueshifted, relativistic jet emitting blue synchrotron radiation created by a 6.5-billion-solar-mass supermassive black hole. And that just might be the best bargain ever.

Any observation of M87's jet is exciting, though, so don't think the view through these big scopes is the only way to go. Even if you just barely discern the jet in your own scope, you've still seen one of the most exotic and exciting astrophysical objects in the universe.

■ Contributing Editor **HOWARD BANICH** is a relatively lucky dog to have seen M87's jet so well.

The Classic Dobsonian Telescope

A relic of the ’70s finally sees the light.

In 1969, John Dobson sent an article query to Charles Federer, founder and editor of this magazine. Dobson had come up with a new way to build large-aperture telescopes cheaply and effectively. But Federer famously rejected Dobson’s submission, saying, “While your shortcuts undoubtedly help to demonstrate large amateur telescopes, they can hardly lead to satisfactory instruments of the kind most amateurs want in these large sizes.”

To say that Dobson had the last laugh is an understatement. Dobsonian telescopes revolutionized amateur astronomy. The majority of large-aperture amateur telescopes today ride upon Dobsonian mounts.

To its credit, *Sky & Telescope* published several articles about Dobson over the years, and I recently wrote a brief article on how to build a modern Dobsonian mount for a hobby killer (*S&T:* Dec. 2019, p. 72). But we haven’t yet published an article on how Dobson did it back in his heyday.

I recently got the opportunity to examine a genuine Dobsonian telescope that had never been finished, and to complete its construction using the original materials of the day. Of course I documented the process. So here, at long last, is the article that we should have published in 1969.

Dobson spent over two decades as a Vedantan monk, and the austere monastic lifestyle stuck with him even after he left the monastery. To make ends meet, and to continue his ongoing goal of promoting amateur astronomy, he taught

Visit https://is.gd/Dobson to watch a video of John Dobson describing how his telescopes are built.

◀ This 8-inch f/6 Dobsonian reflector was built under the personal tutelage of John Dobson during a six-week telescope-making class in Eugene, Oregon. After passing from its original owner to telescope maker Jerry Oltion in 2018, it regularly shares the night sky at star parties hosted by the Eugene Astronomical Society.

ALL PHOTOS BY JERRY OLTION; FLOWER ILLUSTRATIONS: THOMAS PAJOT / SHUTTERSTOCK.COM classes throughout the country on how to build telescopes. During those classes, he would teach students how to grind a primary mirror and how to build the telescope to house it. Students successfully completing the class would take home a finished, functional telescope. Dobson taught one such class in my hometown of Eugene, Oregon.

Jump to 2018. While I was helping put on a star party, a man approached me to ask if I would be interested in having a telescope that he'd started in Dobson's Eugene class but had never finished.

I fell in love at first sight. This scope was an absolute classic, built exactly to Dobson's specifications in every detail. So I set out to finish it, keeping the design as pure as I could make it.

Back to Basics

What makes a classic Dobsonian design? Many elements, but they all revolve around a basic theme: cheap. Dobson's goal was to make telescopes out of scrap materials, items that you could often get for free. Free is the great equalizer, and that was Dobson's primary focus: to put telescopes in the hands of anybody who wanted one.

To start with, attendees ground the mirror out of whatever glass they could find. Dobson used porthole glass for many of his primary mirrors. When he taught classes, the students often bought mirror kits when there was no other source of cheap, thick glass, but John would happily teach people how to grind a chunk of storefront door into a mirror if one was available.

The one in my scope used a Pyrex blank from a kit. It did have one characteristic Dobson-class feature, though: Since the classes typically ran for only six weeks, students rushed from one grit to the next, often not sufficiently grinding out the pits from the previous grit before moving on. This mirror was like that. Even though it had been polished and parabolized, the outer half-inch was so frosted with pits from the previous grits that it was unusable. The maker had in fact masked it off, turning an 8-inch blank into a 7-inch mirror.

I decided that I needn't slavishly accept every aspect of the classic Dobsonian, and in fact most of Dobson's own mirrors (and many, many mirrors from his classes) were excellent, so I took this mirror back to 30-micron grit and ground out the pits, then fine-ground, polished, and re-parabolized it. At f/6, that was a pretty simple job, and that's another aspect of the classic Dobsonian telescope: fairly long focal ratios. No f/4 rich-field scopes here; Dobson and his students made "planet-killers," galaxy-nabbing yard cannons.

When I was done with the mirror, I sent it off to Bob Fies (**alcoat.net**) for aluminizing, since Bob coated many of Dobson's mirrors. I got back a beautifully finished 8-inch f/6 mirror.

The optical tube was a cardboard concrete form. "Sonotubes," as they're typically called even when made by another company, fulfill the goal of being cheap, they come in sizes that complement most standard mirror diameters, and they're stiff enough to hold their shape from horizon to zenith. They're also heavy. And coated with wax. Wax keeps concrete from sticking to the tube, but it also prevents paint from sticking to it. This one must have been an inside form, intended to leave a hole in a foundation, because the wax was on the outside. So I did as Dobson would have done — I peeled off a layer of the cardboard spiral, exposing a rough paper surface that would readily accept paint.

▲ The telescope came to me in this rough condition — nearly finished, but not quite.

Primary Support

The mirror mount was already built, and I'm glad it was because I would have had a very hard time believing that it would work otherwise. It's just a plywood square the same width as the mirror diameter, with the corners cut off so it will fit snugly inside the tube. Three bolts screwed through tight holes in the plywood push against the mirror to provide collimation adjustment. To prevent having metal on glass, the Dobsonian design calls for three squares of ⅛-inch Masonite (called hardboard nowadays) between the bolts and

▼ The flowers and ladybugs were painted by hand. Wearing tie-dye is essential at this stage.

▲ Peel away the waxed outer layer of the tube to allow paint to adhere to its surface. Unwrapping the spiral onto a dowel works like a charm.

the mirror back. What holds these small hardboard squares in place? Why, a triangle cut out of a cereal box, of course, and glued to the front of the plywood square.

To center the mirror in the tube, Dobson used blocks made of that selfsame ¾-inch plywood screwed to the inside of the tube. Cut the plywood to the right thickness and mount it edge-on, and it makes a remarkably good mirror support. To provide good side support for the mirror, Dobson mounted four of these plywood blocks at 45° and 135° from the top on either side, achieving the same 90° support separation that we still use today. If the thickness of the blocks wasn't just right, he shimmed them with pieces of cereal box.

To keep the mirror from falling forward when the scope is tilted low to the horizon, Dobson used furring nails driven into the plywood blocks. The designer of my scope got fancy and used nylon sleeves around screws. Whatever you use, give these mirror stops an eighth of an inch or so of space so you can collimate the mirror upward that much, and that's that. To install the mirror, slide it into place between the blocks, bump it up against the stops, then put the plywood square (called the "tailgate") backing plate up against it and screw it into place. You can screw through the outside of the tube into the edge of the tailgate, or screw upward through the tailgate into the plywood blocks. Tilt the tube upward and you'll hear the mirror go "clunk" against the hardboard collimation pads.

A Simple Secondary

On the other end of the scope, the secondary mirror is held in place by a spider made of narrow slats of cedar shingles simply wedged into place.

No, really.

This was the moment when I truly began to appreciate the genius of Dobson's design. Talk about simple, cheap, and effective!

To make the secondary mount, cut a piece of wide wooden dowel about 3 inches long. Cut one end at a 45° angle. Then cut three ⅛-inch wide grooves along the length of it, spaced 120° apart, and about ¼-inch deep.

Then cut three shingles to size so they'll wedge into the grooves you just cut, and the three-vane propeller you make

▼ *Left:* The mirror is centered in the tube with small blocks of plywood. Nylon sleeves screwed into the plywood keep the mirror from falling forward. *Middle:* Once the mirror is installed, the plywood tailgate is tipped into place and screwed down. *Right:* The spider assembly that holds the secondary mirror in place is made from cedar shingles.

when you do so will wedge tightly into the front of the tube. Glue the secondary mirror to the angled face, aim it at the focuser hole, and adjust the collimation by pushing and pulling on the shingles where they meet the tube.

I'm really not kidding — it works like a charm!

The focuser is equally simple. It's just a cardboard tube sticking out the side of the main telescope tube. You glue it to a rectangle of hardboard that's screwed into place so you can adjust its aim with shims. Your eyepiece goes in another tube that fits inside the first one, which you push inward and pull outward to focus.

As for eyepieces: You don't buy them. Well, you do, but not the way you think. What you buy is an old pair of cheap binoculars at a thrift store or garage sale and take them apart. Instant eyepieces! They'll probably be too small in diameter to fit snugly inside the focuser tube, so wrap some cereal box cardboard around the barrel until it's just right.

The ends of the Sonotube get pretty badly beat up just from resting the scope on the ground before setting it up, and from banging it into door frames on the way in and out of the house. I don't know what, if anything, Dobson did to protect the ends of the tube, but I discovered that ¼-inch gas hose split lengthwise makes a dandy protective trim. Once I was sure of its fit, I glued it into place with Shoe Goo.

A lot of early Dobsonians didn't have finders. Users simply sighted down the tube or along the edge of the tube box. But I built a simple peep-sight finder for mine, reasoning that it was consistent with the simple-and-cheap theme of Dobson's design. A shower cap for a dust cover also fits that theme.

Constructing the Rocker Box

At this point you have a functioning telescope, but you haven't yet built the actual Dobsonian mount.

The OTA mounts inside the rocker box by way of a plywood "tube box" that fits snugly around the cardboard tube. Dobson was a fan of scrap plywood, and this scope was built to spec: ¾-inch thick and fairly smooth on one side, but rough as a cob on the other. That helped immensely with gripping the tube and holding it firmly in place.

The altitude bearings are sewer pipe end caps resting on felt pads. No form-fit circular cutouts here, just a V-shaped notch.

The rest of the mount is built of the same rough plywood. Lots of it. And its design is as brilliant as the OTA. For one thing, seven of the nine plywood slabs that comprise the mount are the same size, making cut-out and construction as simple as you could ask for. Two of those slabs glued and screwed together make up the ground board, while two more make up the bottom of the rocker box. (Can you say "Rigid"?) Two more make up the side boards and another makes the front board. Add two more narrower, tall "cradle boards" with V-shaped notches for the altitude bearings to rest in, and you're done with the rocker box.

One major advantage to this design is that you can customize the cradle boards all day long without having to rebuild the rocker box. If you need more room for the bottom

People love it.
This scope gets the longest line of any of them, first to look *at* it, then to look *through* it, again and again.

◀ A phonograph record on Teflon pads provides an excellent azimuth bearing. Alas, it's not Holst's *The Planets*, but it is a classic.

◀ The rocker box and ground board are made of seven identical rectangular slabs of plywood, plus two upright cradle boards.

of the scope to clear the bottom of the box, simply raise the cradle boards. If you didn't get the V-shaped notches precisely even and your tube box scrapes the rocker box, adjust one or the other of the cradle boards to compensate.

And then there's the *pièce de résistance*: the azimuth bearing. It's a phonograph record! It's nailed to the underside of the rocker box, and Teflon pads on the ground board face upward to glide smoothly on it.

And I do mean smoothly. This scope slews as gracefully as any I've ever used. I can move it diagonally with just the push of a single finger, with no lurching and no preferential direction to its motion.

When I finished the scope, I was insanely happy with how it worked, but I needed to paint it something appropriate. Fellow ATM Robert Asumendi (of 3D-printed binoscope fame, *S&T:* June 2019, p. 74) pointed out that the original Dobsonians were built in the late '60s and early '70s, a time when wild colors were the fashion of the day.

So I used some fluorescent paint and painted the tube tie-dye, and hand-painted hippy-dippy flowers on the rocker box. Now it truly looks like a scope designed in the '70s.

New Life Under the Stars

Today the scope belongs to my astronomy club, the Eugene Astronomical Society. We take it to star parties and use it as a jumping-off point to tell people about the genius of John Dobson, who realized that a cannon mount could be used for telescopes, and how he used that design to revolutionize amateur astronomy.

People love it. This scope gets the longest line of any of them, first to look *at* it, then to look *through* it, again and again. Because despite its funky appearance and simple materials, this classic Dobsonian scope knocks the socks off anything else on the field. And that, dear reader, was John Dobson's entire point. Cheap can still be excellent.

I got the chance to meet Dobson in the mid-2000s. I had just come up with my own mount design (the trackball, *S&T:* Aug. 2006, p. 100), and I happily described it to him, ending with, "I'm really hoping it will catch on like your design did." To which he replied with characteristic bluntness, "Good luck with that. It took 20 years before anybody paid any attention to me."

Indeed, it took awhile. But you can't keep a great design down. And John Dobson's contribution to astronomy, now and forever, is looking up.

■ Contributing Editor **JERRY OLTION** loves classics of every type, including the azimuth bearing.

The Dobsonian Mount

John Dobson didn't want his design to be named after him. He simply called it a cannon mount, or an altitude-azimuth mount. But the astronomy community called them "Dobsonians" and continues to do so to this day. It's a fitting tribute to the man who brought large-aperture scopes to the masses and forever changed the way we do amateur astronomy.

For detailed instructions on building your own classic Dobsonian scope, visit Ray Cash's site at https://is.gd/dobplans.

▲ *Left:* The finder is a simple peep sight. An equally simple cardboard tube slipped inside another cardboard tube serves as the focuser. The OTA end protector is a length of ¼-inch gas hose split lengthwise and glued into place. *Right:* In keeping with the simplicity of the overall design, the dust cover is a shower cap.

The Pleiades will embrace Venus in their dusty veils on the evening of April 3rd.

MASIL IMAGING TEAM

1 DAWN: The beginning of the month treats us to a trio of planets above the southeastern horizon before the Sun rises. Saturn and Mars are 1° apart, with Jupiter a little more than 6° upper right of the pair. Keep an eye on the Red Planet during the month as it puts distance between itself and the gas giants.

3 EVENING: Don't miss this opportunity to see Venus in its closest pass by the Pleiades in decades. You'll have to wait until April 2028 for the brilliant planet's next visit to the Seven Sisters. See pages 46 and 48 for more detail on what promises to be quite the visual delight.

11 EVENING: Algol shines at minimum brightness for roughly two hours centered at 9:14 p.m. PDT (see page 49).

14 DAWN: The last-quarter Moon, Jupiter, Saturn, and Mars form a graceful arc that spans some 20° above the south-southeastern horizon. Catch this quartet before sunrise.

14 EVENING: Algol shines at minimum brightness for roughly two hours centered at 9:03 p.m. EDT.

15 DAWN: The Moon is 3° below Saturn, with Jupiter and Mars flanking the pair.

16 DAWN: The thinning Moon is 3° to 4° lower left of Mars.

22 NIGHT: The Lyrid meteor shower peaks in the early morning hours. The waning crescent Moon, less than one day from new, won't interfere with viewing. This shower is variable, but it can produce fireballs.

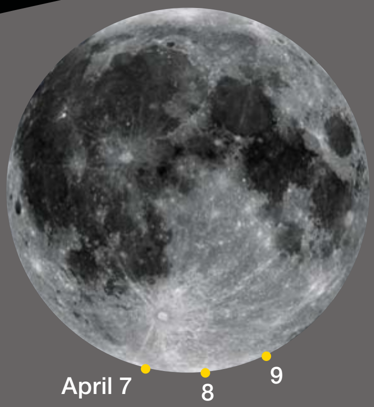
25 DUSK: The thin, waxing crescent Moon, nicely illuminated by earthshine, is 3° to 4° from Aldebaran.

26 DUSK: The fattening Moon is now between the horns of the Bull, some 4° from Zeta (ζ) Tauri. Venus, also in Taurus, is about 7° right of the lunar crescent.

— DIANA HANNIKAINEN

APRIL 2020 OBSERVING

Lunar Almanac
Northern Hemisphere Sky Chart



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

NASA / LRO

MOON PHASES

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

FIRST QUARTER
April 1
10:21 UT

FULL MOON
April 8
02:35 UT

LAST QUARTER
April 14
22:56 UT

NEW MOON
April 23
02:26 UT

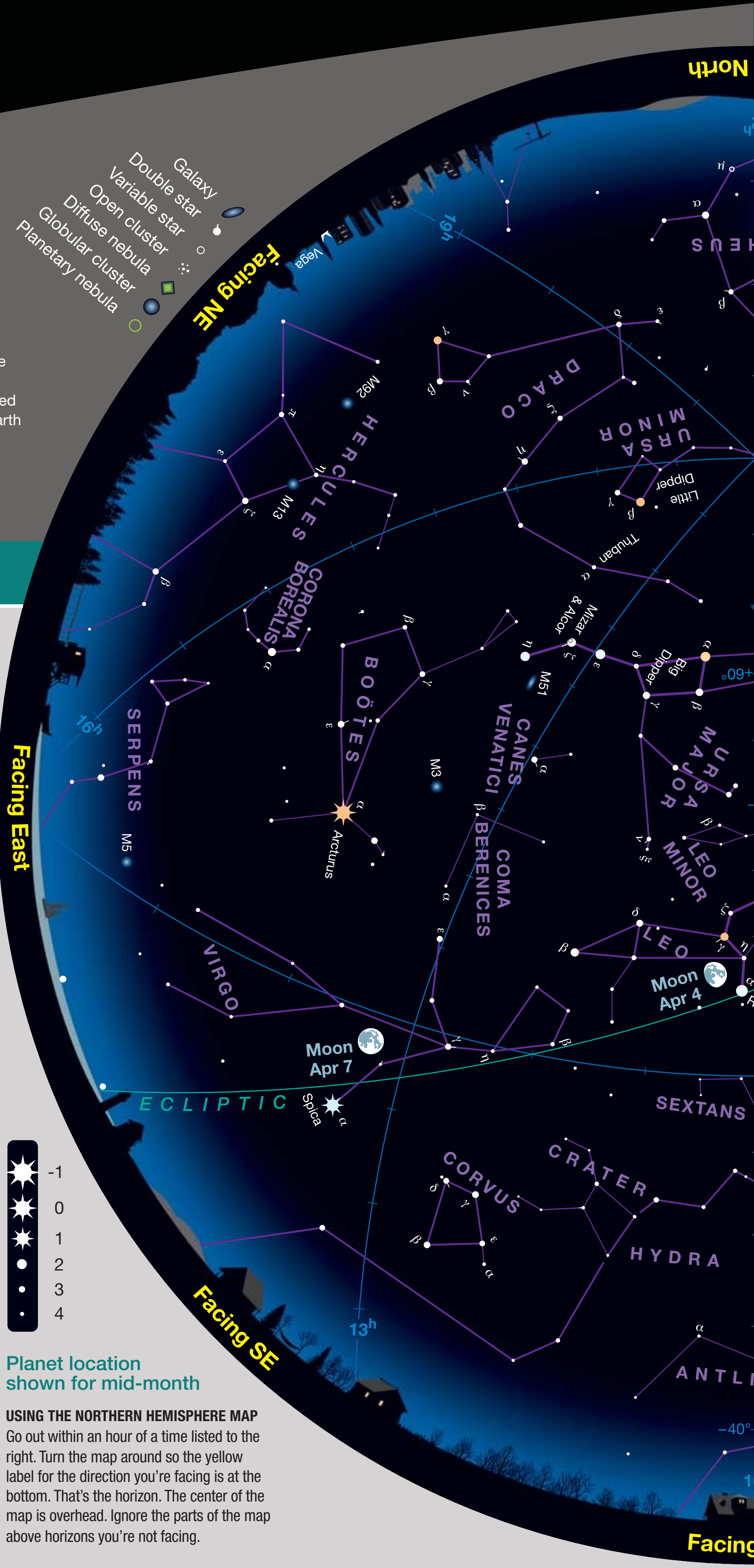
FIRST QUARTER
April 30
20:38 UT

DISTANCES

Perigee	April 7, 18^h UT
356,907 km	Diameter 33′ 29″
Apogee	April 20, 19^h UT
406,462 km	Diameter 29′ 24″

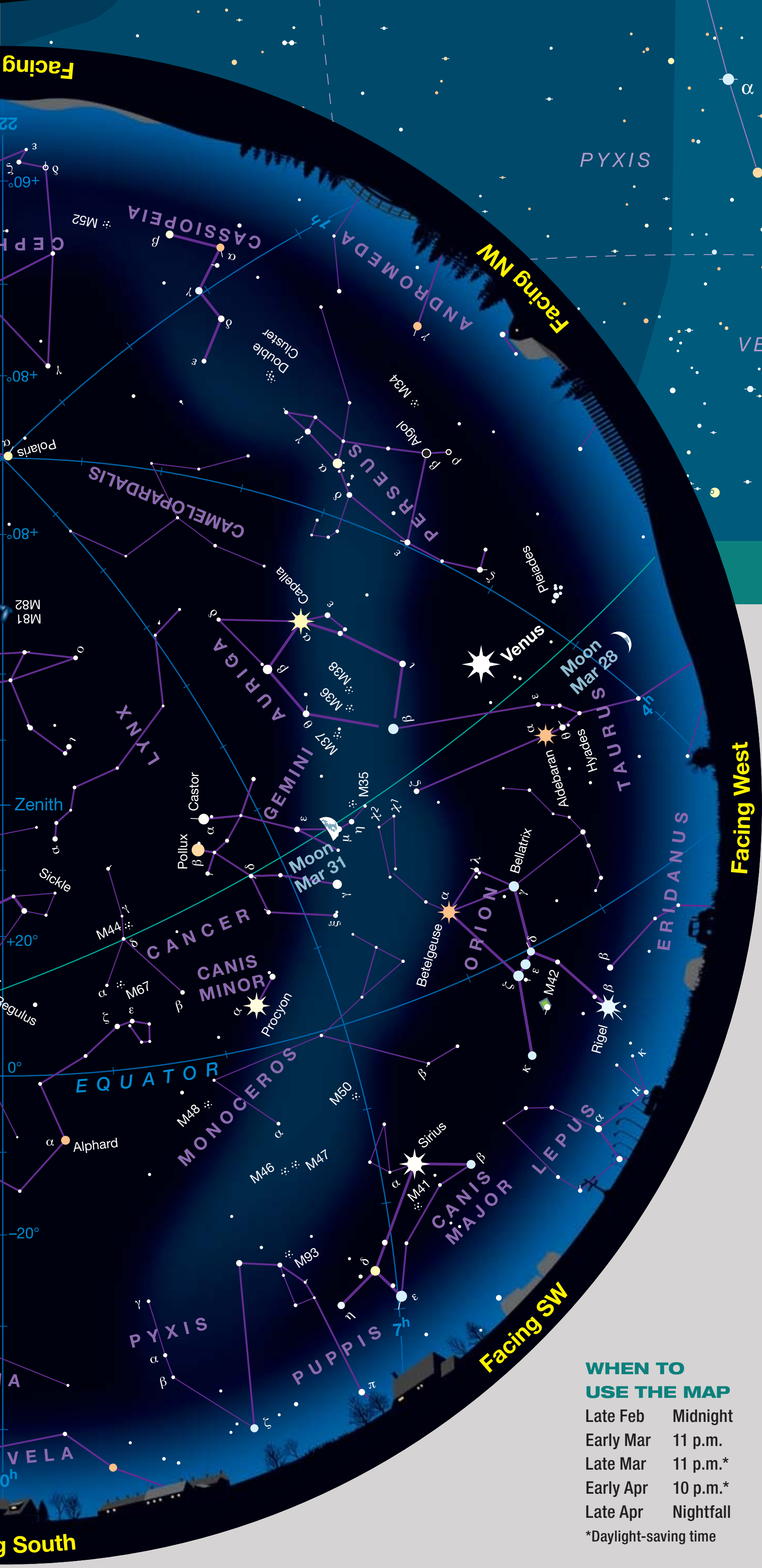
FAVORABLE LIBRATIONS

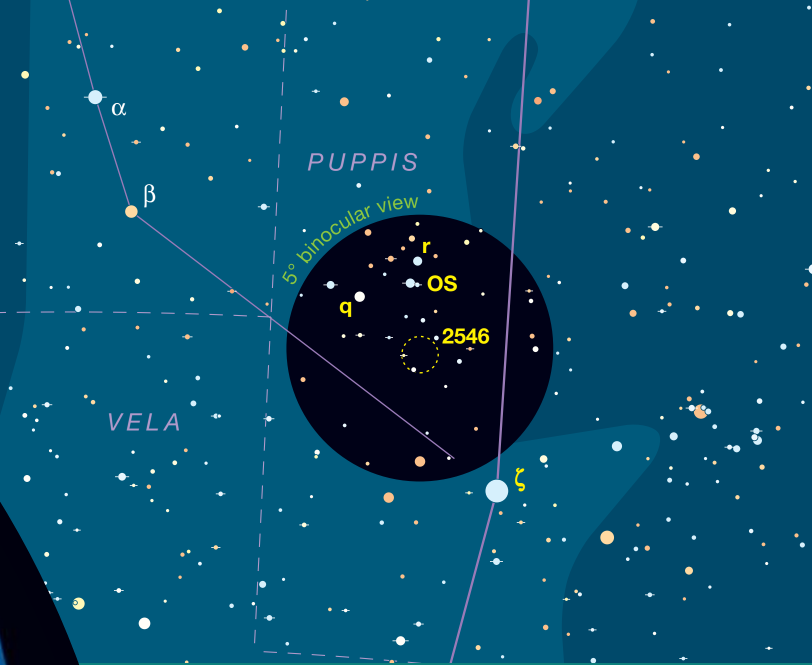
• Kircher Crater	April 7
• Malapert Crater	April 8
• Helmholtz Crater	April 9



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.





WHEN TO USE THE MAP

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

*Daylight-saving time

Binocular Highlight by Mathew Wedel

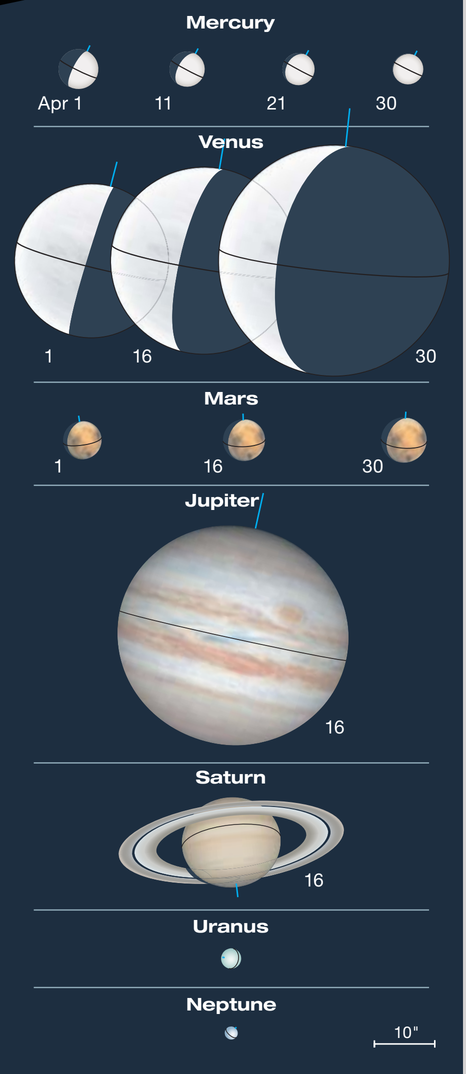
Blind Spot

Something that alarms me as an observer is just how much sky I haven't looked at carefully yet. In particular, I've spent far too little time in the far southern sky, especially the winter and early spring constellations. I tend to think of the tail end of Canis Major, the Big Dog, as being pretty far south, but that constellation ends more than 10° north of Omega Centauri, which I observe every year in the late spring. So there's no real barrier to my observing down south, it's just a mental block.

The constellation Puppis, the stern of the celestial ship Argo Navis (see *S&T:* Mar. 2020, p. 22), is an especially rewarding hunting ground for binocular observers. One of my favorite "deep south but not really" objects is the open cluster **NGC 2546**. The cluster lies 3° northeast of **Zeta (ζ) Puppis**, squarely along the center of the Milky Way. At sixth magnitude, NGC 2546 is fairly bright, although it may be a challenge to figure out where the cluster ends and the rich background star field begins. The cluster sprawls over a full degree of sky, so even in binoculars it shows plenty of detail, with a band of brighter stars running from southeast to northwest.

Another degree to the northeast you'll find a gaggle of bright stars, including **q** and **r Puppis** and the double star **OS Puppis**. These are all foreground objects compared to NGC 2546, lying between 90 and 1,000 light-years away, compared to 3,000 light-years for the cluster. And as long as you're in the neighborhood, have a look back at Zeta Puppis and see if you can detect any color. The star is a 2.2-magnitude *O*-type blue supergiant, vastly brighter and more massive than our own Sun. I hope you enjoy this saunter into more southerly skies.

■ **MATT WEDEL** will be mining his celestial blind spots for observing fuel for years to come.



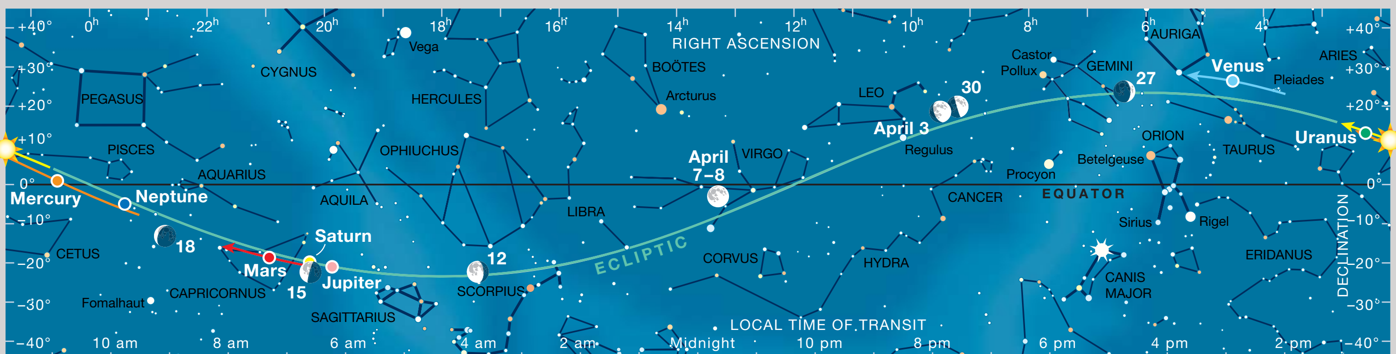
PLANET DISKS have south up, to match the view in many telescopes. Blue ticks indicate the pole currently tilted toward Earth.

PLANET VISIBILITY (40°N, naked-eye, approximate) **Mercury:** hidden in the Sun's glow all month • **Venus:** high at dusk, sets in late evening • **Mars, Jupiter, and Saturn:** reasonably high by dawn; Mars and Saturn very close to each other in early April; Jupiter and Saturn less than 6° apart all month

April Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	0h 42.1m	+4° 32′	—	–26.8	32′ 01″	—	0.999
	30	2h 29.7m	+14° 46′	—	–26.8	31′ 45″	—	1.007
Mercury	1	23h 08.1m	–7° 53′	27° Mo	0.0	6.6″	64%	1.019
	11	0h 01.8m	–2° 33′	22° Mo	–0.2	5.8″	76%	1.152
	21	1h 04.0m	+4° 36′	15° Mo	–0.7	5.3″	88%	1.264
	30	2h 09.0m	+12° 02′	6° Mo	–1.6	5.1″	98%	1.324
Venus	1	3h 36.3m	+23° 02′	46° Ev	–4.5	25.5″	47%	0.654
	11	4h 13.2m	+25° 28′	45° Ev	–4.6	28.9″	41%	0.577
	21	4h 45.4m	+27° 03′	43° Ev	–4.7	33.3″	33%	0.501
	30	5h 07.7m	+27° 43′	39° Ev	–4.7	38.2″	26%	0.436
Mars	1	20h 11.9m	–20° 59′	71° Mo	+0.8	6.4″	88%	1.461
	16	20h 55.2m	–18° 43′	75° Mo	+0.6	7.0″	87%	1.343
	30	21h 34.4m	–16° 07′	79° Mo	+0.4	7.6″	86%	1.236
Jupiter	1	19h 44.1m	–21° 21′	77° Mo	–2.1	37.0″	99%	5.321
	30	19h 54.7m	–20° 57′	103° Mo	–2.3	40.6″	99%	4.860
Saturn	1	20h 10.4m	–20° 07′	71° Mo	+0.7	16.1″	100%	10.304
	30	20h 15.4m	–19° 54′	98° Mo	+0.6	16.9″	100%	9.827
Uranus	16	2h 14.3m	+13° 00′	10° Ev	+5.9	3.4″	100%	20.794
Neptune	16	23h 23.0m	–5° 06′	37° Mo	+7.9	2.2″	100%	30.730

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



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

The Great Comet of 1970

Fifty years ago this month a feathery visitor adorned the spring sky.

▲ **BEAUTIFUL STRANGER** Comet Bennett graced the spring sky 50 years ago and proved to be one of the finest comets of the 20th century. J. U. Gunter captured this photo on the morning of March 28, 1970.

In each Under the Sky column this spring, I'm featuring a different celestial wonder that I witnessed 50 years ago. The initial marvel, which happened on March 7th that year, was my first total eclipse of the Sun (discussed in last month's column). But this month's featured wonder, at its all-around best in April 1970, is what may have been the most beautiful comet of the 20th century.

Enter Comet Bennett. I had recently observed my first comet, Tago-Sato-Kosaka. I found this modestly bright object by myself with both naked eye and telescope in January 1970, the month after my 15th birthday. That was an incredibly thrilling and rewarding experience. But the March 1970 issue of *Sky & Telescope* soon arrived with a brief item announcing the approach of "Bright Comet Bennett."

Discovered at the end of December 1969 by accomplished amateur astronomer John Caister Bennett of South Africa, Comet Bennett (C/1969 Y1, or 1969i as it was then designated) was solely visible in the Southern Hemisphere until it sped north in its highly inclined orbit, passing the Sun and emerging in bright morning twilight in March 1970.

My first sight of Comet Bennett came after watching in stronger and stronger morning twilight in the hope the comet would somehow be bright enough to be visible with the unaided eye when it finally rose above my treeline to the east. I was losing hope that morning and then it appeared — a starlike object brighter than Altair, with an awesome similarly bright short spike of intense tail. I didn't record which date in late March I made that observation, but Bennett passed perihelion, 0.54 a.u. from the Sun, on March 20th and was closest to Earth, at a distance of 0.69 a.u., on March 26th. On March 23rd, one observer followed Bennett naked eye until less than 5 minutes before sunrise, and on the 28th estimated the comet as magnitude –0.3 with 10° of tail visible even in bright moonlight.

April's angel or sword below Cygnus. The rapidly northbound Comet Bennett lofted magically higher and higher out of morning twilight like an angel. So, April 1970 was the month it was most splendid. Bennett sported both dust and gas tails. The gas tail was prominently curved and underwent dramatic changes as a strong (solar maximum) solar wind buffeted it. In telescopes, Bennett also displayed an orange pinwheel of jets from its nucleus and, for master comet observer John Bortle, as many as five jets at once. What was most beautiful about Bennett in my 4¼-inch Edmund reflector that month was the silky strands of streamers in the first star-sprinkled several degrees of the tail — a phenomenon the like of which I've still never seen in any other comet with any telescope.

John Bortle and a few other observers traced Comet Bennett's tail out to well over 20° long. But what was amazing to me was that Bennett's tail wasn't at its brightest for just a few degrees of its length, like Hale-Bopp's and Hyakutake's. As I recall, Bennett's tail maintained similar great intensity out to roughly 10° or 12°. In my book *Comet of the Century*, I had the following to say: "It hung breathlessly like some vast shining swan's feather by the graceful constellation of Cygnus the Swan; it was a snowy sword laid in peace (but power!) near one of the brightest parts of the Milky Way's stream; it floated into the north circumpolar regions of Cassiopeia the Queen to spend ever more of the night aloft."

You can stay up late these nights of April 2020 and watch the lovely constellations Cygnus and Cassiopeia wheel into view in the northeast. But 50 Aprils ago, they were accompanied by the once-in-a-lifetime beauty of Comet Bennett.

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

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

The Evening Star Steals the Show

Brilliant Venus dominates at dusk, while a planetary threesome graces the pre-dawn sky.

Only one naked-eye planet is visible in the evening sky this month, but that planet is Venus, now in one of the very best months of its 8-year cycle of recurring appearances.

This is the April when Venus starts the month still near its highest possible altitude at sunset for mid-northern latitudes, and ends the month at an amazing peak of brilliance. It is also the April that starts with the planet having its closest pass with the Pleiades in living memory.

So, what can April's final four hours of night possibly offer to rival Venus's virtuoso performance in the first four? How about three bright (and brightening) planets in a compact line. This expanding line includes Jupiter followed by Saturn and Mars, which is moving eastward throughout the month.

DUSK AND EVENING

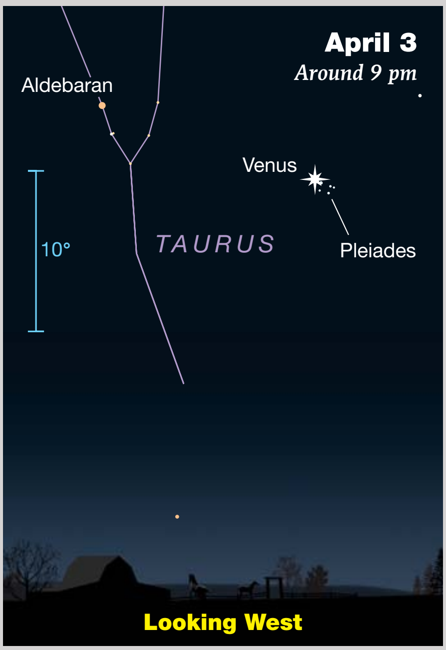
Venus brightens slightly from magnitude –4.5 at the beginning of April, to this apparition's maximum of –4.7 at month's end. During that span, the interval between sunset and Venus-set shortens from 4 hours to less than 3½ hours (for observers near latitude 40° north). At the same time, the planet's altitude at sunset decreases from its absolute maximum of about 43° to 36°. This month, the illuminated percentage of Venus's disk decreases from 47% to 25% lit, while its angular diameter grows from 26″ to 39″.

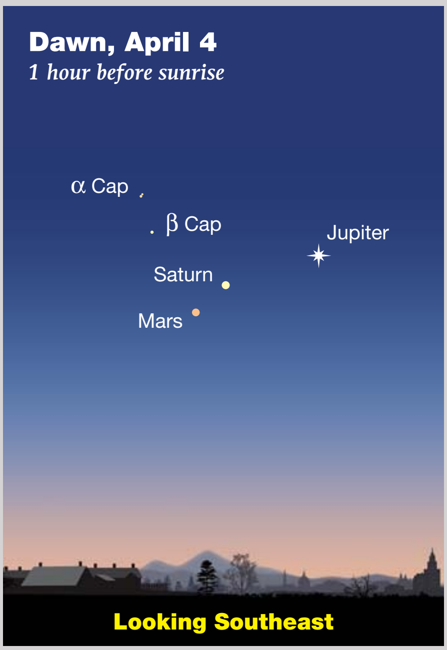
Venus passes very close to the Pleiades "every eighth April" (as Guy Ottewell beautifully phrased it) and has been getting progressively nearer the cluster at each succeeding pass for a long time. On the evening of April 3rd, Venus is positioned just ¼° southeast of Alcyone, the brightest Pleiad. But it turns out this is only a warmup for what's to come. On April 3, 2028, Venus will pass incredibly close to Merope, and less than a day later the planet slips between the tight pair of Atlas and Pleione (albeit during daylight hours for North America). And during the next two visits (in 2036 and 2044), Venus's path finally takes it directly through the tiny bowl of the cluster's dipper pattern.

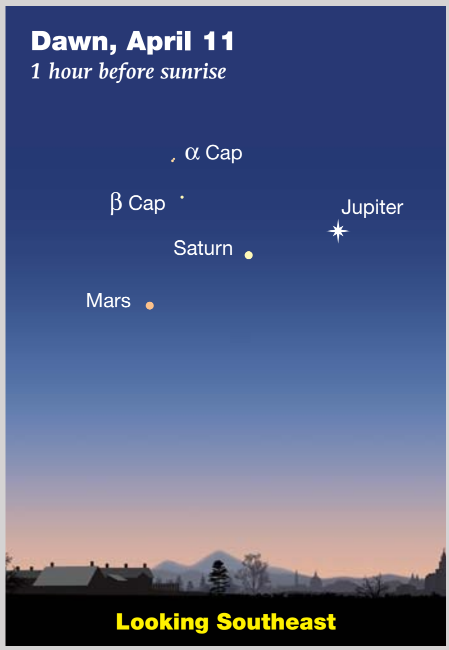
Uranus can be glimpsed with binoculars in southern Aries at dusk at the very start of the month, but is in conjunction with the Sun on April 26th.

PRE-DAWN

As April begins, **Jupiter** rises about 3½ hours before the Sun, followed less than half an hour later by **Saturn** and **Mars**.



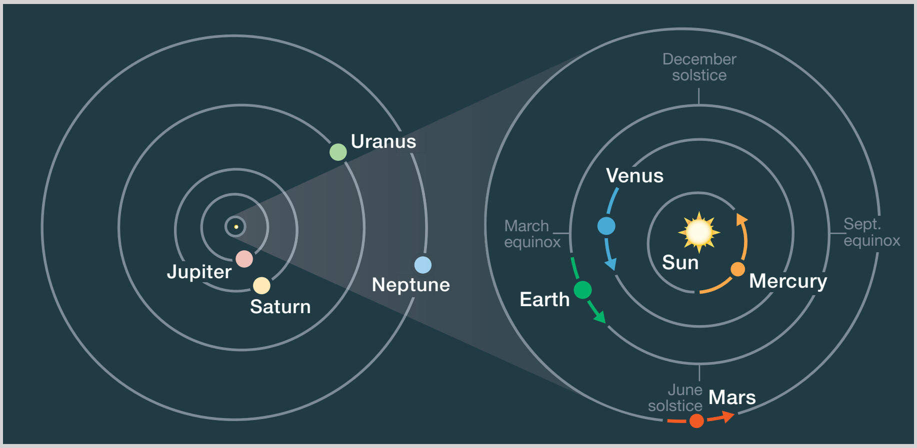




Jupiter is only 6° west of the pair at that time, and Mars has moved just a bit farther eastward from its closest approach of less than 1° from Saturn on the final morning of March. At the beginning of April, Jupiter greatly outshines the other two worlds with its –2.1-magnitude radiance, while Mars and Saturn are nearly as bright as each other; Saturn glows at magnitude +0.7 and Mars at +0.8. Be sure to compare their colors with your naked eye and in binoculars.

All three planets brighten slightly during the month. Jupiter increases to magnitude –2.3, Saturn to +0.6, and Mars to +0.4. Unfortunately, Mars spends the month gliding swiftly away from Saturn. On April 9th the group of planets are almost equally spaced, with Saturn in the middle, about 5⅔° from Jupiter and Mars. But Mars speeds on, almost crossing the entire width of Capricornus as it puts more than 19° between itself and Saturn by month's end. Meanwhile, the gap between Jupiter and Saturn shrinks slightly to 5°, with Saturn in westernmost Capricornus and Jupiter just over the border in easternmost Sagittarius. As April winds down, Jupiter and Saturn rise around 1:30 to 1:50 a.m. local daylight time — almost 1½ hours before Mars.

During April, the apparent diameter of each planet grows slightly, from 37″ to 41″(Jupiter), 16″ to 17″ (Saturn) and 6.4″ to 7.6″ (Mars). Use your telescope to see if you can detect the gibbous phase of the Red Planet (its disk is less than 90% lit throughout the month). Meanwhile, Jupiter and Saturn reach quadrature (90° west of the Sun) on April 15th and 21st, respectively. As a result, the two gas giants cast their shadows far to the side, permitting better views of Jupiter's shadow eclipsing the Galilean satellites, and enhancing the three-dimensionality of Saturn's globe and rings. Those rings are now slightly less tilted (21°) than they've been over the past several years.



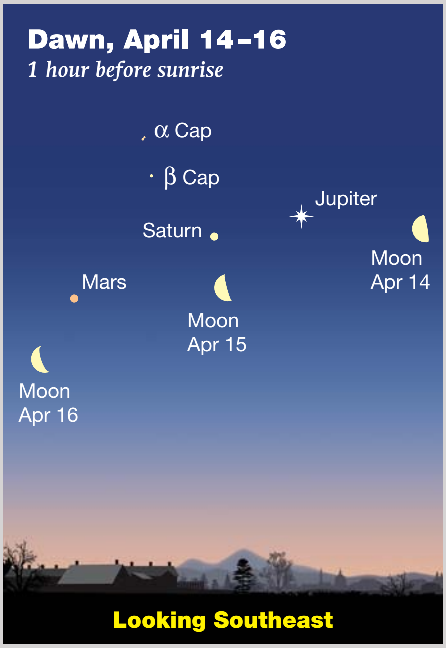
ORBITS OF THE PLANETS

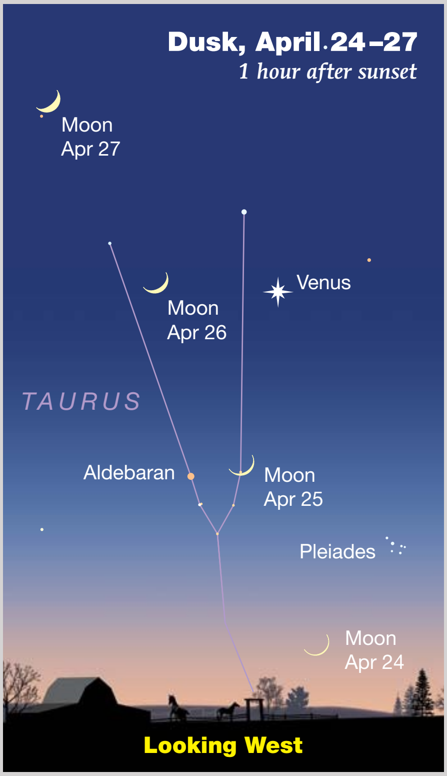
The curved arrows show each planet's movement during April. The outer planets don't change position enough in a month to notice at this scale.

MOON PASSAGES

The **Moon** is at its nearest for 2020 at 17:59 UT on April 7th, just 8½ hours before it reaches full. (Expect to hear the phrase "supermoon" bandied about.) The Moon is passing through last-quarter phase as it moves from well right of Jupiter on April 14th, to close below Saturn on April 15th. Finally, on April 16th it's positioned not far lower left of Mars. When the Moon returns to the evening sky as a thin waxing crescent, it passes by the Hyades to the right of Aldebaran — and very near Epsilon (ε) Tauri — on April 25th, and sits far left of Venus the following night.

■ **FRED SCHAAF** teaches astronomy at both Rowan University and Rowan College in Gloucester County, southern New Jersey.





◀ 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.

Venus Skirts the Pleiades

The Seven Sisters welcome a brilliant visitor.

Venus most recently gleamed within the Pleiades star cluster (M45) on April 3, 2012. This 13-second exposure (at ISO 200) was captured with a 92-mm refractor (working at f/4.5) and a Canon EOS 7D DSLR camera. A pair of wires taped in front of the lens produced the diffraction spikes.

The brightest planet and the best-known naked-eye star cluster join forces on the evening of April 3rd for a spectacular conjunction visible just about everywhere. That evening, for observers in North America, Venus tiptoes through the outskirts of the Pleiades and passes only ¼° south of the cluster's brightest star, 3rd-magnitude Alcyone. From other locales farther east, the planet nudges within 11′ of Merope. If this very close conjunction feels familiar, it should. A nearly identical one took place on April 3, 2012, and the next will happen on April 3, 2028.

Conjunctions of the cluster and planet aren't unusual — in fact they happen annually — with Venus passing near but rarely *through* the Pleiades. However, every eight years nearly to the day, Venus busts down the door and strolls right in. What strange clockwork is behind this every-eight-year pattern?

Over many millions of years, the regular and repeated gravitational interactions between Venus and Earth have caused their orbits to achieve what astronomers call a *near resonance*. For every eight Earth years, Venus circles the Sun almost exactly 13 times. This 8:13 ratio means that Earth and Venus return to nearly the same positions in their orbits at eight-year intervals. Venus then repeats its trek across the evening sky, which always includes a special visit to the Pleiades.

Because neither planet's orbit is a perfect circle, the resonance is imprecise. In addition, Venus's orbit is inclined 3.4° to the plane of the ecliptic. These two factors combine to ensure that each Pleiades passage is similar yet unique.

◀ In Greek mythology, the Pleiades represent the seven daughters of Atlas and Pleione.

Finding Venus on April 3rd will be simple — look halfway up the western sky, starting about half an hour after sunset. Only 10 days past greatest eastern elongation (which occurred on March 24th), the planet will positively dazzle at magnitude –4.6. You may even notice a few individual Pleiades stars poking out next to Venus as the sky darkens. But the best way to encompass the unfolding drama of laserlike Venus and its temporary retinue of blue-white diamonds is with binoculars or a small, low-power telescope, both of which offer wide fields of view. If ever there were an event for humble equipment, this is it.

Begin observing early and note Venus's position in relation to the brightest cluster stars. After an hour or two, you should be able to detect the planet's eastward motion. Clipping along at 127,000 km/h (79,000 mph), Venus traverses the Moon's diameter in about 15 hours.

Clouds often have a way of ruining a good conjunction. Not to worry. Venus will shine within 2° of the Pleiades' bright, dipper-like figure from March 31st through April 6th, enough time to appreciate the sweet sight and get a photo. On March 28th, the four-day-old waxing crescent photobombs the picturesque duo. Have your camera ready!

VENUS IN PLEIADES: ALAN DYER; PLEIADES LABELED: BOB KING

April Shower Power

AS WINTER SNOW FLURRIES give way to spring rains, the annual Lyrid meteor shower spatters Earth's atmosphere with up to 20 meteors per hour on the peak night of April 21–22. This year, the event unfolds under ideal conditions in a moonless sky. While the Lyrids are considered a minor shower, the display is known for curveballs, like the 1982 outburst when American observers briefly recorded around 100 meteors per hour, or in 1945 when the same number was witnessed over Japan. In his book *Meteor Showers and Their Parent Comets*, meteor expert Peter Jenniskens predicts possible repeat Lyrid flare-ups in 2040 and 2041.

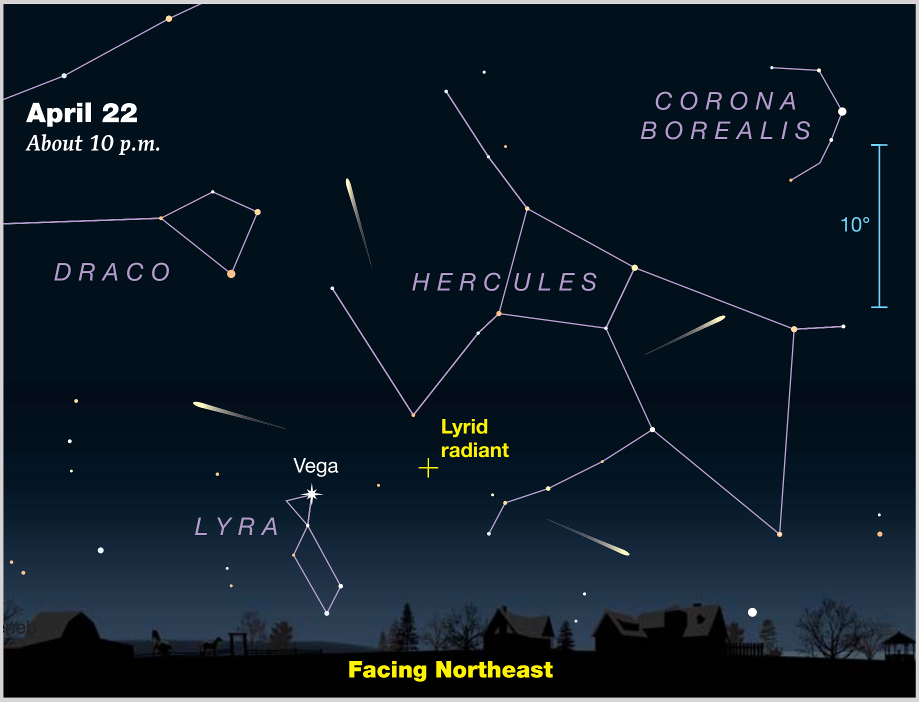
Each Lyrid that streaks across the sky is a bit of dust or rock shed by Comet Thatcher (C/1861 G1), which orbits the Sun every 415 years. During April, Earth plows headlong through the comet's debris trail. As the cometary shards slam into our planet's atmosphere at more than 165,000 km/h, they leave behind glowing trails of ionized air, still referred to as "shooting stars."

Meteor showers get their names based on where they appear to radiate from in the sky. That being the case, the Lyrids should really be called the Herculids because the shower radiant lies 8° west-southwest of Vega, just inside the eastern border of Hercules. Before constellation boundaries were standardized in 1930, the display was associated with Vega, in Lyra. Of course, it still is even if the radiant has been "relocated."

According to the American Meteor Society, the Lyrids produce a good show for three nights centered on the date of the peak. You might spy a few meteors during evening hours when Vega shines low in the northeastern sky, but your best bet will be to rise early on the morning of the 22nd when the shower peaks and the radiant stands near the zenith before dawn.

As you watch sparks fly, consider that you're only the most recent in a long line of skywatchers to marvel at this spring apparition. Observations of the Lyrids date back to 687 BC, making the display one of the oldest recorded meteor showers.

Spring mornings can often be quite chilly, so be sure bundle up well. Break out the lawn chair, recline, and enjoy the show. Given the radiant's high predawn position, it doesn't really matter which direction you face — you'll likely see a good mix of Lyrids and sporadics. Worth enduring the spring chill for!

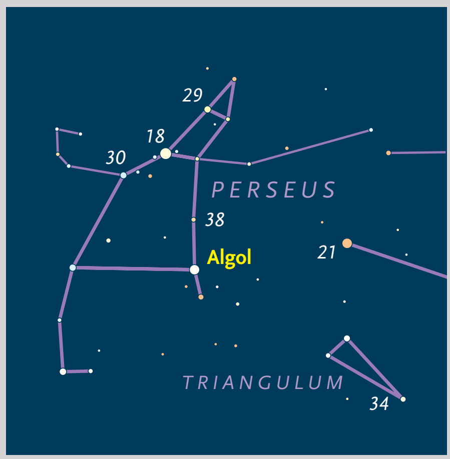


▲ The radiant for the Lyrid meteor shower is indicated in the diagram above. Although you can begin your meteor watch late in the evening of April 21st, the display will be at its best during the pre-dawn hours of the 22nd.

Minima of Algol

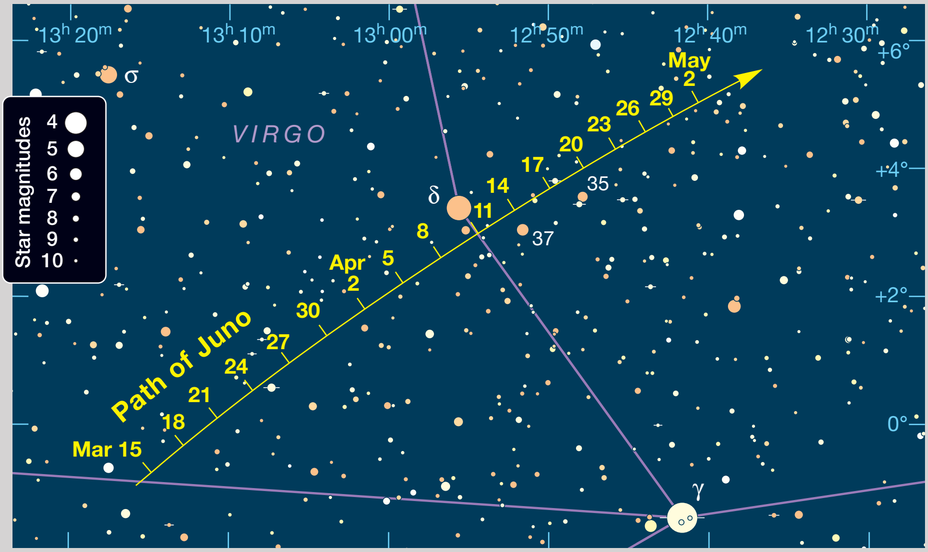
Mar.	UT	Apr.	UT
3	0:45	3	13:47
5	21:34	6	10:36
8	18:23	9	7:25
11	15:13	12	4:14
14	12:02	15	1:03
17	8:51	17	21:52
20	5:40	20	18:42
23	2:30	23	15:31
25	23:19	26	12:20
28	20:08	29	9:09
31	16:57		

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**.



▲ As spring deepens, Perseus sets earlier, making April the last practical month for evening observation until autumn. 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 and 3.4.

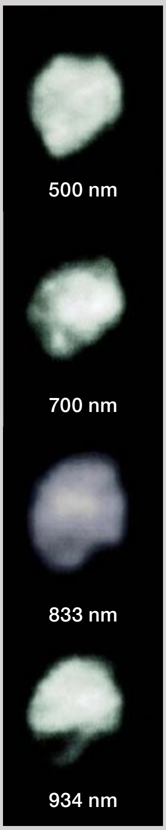
Meet and Greet with Jupiter's Wife



IF YOU LIKE ASTEROID RIDE-ALONGS, break out a small telescope (or even large binoculars) and join Juno on its multi-night cruise through central Virgo this month. Juno reaches opposition on April 2nd, when it shines at magnitude 9.5 as it slides slowly westward in retrograde motion near Delta (δ) Virginis. In fact, on the nights of April 9th and 10th, Juno passes just ½° south of the 3rd-magnitude star, providing a fine opportunity to observe the asteroid's night-to-night movement. Gradually fading after opposition, Juno ends the month at 10th magnitude.

German astronomer Karl Harding discovered Juno in 1804, when asteroids were still considered planets. They were reclassified as minor planets in the 1850s. Harding named Juno after the Roman goddess and wife of Jupiter. NASA later borrowed the name for its current Jupiter mission, designed to peer beneath the gas giant's cloudtops and measure its gravitational field, internal makeup, and more (*S&T:* May 2019, p. 14). The name is particularly apt. Juno was well aware of her husband's attempts to conceal his mischief under cover of clouds, so she always kept an eye on him.

Astronomers used the 100-inch Hooker telescope at Mount Wilson in 2003 to photograph the irregularly shaped, 247-kilometer-wide asteroid, and discovered what appears to be a 97-kilometer-wide crater on its surface.



▶ The asteroid Juno was recorded with the 100-inch Hooker telescope at Mount Wilson Observatory, California. The images show what appears to be a 97-kilometer-wide crater.

HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS

Action at Jupiter

JUPITER RISES about 3 a.m. local daylight-saving time at the beginning of April and by the start of morning twilight is high enough for satisfying telescopic views. Throughout April Jupiter's disk grows slightly from 37″ on the 1st to 41″ by the 30th.

Any telescope shows 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 time and date.

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

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

March 1: 1:08, 11:03, 20:59; **2**: 6:55, 16:51; **3:** 2:46, 12:42, 22:38; **4**: 8:34, 18:29; **5**: 4:25, 14:21; **6**: 0:17, 10:12, 20:08; **7**: 6:04, 16:00; **8**: 1:55, 11:51, 21:47; **9:** 7:43, 17:38; **10**: 3:34, 13:30, 23:26; **11**: 9:21, 19:17; **12:** 5:13, 15:09; **13**: 1:04, 11:00, 20:56; **14**: 6:51, 16:47; **15**: 2:43, 12:39, 22:34; **16**: 8:30, 18:26; **17:** 4:22, 14:17; **18**: 0:13, 10:09, 20:05; **19**: 6:00, 15:56; **20**: 1:52, 11:48, 21:43; **21:** 7:39, 17:35; **22**: 3:30, 13:26 23:22; **23:** 9:18, 19:13; **24**: 5:09, 15:05; **25**: 1:00, 10:56, 20:52; **26**: 6:48, 16:43; **27**: 2:39, 12:35, 22:31; **28**: 8:26, 18:22; **29**: 4:18, 14:13; **30**: 0:09, 10:05, 20:01; **31**: 5:56, 15:52

April 1: 1:48, 11:43, 21:39; **2**: 7:35, 17:30; **3**: 3:26, 13:22, 23:18; **4:** 9:13, 19:09; **5**: 5:05, 15:00; **6**: 0:56, 10:52, 20:47; **7**: 6:43, 16:39; **8**: 2:35, 12:30, 22:26; **9**: 8:22, 18:17; **10**: 4:13, 14:09; **11**: 0:04, 10:00, 19:56; **12**: 5:52, 15:47; **13**: 1:43, 11:39, 21:34; **14**: 7:30, 17:26;

15: 3:21, 13:17, 23:13; **16**: 9:08, 19:04; **17**: 5:00, 14:55; **18:** 0:51, 10:47, 20:42; **19**: 6:38, 16:34; **20:** 2:29, 12:25, 22:21; **21**: 8:16, 18:12; **22**: 4:08, 14:03, 23:59; **23**: 9:55, 19:50; **24**: 5:46, 15:42; **25**: 1:37, 11:33, 21:29; **26**: 7:24, 17:20; **27**: 3:16, 13:11, 23:07; **28:** 9:03, 18:58; **29**: 4:54, 14:50; **30**: 0:45, 10:41, 20:37

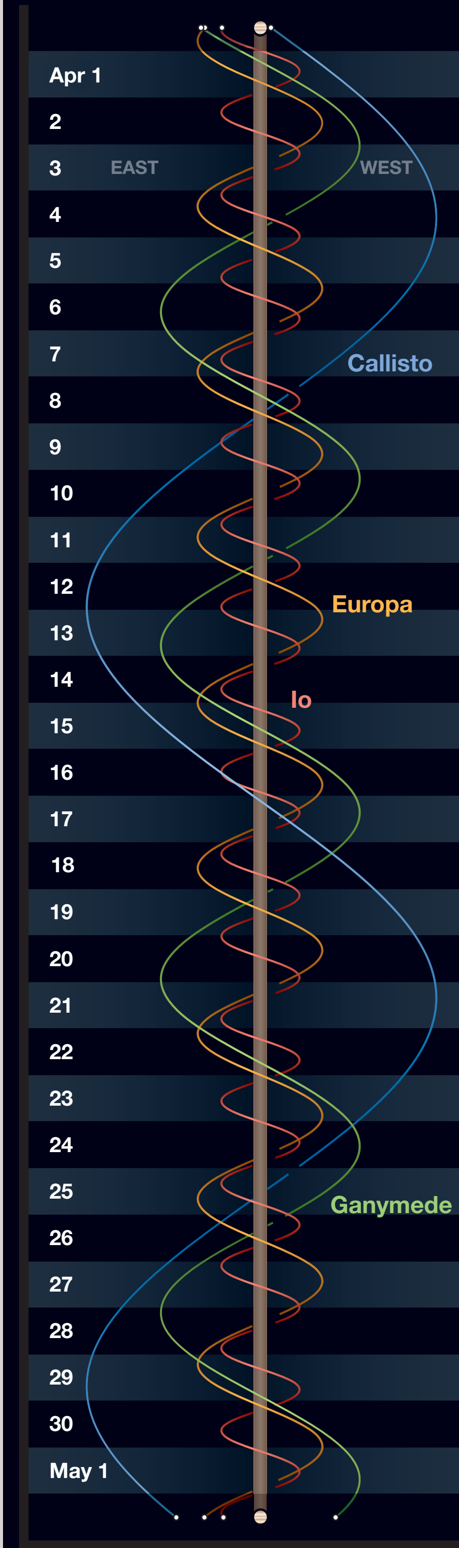
These times assume that the spot will be centered at System II longitude 330°. If the Red Spot has moved elsewhere, it will transit $1\frac{2}{3}$ minutes earlier for each degree less than 330° and $1\frac{2}{3}$ minutes later for each degree more than 330°.

Phenomena of Jupiter's Moons, April 2020

Date	Time	Event
Apr. 1	1:01	I.Tr.E
	1:54	III.Sh.E
	3:54	III.Tr.I
	7:09	III.Tr.E
	12:20	II.Sh.I
	14:50	II.Tr.I
	15:02	II.Sh.E
	17:35	II.Tr.E
	18:49	I.Ec.D
	22:21	I.Oc.R
Apr. 2	15:59	I.Sh.I
	17:15	I.Tr.I
	18:13	I.Sh.E
	19:30	I.Tr.E
Apr. 3	6:33	II.Ec.D
	11:58	II.Oc.R
	13:17	I.Ec.D
	16:50	I.Oc.R
Apr. 4	10:27	I.Sh.I
	11:44	I.Tr.I
	12:42	I.Sh.E
	12:57	III.Ec.D
	13:59	I.Tr.E
	16:05	III.Ec.R
	18:06	III.Oc.D
	21:23	III.Oc.R
Apr. 5	1:37	II.Sh.I
	4:08	II.Tr.I
	4:19	II.Sh.E
	6:53	II.Tr.E
	7:46	I.Ec.D
	11:19	I.Oc.R
Apr. 6	4:56	I.Sh.I
	6:12	I.Tr.I
	7:10	I.Sh.E
	8:28	I.Tr.E
	19:51	II.Ec.D
Apr. 7	1:17	II.Oc.R
	2:14	I.Ec.D
	5:47	I.Oc.R
	23:24	I.Sh.I
Apr. 8	0:41	I.Tr.I
	1:39	I.Sh.E
	2:47	III.Sh.I
	2:57	I.Tr.E
	5:19	IV.Ec.D
	5:53	III.Sh.E
	7:58	III.Tr.I
	8:39	IV.Ec.R
	11:14	III.Tr.E
	14:54	II.Sh.I
	17:21	IV.Oc.D
	17:26	II.Tr.I
	17:36	II.Sh.E
	20:11	II.Tr.E
	20:42	I.Ec.D
	21:14	IV.Oc.R
Apr. 9	0:16	I.Oc.R
	17:53	I.Sh.I
	19:10	I.Tr.I
	20:07	I.Sh.E
	21:25	I.Tr.E
Apr. 10	9:09	II.Ec.D
	14:37	II.Oc.R
	15:11	I.Ec.D
	18:45	I.Oc.R
Apr. 11	12:21	I.Sh.I
	13:38	I.Tr.I
	14:36	I.Sh.E
	15:54	I.Tr.E
	16:56	III.Ec.D
	20:05	III.Ec.R
	22:09	III.Oc.D
Apr. 12	1:27	III.Oc.R
	4:11	II.Sh.I
	6:44	II.Tr.I
	6:53	II.Sh.E
	9:29	II.Tr.E
	9:39	I.Ec.D
	13:13	I.Oc.R
Apr. 13	6:49	I.Sh.I
	8:07	I.Tr.I
	9:04	I.Sh.E
	10:22	I.Tr.E
	22:26	II.Ec.D
Apr. 14	3:55	II.Oc.R
	4:07	I.Ec.D
	7:41	I.Oc.R
Apr. 15	1:18	I.Sh.I
	2:36	I.Tr.I
	3:33	I.Sh.E
	4:51	I.Tr.E
	6:45	III.Sh.I
	9:52	III.Sh.E
	11:59	III.Tr.I
	15:16	III.Tr.E
	17:28	II.Sh.I
	20:01	II.Tr.I
	20:10	II.Sh.E
	22:36	I.Ec.D
	22:46	II.Tr.E
Apr. 16	2:10	I.Oc.R
	12:32	IV.Sh.I
	15:52	IV.Sh.E
	19:46	I.Sh.I
	21:04	I.Tr.I
	22:01	I.Sh.E
	23:19	I.Tr.E
Apr. 17	0:43	IV.Tr.I
	4:36	IV.Tr.E
	11:45	II.Ec.D
	17:04	I.Ec.D
	17:14	II.Oc.R
	20:38	I.Oc.R
Apr. 18	14:15	I.Sh.I
	15:32	I.Tr.I
	16:29	I.Sh.E
	17:48	I.Tr.E
	20:54	III.Ec.D
Apr. 19	0:04	III.Ec.R
	2:08	III.Oc.D
	5:27	III.Oc.R
	6:45	II.Sh.I
	9:17	II.Tr.I
	9:27	II.Sh.E
	11:32	I.Ec.D
	12:03	II.Tr.E
	15:06	I.Oc.R
Apr. 20	8:43	I.Sh.I
	10:01	I.Tr.I
	10:58	I.Sh.E
	12:16	I.Tr.E
Apr. 21	1:02	II.Ec.D
	6:00	I.Ec.D
	6:31	II.Oc.R
	9:34	I.Oc.R
Apr. 22	3:11	I.Sh.I
	4:29	I.Tr.I
	5:26	I.Sh.E
	6:45	I.Tr.E
	10:43	III.Sh.I
	13:51	III.Sh.E
	15:56	III.Tr.I
	19:14	III.Tr.E
	20:01	II.Sh.I
	22:33	II.Tr.I
	22:44	II.Sh.E
Apr. 23	0:29	I.Ec.D
	1:19	II.Tr.E
	4:03	I.Oc.R
	21:40	I.Sh.I
	22:57	I.Tr.I
	23:55	I.Sh.E
Apr. 24	1:13	I.Tr.E
	14:20	II.Ec.D
	18:57	I.Ec.D
	19:49	II.Oc.R
	22:31	I.Oc.R
	23:17	IV.Ec.D
Apr. 25	2:46	IV.Ec.R
	11:19	IV.Oc.D
	15:19	IV.Oc.R
	16:08	I.Sh.I
	17:25	I.Tr.I
	18:23	I.Sh.E
	19:41	I.Tr.E
Apr. 26	0:52	III.Ec.D
	4:03	III.Ec.R
	6:02	III.Oc.D
	9:18	II.Sh.I
	9:22	III.Oc.R
	11:49	II.Tr.I
	12:01	II.Sh.E
	13:25	I.Ec.D
	14:35	II.Tr.E
	16:59	I.Oc.R
Apr. 27	10:37	I.Sh.I
	11:53	I.Tr.I
	12:52	I.Sh.E
	14:09	I.Tr.E
Apr. 28	3:38	II.Ec.D
	7:54	I.Ec.D
	9:05	II.Oc.R
	11:27	I.Oc.R
Apr. 29	5:05	I.Sh.I
	6:21	I.Tr.I
	7:20	I.Sh.E
	8:37	I.Tr.E
	14:42	III.Sh.I
	17:52	III.Sh.E
	19:50	III.Tr.I
	22:35	II.Sh.I
	23:08	III.Tr.E
Apr. 30	1:04	II.Tr.I
	1:17	II.Sh.E
	2:22	I.Ec.D
	3:50	II.Tr.E
	5:54	I.Oc.R
	23:34	I.Sh.I

Every day, interesting events happen between Jupiter's satellites and the planet's disk or shadow. The first columns give the date and mid-time of the event, in Universal Time (which is 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



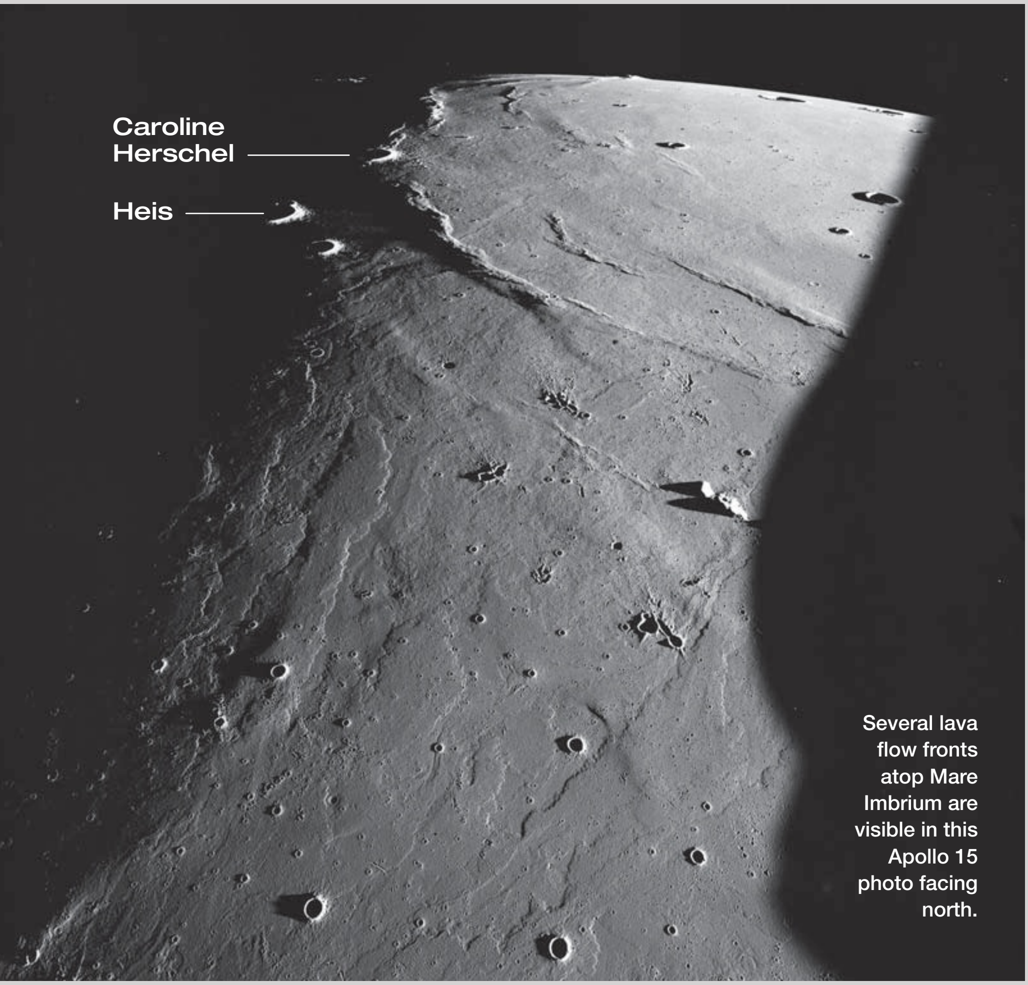
The wavy lines represent Jupiter's four big satellites. The central vertical band is Jupiter itself. Each gray or black horizontal band is one day, from 0^h (upper edge of band) to 24^h UT (GMT). UT dates are at left. Slide a paper's edge down to your date and time, and read across to see the satellites'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

Filling Holes

Understanding lunar erosion helps scientists measure the depths of impact basins.

Many thousands of holes are visible on the Moon through a telescope, from crater pits 2 or more kilometers wide to giant impact basins such as the 1,300-km-wide depression underlying **Mare Imbrium**. But over time these holes tend to get filled — by slumping, ejecta infill, and lava flooding.

Lunar craters are most often filled in by the gradual (or rapid) slumping of their rims, with debris sliding down onto the crater floor. Debris ejected from subsequent crater and basin excavations can significantly accumulate within craters and basins — or even bury them. For example, ejecta from the formation of the Imbrium basin heavily modified and shallowed **Alphonsus** and **Ptolemaeus**. Lava also flooded other craters that formed on or near maria. Other examples of flooded craters whose central peaks and other original floor features have been buried are **Plato**, **Archimedes**, and **Billy**.



Several lava flow fronts atop Mare Imbrium are visible in this Apollo 15 photo facing north.

NASA

The most scientifically important filling occurs within impact basins. Older basins are often degraded and at least partially filled by ejecta from nearby younger ones — think of all the debris ejected during Orientale's formation inundating Grimaldi. However, flooding by mare lavas was the most pervasive process filling basins, at least on the lunar nearside. Most basins visible from Earth — including Imbrium, **Serenitatis**, **Crisium**, and **Humorum** — were flooded (sometimes to the point of overflowing).

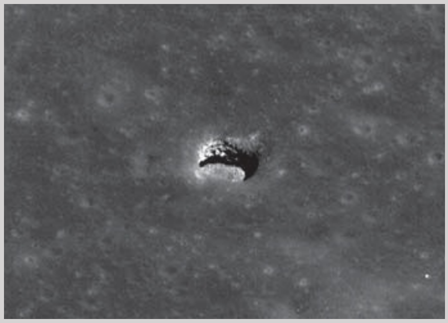
But the total thicknesses of the lava filling them are poorly known. That's unfortunate, because the average fill thickness times the basin diameter gives the total volume of erupted lavas. This total is a major constraint on theories of magma generation and, specifically, how much of the lunar mantle melted to create these immense flows.

Most Apollo missions landed on or near basin maria, which astronaut-collected samples prove are basaltic lava. These are similar to basalts that form Earth's ocean floors and giant volcanoes such as the Hawaiian Islands. Because of slow, steady eroding of the basins' edges over the past 2 to 3 billion years, few discrete lava flows are visible today. The best-preserved ones are along the western boundary of Mare Imbrium near the crater **Euler**. These flow fronts — the solidified margins of once-moving eruptions — are up to about 100 meters thick. Yet more than half of them are thinner than 15 m. This is consistent with the 10- to 20-m-thick layers of Mare Imbrium lavas that Apollo 15 astronauts found exposed in the walls of **Hadley Rille**.

Another place to actually see lava flow thicknesses is in the walls of collapsed pits (skylights) of subsurface lava tubes. Skylights are typically small — only a few tens of meters across — and are only seen with the ultra-high-resolution Narrow Angle Cameras of NASA's Lunar Reconnaissance Orbiter pointed at oblique angles. Based on measurements at a few skylights, the associated mare flows are only 3 to 14 m thick. Coarser measuring techniques (including radar) indicate thicker flows, tens to hundreds of meters, but it isn't clear that these are single-event layers.

So how thick are the massive lava plains filling Imbrium and other basins? Lunar geologist Rene DeHon pioneered the estimation of total maria thicknesses in the 1970s by measuring the heights of the exposed rims of partially buried craters. Subtracting those values from the rim heights of similar-sized but pristine craters elsewhere yields the lava thickness surrounding the inundated crater. For example, the rim of 93-km-wide **Copernicus** rises 1,100 m above the surrounding surface. If some other 93-km-wide rim stands only 500 m above its surrounding lavas, then that mare's thickness should be about 600 m. If the older crater formed on the pre-mare floor of the basin, 600 m would be the total thickness of all the lava layers between the basin floor and the topmost lava layer. DeHon's measurements suggest that the total maria fill thicknesses for various basins ranges between 50 and 400 m.

But did the craters that DeHon measured form on a basin floor or on some intermediate lava flow? Later investigators used the distinct spectral difference between mare lavas and the lunar highlands rocks (assumed to underlie the basins) to identify craters that penetrated all the way through basin-filling lavas to the true basin floor below. These



◀ This high-resolution Lunar Reconnaissance Orbiter Narrow Angle Camera image reveals several distinct layers to the mare lava flows revealed in a 65-meter collapsed lava tube.

results imply that the total thicknesses of the lava plains atop the big basins were even less than DeHon's estimations.

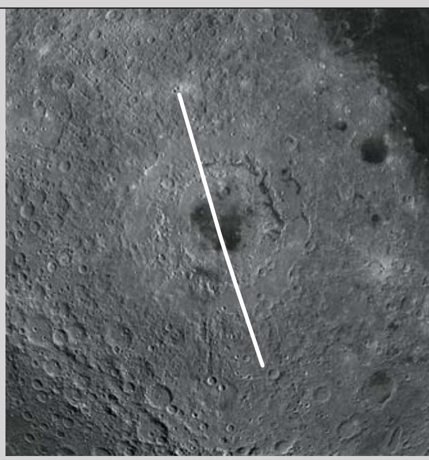
Now a team of mostly Chinese scientists has added a correction to the DeHon method. Jun Du (Peking University), together with colleagues from other institutions, points out that the heights of crater rims today are not the same as when the craters initially formed. Specifically, erosion by micrometeoroid bombardment, thermal expansion and contraction of surface rocks, and seismic shaking slowly wears down these exposed crater rims. Considering that partially lava-buried craters have typically been exposed to such relentless degradation for 1 to 2 billion years, their rims must be significantly lower than when lavas first surrounded them. Du's team concludes that the total thickness of basin-filling lava plains is on average only about 100 m.

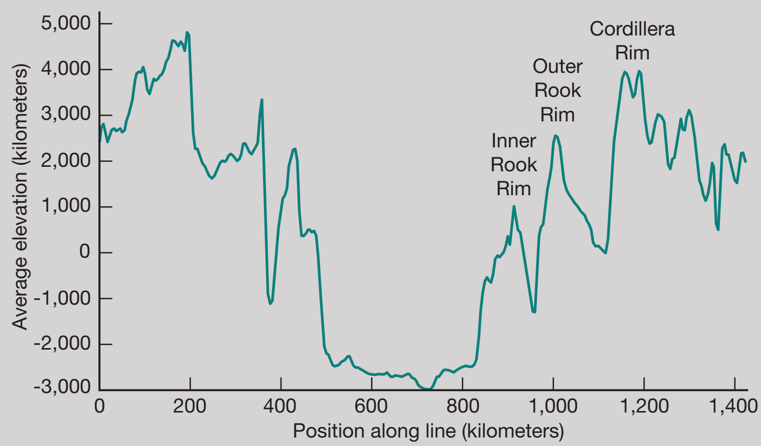
But take a look at where craters are visible on the lava-flooded surfaces of basins. Only a small number of craters pockmark Mare Crisium, and those are near its edges. Similarly, Mare Imbrium's craters are almost entirely outside the system of circular mare ridges that defines the inner part of the Imbrium basin. The central regions of basins are presumably the deepest parts, and the lack of craters suggests that the lavas there are so thick that any craters have been completely overrun. The detection of buried craters by high-quality gravity data (*S&T:* Apr. 2019, p. 52) confirms that any craters in the central regions of basins are too deeply covered to poke into view.

A confirmation of this proposal comes from looking at the young, 930-km-wide Orientale basin, which has nearly no maria infill at all. Its interior is magmatically nearly dry, and the floor is about 3 km below the average lunar elevation. Orientale is a really deep hole, as other basins most likely were too. But multi-kilometer-thick accumulations of lava, perhaps erupted as hundreds or even thousands of individual flows only a few tens of meters thick, shallowed most other basins. Dating estimates of marias suggest that more than a billion years elapsed between the earliest and final eruptions at some basins. And it all ended before life came out of the seas on Earth — we missed it all.

■ Contributing Editor **CHUCK WOOD** often looks below the lunar surface to piece together the Moon's history.

▶ Orientale basin on the Moon's farside is about 7 km deep. That's how thick a filling of lava it would take to make it look like Mare Imbrium, with only the highest peaks of Montes Cordillera visible.





NASA / GSFC / ARIZONA STATE UNIVERSITY (2); GRAPH: GREGG DINDERMAN / S&T

◀ NGC 3115 is a classic example of a lenticular galaxy — flattened like a spiral galaxy but amorphous like an elliptical.

DANIEL VERSCHATSE

Sextans Uraniae

This obscure constellation is swarming with galaxies.

In 1679 a disastrous fire swept through the estate of renowned Danzig astronomer Johannes Hevelius. His home and observatory, Stellaburgum, burned to the ground. Most of his books and records were consumed by flames, and none of his fine instruments survived — including his prized six-foot brass sextant for measuring the angular separation between stars. Hevelius immortalized his lost sextant by creating the constellation Sextans Uraniae between astrologically fiery Leo and Hydra. It endures today under the shortened name Sextans.

Sextans plays host to many galaxies, and we're going to visit a sample of them, limiting ourselves to galaxies brighter than visual magnitude 12.0. If you think that means they'll all be easy, you're mistaken. You'll soon find that a galaxy's magnitude doesn't tell the whole story.

To celebrate 20 years of Sue French's stellar contributions to *Sky & Telescope*, we will be sharing the best of her columns in the coming months. We have updated values to current measurements when appropriate.

We'll start with **NGC 3115**, a large lenticular (lens-shaped) galaxy about 34 million light-years away with a black hole a billion times the mass of our Sun lurking in its heart. It's the brightest galaxy in Sextans at magnitude 8.9.

NGC 3115 sits halfway between the 5th-magnitude stars Gamma (γ) and Epsilon (ε) Sextantis and 22′ north of an imaginary line connecting them. Even at 23× through my 130-mm (5.1-inch) refractor, the galaxy is a bright oval that greatly intensifies toward the center. Three times longer than wide, it lives up to its nickname, the Spindle Galaxy. The size is easier to estimate at 117×, appearing approximately 4½′ × 1½′ to my eye. It leans northeast and holds a small round nucleus. In my 10-inch reflector at 171×, NGC 3115 is 5′ long with its tips gradually blending into the background. A thin core about 2′ long brightens toward the nucleus, and the halo has a faint star superposed south of the galaxy's center.

The interacting spirals **NGC 3169** and **NGC 3166** are twice as distant as the Spindle and weigh in at magnitudes 10.2 and 10.4. To locate them, aim for a 25′ asterism of several 7th- to 12th-magnitude stars (pictured in sketch below right) that makes an isosceles triangle with Alpha (α) and Beta (β) Sextantis. To me, the group resembles the lowercase Greek letter nu (ν) with a tipped capital delta (Δ) to its west. The galaxies float 12′ north of the ν.

The asterism is mirror-reversed in my 130-mm refractor but still quite distinctive. Both galaxies are small ovals with bright cores at 23×. NGC 3169 leans northeast, and NGC 3166 reclines east-west. At 117×, an 11th-magnitude star hugs the flank of NGC 3169, east of center. The galaxy appears roughly 3½′ × 1½′, and its core is oval. NGC 3166 is similar in size but has a rounder and brighter core. My 10-inch scope at 171× bestows a stellar nucleus.

On the way to our next galaxy, let's stop to admire **35 Sextantis**. Through my 130-mm scope at 37×, it's a lovely double with a yellow-orange 6th-magnitude star nuzzling a deep-yellow companion to the west-southwest. They occupy the northeastern corner of an 8′ trapezoid formed with three field stars. A recent spectroscopic study indicates that the companion is composed of two stars in such close embrace that they cannot be seen separately through a telescope.

35 Sextantis heads a remarkable line of stars that has caught the attention of various people over the years. With a slight kink in the top, the sparkling cascade tumbles south-southeast from 35 Sextantis for 3°. Eugene (Oregon)

Astronomical Society members call this "beautiful little starfall" **Rinnan's Run** after Dan Rinnan (see page 84), who chanced upon it during one of their 2009 observing sessions while perusing the sky with binoculars. Tomm Lorenzin zeroed in on the southern end of the line, where the stars are fainter but more densely packed. He dubbed that section The Scar in his 1997 online 2000+ Catalog. With 11×80 binoculars in 1980, California's Dana Patchick saw a wide V made up of The Scar and a second starry line reaching northeast from its southern end. I've always called it Dana's V.

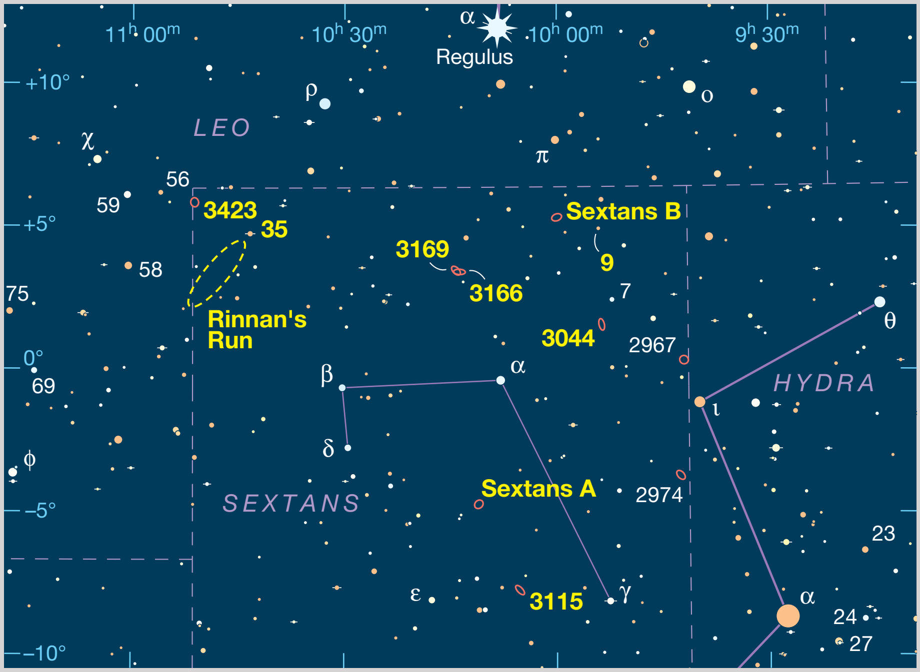
Now that you're acquainted with the area, look for the galaxy **NGC 3423** two-thirds of the way from 35 Sextantis to the reddish orange star 56 Leonis. It's stored on the attic floor of a skinny, Cepheus-like, stick-figure house of five stars. The house is ½° tall with its sharply peaked roof aimed south-southwest. NGC 3423 is magnitude 11.1 and as distant as the Spindle Galaxy.

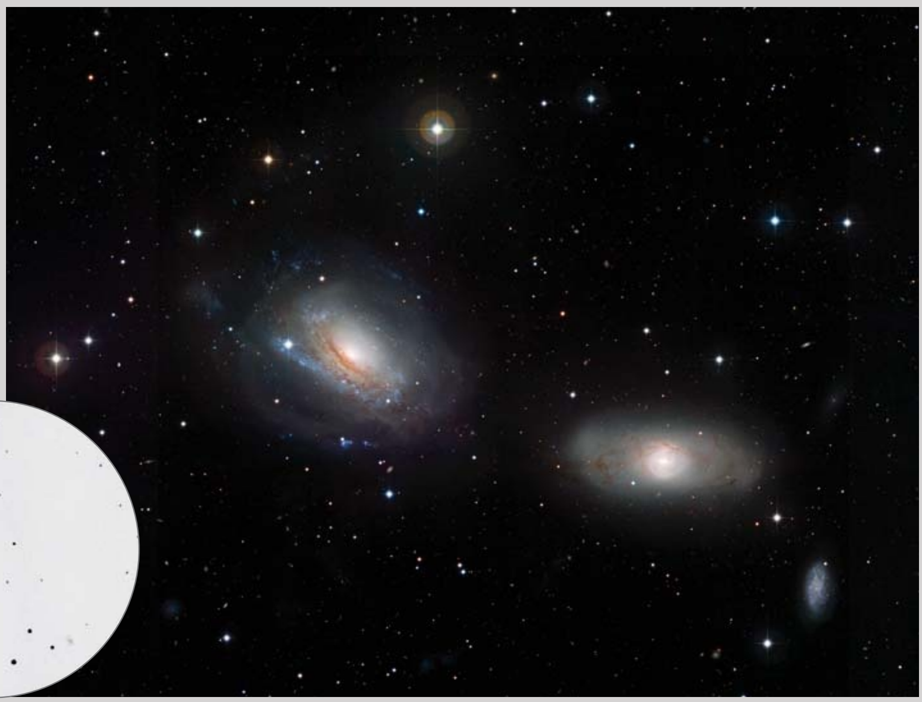
Through my 130-mm refractor at 63×, NGC 3423 is a 2½′ roundish glow of fairly low surface brightness embracing a small, slightly brighter core. At 117×, a faint star guards the northeastern edge of the galaxy. My 10-inch reflector at 171× reveals a lovely 3¼′ × 1¼′ oval tipped north-northeast. It appears very patchy, especially around the outer edges, giving the impression of weakly defined spiral arms wrapping clockwise outward. The core is round and spans 40″.

Our next two galaxies are nearly the same magnitude as NGC 3423, but they're much harder to see. **Sextans B** (UGC 5373) is magnitude 11.3, and **Sextans A** (MCG–1-26-30) is 11.5. At 5 million light-years, these dwarf galaxies dwell just beyond the boundaries of our Local Group.

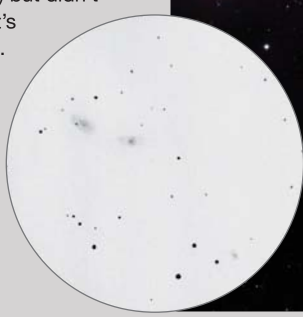
Sextans B sits 1½° east-northeast of the pretty, wide, orange-and-gold double **9 Sextantis**. In my 10-inch scope at 171×, Sextans B is a very faint glow that covers about 3′ × 2′ and leans west-northwest. A 14th-magnitude star is pinned to its northern edge, and 13th-magnitude stars rest 2½′ north and east-northeast of the galaxy's center.

Sextans A is located 4.4° south and a bit east of Alpha Sextantis. With my 10-inch reflector at 187×, I could only pick out its brightest patch, which lies in the western side of a faint star pattern that's a lopsided version of





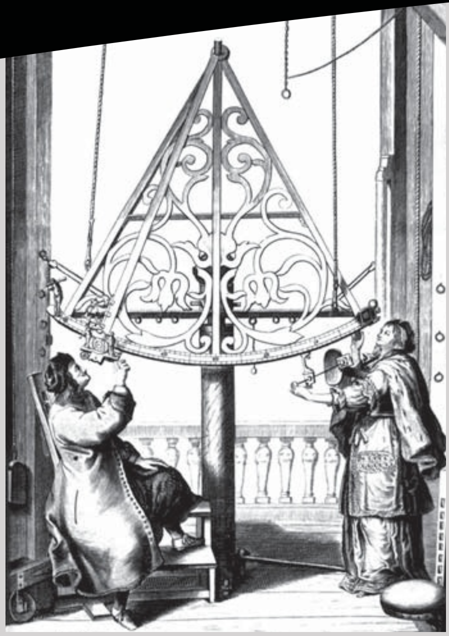
▶ NGC 3169 (left) and 3166 are distorted by each other's gravitational pulls. The author also spotted little NGC 3165 (far right) but didn't include it in the article because it's below the 12.0-magnitude cutoff.



▶ At 60×, the galaxies NGC 3166 and 3169 are easily located north of a prominent asterism. Fainter NGC 3156 lies just west of the asterism's brightest stars. All sketches represent views through a 6-inch reflecting telescope.

SKETCH: ERIC GRAFF; TWO GALAXIES: ESO / IGOR CHEKALIN

◀ *Far left:* Faint Sextans B sits in a pretty star field at 60×. *Left:* NGC 3044 is a long sliver at 120×.



▶ Johannes Hevelius and his wife Elisabetha measured star positions with extraordinary accuracy using their giant sextant, now immortalized as one of the 88 constellations.

the 5-spots on dice. The patch is very grainy, less than 1′ long, and wider at its southwestern end. Through my 15-inch reflector at 79×, this little scrap of the galaxy is embedded in the eastern side of a ghostly 3′ glow.

Our final galaxy is the faintest of all, yet I can glimpse it in a small telescope. **NGC 3044** shines at magnitude 11.9, and it's about the same distance away from us as NGC 3166 and NGC 3169. We find it dangling 57′ south-southeast of 7 Sextantis.

Through my 105-mm scope at 122×, NGC 3044 is a very faint slash about 3′ long with a brighter, elongated core. The galaxy points toward an 11.7-magnitude star 6′ away from its west-northwestern tip. The view through my 10-inch scope increases the length of this slender streak to about 4′.

Why are Sextans A and B so difficult to see if their magnitudes are only a little dimmer than NGC 3423's and brighter than NGC 3044's? The answer lies largely in their apparent size.

In our table, the listed magnitude for NGC 3423 is 11.1. In other words, if all the galaxy's light were gathered into a single point, it would look like an 11.1-magnitude star. But that light is actually smeared across an oval 3.8′ × 3.2′ in size, making each square arcminute of the galaxy, on average, magnitude 13.7. This value is known as surface brightness (SB), and a quick glance at the size and SB columns in the table will tell you why Sextans A and B are tough to see. Their light is attenuated by being spread over a larger area than the other two galaxies.

These four galaxies are challenging to find, and a good star atlas can be a helpful tool for tracking them down. All the objects in this sky tour are plotted in the second edition of *Sky Atlas 2000.0*.

■ Contributing Editor **SUE FRENCH** wrote this column for the April 2011 issue of *Sky & Telescope*.

Exploring Hevelius's Sextant

Object	Type	Mag(v)	Size/Sep	SB	RA	Dec.
NGC 3115	Galaxy	8.9	7.2′ × 2.4′	11.9	$10^h\ 05.2^m$	–7° 43′
NGC 3169	Galaxy	10.2	4.4′ × 2.8′	12.8	$10^h\ 14.2^m$	+3° 28′
NGC 3166	Galaxy	10.4	4.8′ × 2.3′	12.8	$10^h\ 13.8^m$	+3° 26′
35 Sextantis	Double star	6.2, 7.1	6.8″	—	$10^h\ 43.3^m$	+4° 45′
Rinnan's Run	Asterism	—	3°	—	$10^h\ 46.3^m$	+3° 26′
NGC 3423	Galaxy	11.1	3.8′ × 3.2′	13.7	$10^h\ 51.2^m$	+5° 50′
Sextans B	Galaxy	11.3	5.5′ × 3.7′	14.5	$10^h\ 00.0^m$	+5° 20′
Sextans A	Galaxy	11.5	5.5′ × 4.5′	14.8	$10^h\ 11.0^m$	–4° 42′
9 Sextantis	Double star	6.9, 8.4	52.5″	—	$9^h\ 54.1^m$	+4° 57′
NGC 3044	Galaxy	11.9	4.9′ × 0.7′	13.1	$9^h\ 53.7^m$	+1° 35′

Surface brightness (SB) is in magnitude per square arcminute. 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.

SKETCHES: ERIC GRAFF; HEVELIUS ETCHING: WIKIMEDIA COMMONS

 by Gabriella Bernardi

Paragoni!

▲ **OPTICAL ROYALTY** In this painting by Mariano Piervittori, famed 17th-century optician Eustachio Divini is depicted presenting one of his telescopes to the Grand Duke of Tuscany, Ferdinand II de' Medici. Ferdinand was a patron and friend of Galileo Galilei, and his youngest brother established the Accademia del Cimento (Academy of Experiment).

Two of Europe's greatest 17th-century opticians battle for fame and fortune.

Florence. On a clear night in October 1663, two men walk through salons crowded with guests at the Medici palace, home to the most powerful family in Florentine Italy. The event isn't a party, and though the two men aren't princes or noblemen, they're the center of attention. Both are extraordinary opticians. And while the older man is very tense, the younger man swaggers around full of confidence.

A famous man has also just arrived at the palace: Giovanni Domenico Cassini, one of the most renowned astronomers of the era, and professor of astronomy at the University of Bologna. On this night he is in attendance as one of the distinguished referees. The first official competition to find the best telescope maker in the world is about to start.

Such competitions, known as *paragoni* — an Italian word meaning "comparisons" — were fostered by the Florentine scientific society, Accademia del Cimento (Academy of Experiment). A *paragone* was based on a simple premise: to have experts make direct comparisons between tools (telescopes, in this case) under the same experimental conditions. Such competitions originated with Galileo Galilei and soon became regular, highly anticipated events in Florence.

▲ **MASTER OPTICIAN** Eustachio Divini was born in 1610 in San Severino Marche. His early life was marked by tragedy — he lost both his mother and father while still a child. Raised by his brothers, Eustachio eventually settled in Rome, where he eventually became a successful telescope maker.

A Battle Royale

This evening's paragone is not the first involving telescopes, but it's especially thrilling because it's between the two most skilled opticians in all of Europe.

The older craftsman is Eustachio Divini, and his younger rival is Giuseppe Campani. At the time of the paragone, both lived and worked in Rome. Divini was born in San Severino Marche, central Italy, and, following a stint in the military, studied geometry and astronomy in Rome with eminent scholars such as Evangelista Torricelli, a pupil of Galileo's and mathematician to the Grand Duke of Tuscany. Divini entered into business as a clockmaker and manufacturer of lenses for telescopes and microscopes, eventually establishing himself as Italy's most sought-after optician.

Divini was also a keen observer and used his own telescopes to create a detailed map of the Moon — an undertaking aided by a micrometer eyepiece he'd devised to accurately position lunar features. He also viewed the planets and their satellites, which engaged him in some of the scientific controversies of the day, such as the true nature of Saturn's rings. This topic brought him into conflict with the prestigious Dutch scholar and discoverer of Titan, Christiaan Huygens. However, Huygens may have been primarily motivated by the desire to defend the quality of his optics, which dominated the telescope market at the time.

Divini's competitor, Giuseppe Campani, was born 25 years after Divini, near Spoleto, also in central Italy. Despite his rural origin, he managed to improve his social position thanks to his two older brothers, Matteo and Pier Tommaso, who were expert clockmakers and introduced Giuseppe to the art of lens grinding. The three also teamed up to build an excellent clock for Pope Alexander VII.

The State of the Art

What kind of telescopes would we have seen that night in Florence? Telescopes and spyglasses were a relatively recent invention, having originated in the Netherlands, where Hans Lippershey, a 38-year-old spectacle maker, built the first telescope in 1608. The following year Galileo Galilei fabricated his own instrument and trained it on the night sky for the first time, making several remarkable discoveries in the process.

Galileo's telescope employed two lenses: a convex objective and a concave eyepiece, together yielding a right-side-up view. It was Johannes Kepler who, in 1611, suggested using a convex lens for the ocular. Although the resulting image was inverted, for a given magnification its field of view was much larger than with the Galilean design.

Telescopes built with simple, single-element objective lenses — even those of high quality — suffer greatly from spherical and chromatic aberration, which produces images that are both soft and fringed with spurious color. To combat these defects, telescope makers produced lenses of ever-increasing focal lengths, led by Johannes Hevelius, who built one instrument with a tube 150 feet long! Later, tubeless "aerial" telescopes had even longer focal lengths. Despite the monumental ungainliness of these instruments, they were used to make many important astronomical discoveries. It was with a 2-inch-aperture, 12-foot-focal length instrument that Huygens discovered Saturn's biggest moon, Titan, in 1655. A few years later, in 1659, he used another long refractor to accurately determine the rotational rate of Mars by observing the dark feature Syrtis Major.

Manufacturing lenses of consistently good quality remained challenging, even as new grinding techniques were being introduced. Usually lenses were made in batches, then inspected for obvious defects, such as bubbles and cracks. The survivors of these preliminary checks were eventually installed in telescopes. In the absence of specialized testing equipment, the only available evaluation method was direct use — often by comparing instruments to each other under more or less controlled conditions, and with the help of a jury of impartial referees.

And the Winner Is

Let's return to Florence and the night of the paragone. The observations have been made, the telescopes taken down, and the guests have left. After a very heated discussion, the palace is now silent. The testing has concluded, but without a reaching a definitive judgment. Another paragone would be necessary.

Campani preferred not to do it in Florence again, probably because he suspected an element of bias since Divini had previously sold instruments to the Duke of Tuscany and other notables of the region. As a result, the next paragone was held in Rome. But once again, the outcome remained unsettled. By the end of 1664, the general conclusion was that Campani's instruments showed objects more clearly, while those of Divini provided greater magnification.

It's perhaps surprising that these paragoni failed to designate a clear winner given that Campani had a considerable edge thanks to his brother, Matteo, who was not only a priest in Rome, but an optician as well. And the brothers weren't above cheating. During the April 30, 1664, paragone, Divini exhibited a telescope featuring a complex, multielement design. The instrument was one commissioned by Cardinal Flavio Chigi, nephew of Pope Alexander VII. The telescope was already in possession of the Cardinal, but the Campani brothers managed to arrive early and sabotage Divini's instrument. Their tampering was so effective that they easily defeated their competitor. Divini was humiliated, but his sense of fairness prevented him from questioning the surprising results. He not only had to admit that Campani's optics performed better, but also felt obliged to replace the Cardinal's expensive (but evidently defective) telescope.

The Academy of Florence, however, was reluctant to accept the results of this paragone and, possibly suspecting some irregularities, proposed an additional series of tests based on examining text placed at a distance. Once again, Campani insisted the competitions take place in Rome, though they were held in several different locations. Despite other alleged frauds perpetrated by the Campani brothers, by the end of 1664 a definitive verdict continued to elude the judges.

◀ **17TH-CENTURY ROCK STAR** Giovanni Domenico Cassini was the most celebrated astronomer of his day, making numerous important discoveries while using telescopes made by Giuseppe Campani. Today Cassini is best remembered for the NASA/ESA space mission named after him, and for the Saturnian ring feature known as the Cassini Division.

Game Over?

The turning point finally arrived in 1665, when the Duke of Tuscany, who was an expert astronomical observer and one of the founders of the Academy of Florence, acquired telescopes from both Divini and Campani with the goal of testing them on the night sky.

In July, Campani was declared the winner, thanks to a telescope he'd made especially for a Cardinal Borromeo. Having successfully toppled Divini as the finest telescope maker of the age, Campani saw his reputation grow rapidly as European kings, queens, and nobles commissioned him to make instruments for their use.

Divini didn't take this verdict well. As he stressed in his letters, after three years of competition Campani won only this single comparison, and the outcome rested on the capabilities of a single instrument. Another, different kind of test would be necessary to establish who truly was the best optical craftsman.

Just like today, the optics in a 17th-century telescope consisted of an objective and a magnifying eyepiece. Both parts must be of high quality to deliver the best results. However, manufacturing objective lenses and eyepieces requires different skills. Following the advent of the Keplerian design,

In effect, the paragone ultimately served as a kind of 17th-century "brand launch."

▶ **FIRST ON THE MOON** In 1609 Galileo Galilei famously inspected the Moon's "rough and uneven" surface. Comparing Galileo's crude depictions with that made by Divini (on facing page) reveals the improvements in telescopes in the 40-year span between renderings.

CASSINI: NEW YORK PUBLIC LIBRARY / SCIENCE SOURCE; GALILEO MOON SKETCH IMAGE: S&T ARCHIVES

CASSINI MOON This 1679 map of the Moon was rendered by Cassini, using instruments made by Campani. At the time of its publication, it was the most detailed depiction of the lunar surface — a reflection of both the skill of the observer and his telescope's optical quality.

CASSINI MOON: OBSERVATOIRE DE PARIS;
DIVINI MOON: DIGITAL MUSEUM OF PLANETARY MAPPING

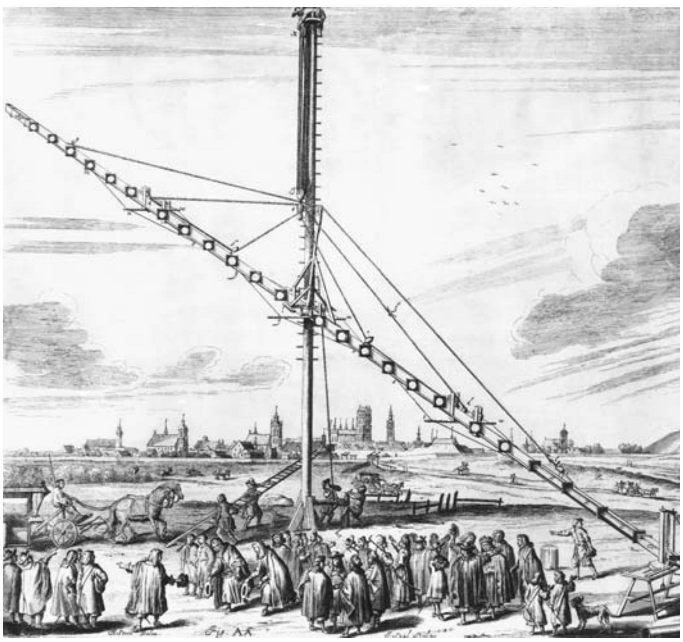
LUNAR OBSERVER Divini was not only a skilled optical craftsman, he was also a dedicated observer of the Moon and planets. This detailed map (heavily "inspired" by an earlier effort by Hevelius) was produced in 1649, just 40 years after Galileo first turned a telescope skyward.

opticians began producing more complex eyepieces utilizing additional lenses. This development was sparked by the discovery that extra lenses would correct an upside-down image, ushering in the possibility of terrestrial spyglasses made only with convex lenses. Furthermore, opticians later found that the appropriate combinations of additional lenses could allow oculars to correct various optical aberrations. Each manufacturer made their own eyepieces, and it seems that the sharper images produced by Campani's telescopes owed much to the oculars he built. On the other hand, it was commonly agreed that the true talent of a craftsman was revealed by the quality of the objective alone, since such a lens was larger and more difficult to make.

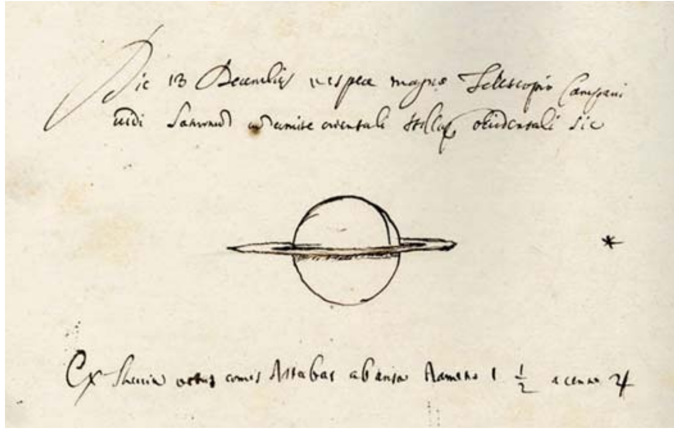
In the 17th century, lensmakers generally followed a method that is familiar to present-day telescope makers. First, a roughly shaped lens blank is produced from an initial piece of glass. Next, a spherical figure of the desired focal length is ground into the lens. Finally, the lens is polished to remove pits and surface roughness.

So, one way to establish conclusively the better optician would be to have them fabricate an objective lens, with specific characteristics, from the same piece of glass split in two, one for each contender. Curiously, even after the Duke of Tuscany had declared Campani the winner, both challengers requested precisely this kind of test. The Academy, however, refused to accommodate this last paragone and closed the dispute forever.

It's tempting to consider how events might have unfolded if this contest had been allowed to proceed. Would Campani still have come out on top? Likely he believed he had a significant advantage. Campani claimed that he was able to make very good objective lenses thanks to an innovative technique that allowed him to produce lenses in their final form directly on a lathe. However, no proof was ever offered to support this claim, and no evidence of such equipment has survived, even though his workshop was donated to the Academy of Science of Bologna 30 years after his death. The secrets of this method — if it ever existed — died with Campani.



▲ **GOING LONG** To mitigate the effects of chromatic and spherical aberration, 17th-century telescope builders resorted to extreme focal lengths. Leading the charge were Christiaan Huygens and Johannes Hevelius, who ultimately created this 150-foot-long, open-tubed instrument, which was erected in Danzig, Poland.



▲ **NEW SATURNIAN MOONS** Cassini used Campani optics to discover four satellites of Saturn: Iapetus, Rhea, Tethys, and Dione. The Cassini sketch (above) depicts Iapetus on the night it was first seen in 1671.

Fame and Fortune

Like Divini, Campani was a talented observer, and he was able to team up with the great astronomer Giovanni Cassini. Their relationship proved mutually beneficial. The superb quality of Campani's telescopes helped Cassini make many important discoveries and, at the same time, Cassini's fame likely did more to promote Campani's instruments than the outcome of the paragoni. Sadly, Divini never had a similar partner at his side.

Although Campani's victory remains undeniable, it's worth remembering that both contenders were equally skilled and produced instruments of comparable quality. That means that the discoveries that brought so much fame to Campani just as easily could have been made with Divini's telescopes. Indeed, it can be said that fate likely played a much greater role in the fortunes of these two rivals than their relative abilities. In effect, the paragone ultimately served as a kind of 17th-century "brand launch," cleverly prepared by Campani and his brother. But Divini also benefited. He wrote that "after the contest . . . I have new orders." In that sense, both men came out winners.

■ **GABRIELLA BERNARDI** is a freelance science journalist with six books to her credit, including one on Giovanni Domenico Cassini. Her most recent book is *Understanding Gaia: A Mission to Map the Galaxy*, which she coauthored with Alberto Vecchiato.

▶ HEAVY-DUTY MOUNT

Sky-Watcher announces its most advanced German equatorial mounts to date: the EQ8-R and EQ8-Rh (starting at $4,050 and $7,100, respectively). These new mounts feature whisper-quiet dual belt drives combined with hybrid stepper-motors that provide increased accuracy when slewing and guiding. The mount head weighs 56.8 lbs and is capable of bearing an instrument load of 110 lbs, not including the counterweights. Both mounts include a new cable management system with four USB 3.0 ports, three 2.1-mm power ports, and three serial ports that helps to prevent cable snags during operation. The EQ8-Rh incorporates a Renishaw incremental encoder on its RA axis, virtually eliminating periodic error. Both mounts are controlled with Sky-Watcher's upgradable SynScan Go-To hand paddle with a database of more than 42,000 objects. Each mount ships with two 22-lb counterweights. An optional heavy-duty portable pier tripod and polar-alignment scope are each available at an additional cost.

Sky-Watcher USA
475 Alaska Ave., Torrance, CA 90503
310-803-5953; skywatcherusa.com

◀ CLIP-IN FILTERS

Astronomik now offers a series of clip-in filters for the Canon EOS R-series mirrorless cameras. The EOS R XL Clip-Filter series is designed to minimize vignetting introduced into the camera's light path by the clip-in system. They are compatible with Canon's new EF-M lens system as well as the older EF-series lenses using a proper lens adapter (see page 64). Choose from 15 passbands ranging from a clear filter that protects a modified sensor from dust (starting at €109.00) to several narrowband wavelengths useful for imaging nebulae.

Astronomik
astronomik.com

▶ PLATE-SOLVING SCOPE

Celestron rolls out its newest telescope innovation, the StarSense Explorer DX 130AZ ($399.95). This 5.11-inch reflector uses patent-pending technology to offer precise navigation with the help of your smartphone. Simply install the *StarSense Explorer* and *SkyPortal* apps on your compatible device and place the device in the telescope's smartphone docking port. The app will determine the exact location and direction that the telescope is pointing by analyzing short exposures with your phone's camera. It then identifies star patterns in its internal database, no matter where it's pointed in the sky, without the need of a complex alignment routine. The StarSense Explorer DX 130AZ includes a red-dot finder, 25- and 10-mm eyepieces, and an aluminum tripod. No additional power is necessary. Requires devices with Android 7.1.2 and later or iPhone 6 and newer phones.

Celestron
2835 Columbia St., Torrance, CA 90503
310-328-9560; celestron.com

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

Canon's Mirrorless EOS Ra

We test Canon's EOS R mirrorless cameras, including the new "Ra" model made for astrophotography.

▲ *Above:* The EOS Ra differs from the stock EOS R in its greater red sensitivity and 30x Live View magnification. Its compact body weighs 1.6 pounds, but with the optional EF-EOS R lens adapter the weight goes up to 2 pounds. *Top:* Red emission nebulae such as the North America Nebula, NGC 7000, are prime targets for Canon's EOS Ra camera. This is a processed stack of four 6-minute exposures, with the camera set to ISO 1600 and shooting through an Astro-Physics 105mm refractor at f/6.

ALL PHOTOGRAPHS ARE BY THE AUTHOR.

Canon EOS R

U.S. Price: $1,799

Canon EOS Ra

U.S. Price: $2,499

usa.canon.com

What We Like

Excellent red sensitivity in the Ra model

30× magnification for precise focusing

Excellent battery life

What We Don't Like

Lacks dark frame buffer

No built-in intervalometer

4K movies are cropped 1.8×

EVERY SEVEN YEARS, astrophotographers have reason to celebrate as Canon issues an astronomical version of one of their current cameras. The new EOS Ra is the third astrophoto camera offered by Canon, following its ground-breaking 20Da in 2005 (*S&T:* Nov. 2005), and seven years later the 60Da (*S&T:* Sept. 2012).

We already had a test underway of Canon's mirrorless EOS R when rumors began flying of the astronomical "Ra" model. Using an early sample of the EOS Ra, we put both versions of the EOS R through their paces under the stars.

Red Sensitivity

In the days when film was the dominant photographic medium, we coveted the few color emulsions (remember Kodak Ektachrome 200 or Fuji Super G 400?) that recorded reddish hydrogen-alpha (Hα) nebulosity that permeates the Milky Way better than other films. In the digital age, most general-purpose cameras perform poorly for picking up emission nebulae.

The reason is that all have a blocking filter installed in front of the sensor that cuts out infrared (IR) light that would otherwise add an unfocused haze over the image. But filtering out IR also filters out most of the deep red Hα emission at a wavelength of 656.3 nm.

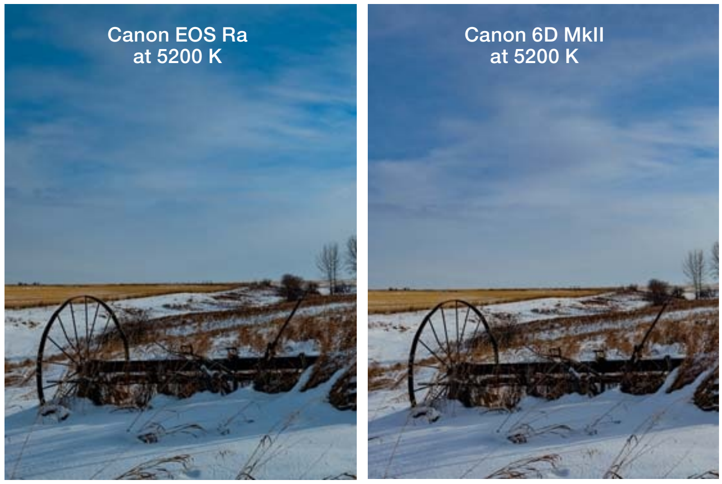
Not so with the EOS Ra. Its factory-installed IR-cutoff filter transmits a much higher level of Hα than the stock EOS R.

I found that the Ra's ability to record red emission nebulosity to be on par with my modified Canon EOS 5D Mark II that I've used for almost all my deep-sky imaging since 2009. My venerable EOS 5D MkII is an example of a DSLR that was modified by a third party, in this case Astro Hutech (**hutech.com**).

It appears that Canon has given the new Ra camera a filter with greater transmission of Hα emission than on its earlier "a" cameras. The Hα performance of the Ra proved better than Canon's previous 60Da. Whether it will match the performance of "spectrum-enhanced" cameras modified by third party vendors will depend on the filters those cameras use. Some, dubbed "full spectrum" cameras, use no IR-blocking filter at all.

The EOS Ra is certainly not a full-spectrum camera, but then again it doesn't require the addition of costly clip-in filters to cut infrared for normal daytime use.

▶ Due to its factory calibration, shooting the EOS Ra by day (left) at a daylight color temperature of 5200 K produces a raw file (as of firmware version 1.6) that looks similar to that of a normal camera, a Canon 6D MkII at right, also shot at 5200 K. The EOS Ra can be used for normal photography.



Daytime Use

The advantage of purchasing Canon's enhanced-red Ra camera is that the manufacturer has calibrated the camera's white balance to produce a nearly normal color rendition even when using Auto or Daylight White Balance. Custom White Balance, a necessity when using third-party modified cameras by day, isn't required with the Ra. Where the Ra's added red sensitivity did become apparent in "normal" use was during twilight and sunset shots, which recorded with rich reds.

While it can be used by day "as is," the EOS Ra is definitely not for subjects in which color accuracy is critical. I wouldn't shoot weddings or portraits with it!

Framing and Focusing

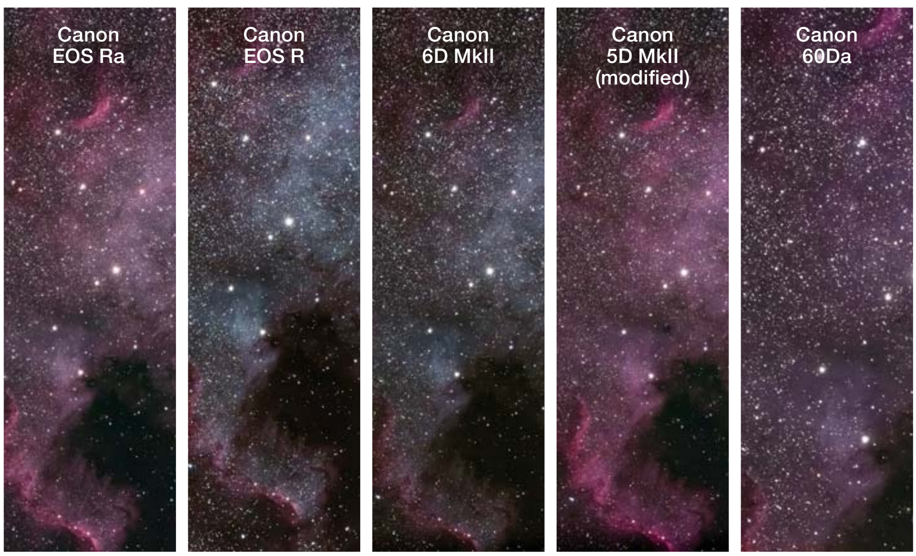
Both EOS R cameras offer a Live View screen sensitive enough to allow framing dark nightscapes, and to show enough stars through a telescope to identify your field, perhaps even your target, all on its comfortably tilted rear LCD screen. That improvement alone makes the upgrade to an EOS mirrorless camera very attractive for astrophotography.

The EOS Ra has one welcome firmware upgrade over the standard EOS R that benefits astrophotography. Instead of Canon's standard 10× magnification in its Live View focusing feature, the EOS Ra offers 30×, great for precisely focusing on stars. I found this especially useful when focusing wide-angle lenses with their tiny star images.

Image and Edge Artifacts

The long exposures and extreme contrast-stretching applied when processing deep-sky images can reveal image flaws that go unnoticed in conventional photography. However, I found no issues with "star eating," nor discolored stars that plague some manufacturers' cameras. There were no edge-glows or light-leaks and, as expected for a mir-

▼ The EOS Ra (far left) picked up the North America Nebula with richer red nebulosity than Canon's 60Da camera (far right), and with a level similar to the author's third-party modified EOS 5D MkII. By comparison, images with the stock EOS R and 6D MkII show what a normal camera typically records — very little red nebulosity. This comparison set uses single raw images processed identically to increase contrast and neutralize the sky background, but without any alteration of the nebula colors.



▲ At night, the EOS R cameras (left) present a much brighter image in Live View (the only way to preview a scene with a mirrorless camera) than does the Canon 6D MkII (right), which barely shows a few stars.

rorless camera, no edge shadows cast by upraised mirrors or sensor masks. The frame was clean to the edge. That's a significant advantage over most full-frame DSLRs.

Another advantage to purchasing a factory-modified camera is that the sensor dust cleaning function is retained in the EOS Ra, a feature that is often removed by some third-party modifications.

Noise Levels and ISO Invariancy

The noise levels in images taken with the EOS Ra proved identical to the stock EOS R. Both cameras' 30-megapixel sensors have a pixel pitch of 5.36 microns versus the 5.76-micron pixels of Canon's 26-megapixel EOS Rp mirrorless and 6D MkII DSLR. Not having an Rp on hand, I compared the R models to the 6D MkII.

I was pleased to see that the EOS R cameras exhibited noise levels that are as good as, if not slightly lower than, the Canon 6D MkII despite the latter's larger pixels. Noise appeared to be no more than half a stop worse than in the 24-megapixel Sony α7III we tested (*S&T:* Apr. 2019, p. 60), with its 6-micron pixels.

Where the EOS R models really excel over Canon's 6D MkII is in "ISO invariancy." Underexposing at a lower ISO, then boosting the exposure later during RAW processing should, with an ISO invariant sensor, produce identical results to shooting at a high ISO in the field. That's the case with Sony cameras and many Nikons.

By contrast, the Canon 6D MkII is terribly unforgiving of underexposure. When boosted later to extract details, dark shadows in its nightscapes exhibit high noise levels, poor contrast, and artifacts such as discoloration and banding.

Happily, both EOS R cameras exhibited minimal additional noise and artifacts in shadows when brightened in post-processing. This makes them superb for nightscape stills and time-lapse photography. They are perhaps Canon's best cameras for this purpose.

Battery Life

A single battery lasted seven hours on autumn nights at near-freezing temperatures in the EOS Ra (just as advertised by Canon), recording 1,500 consecutive 15-second exposures. That was with Wi-Fi turned off and the power-saving "Eco Mode" disabled.

Canon also supplied us with the BG-E22 dual battery grip — a $250 accessory. Powering the camera with it in freezing temperatures extended the life to 16 hours and 3,600 shots, more than enough for night-long time-lapses during the winter. The worry that mirrorless cameras quickly exhaust their batteries is a concern of the past — at least with these Canon cameras.

Compatibility Concerns

Oddly, as of version 1.6 of the firmware, both EOS R cameras lack a built-in intervalometer, useful for shooting time-lapses, a feature present in all recent Canon DSLRs and even the EOS Rp. You must use an external intervalometer to run the cameras.

The EOS R cameras use Canon's E3 sub-mini jack for their shutter release port, not the more robust three-pronged N3 port used on Canon's full-frame DSLRs. Using an intervalometer with a type N3 plug requires the Canon RA-E3 adapter cable. But with the right connector, any time-lapse controller that operates the camera through the shutter release port will work with the EOS R cameras.

However, for devices or software that operate the camera through its USB port, compatibility will be an issue. For example, as of this writing the popular control program *BackyardEOS* (v3.1) would not connect to an EOS R, but *AstroPhotography Tool* (v3.82) would and operated the Ra just fine. As you

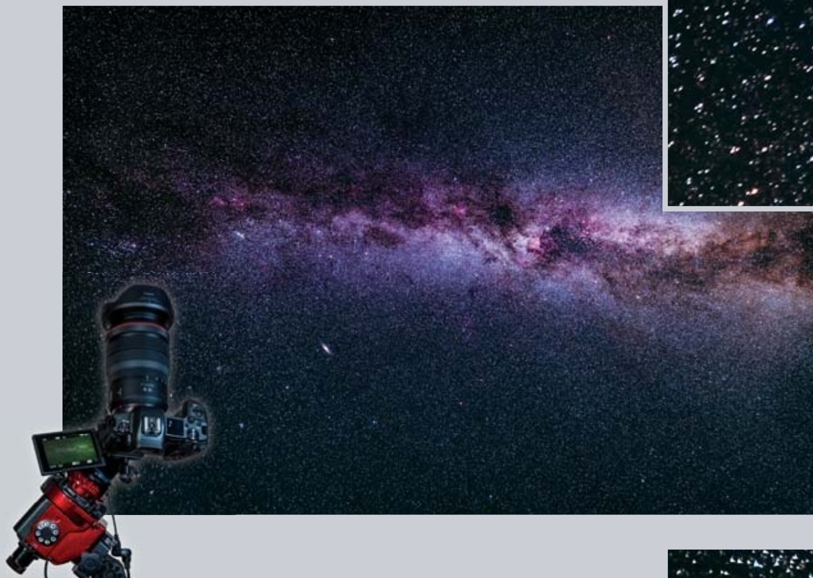
◀ Canon's mirrorless cameras include a flip-out LCD screen that's comfortable to use when the camera is aimed up. Its touch screen ability can access most camera settings. A top-mounted OLED screen provides an ongoing readout of battery life and exposure time.

▶ The EOS Ra's unique 30× magnification when in Live View mode makes it easy to precisely focus on stars, as seen here with a Bahtinov mask added over the telescope aperture to aid in focusing.

Canon's Premium RF Lenses

Along with the R cameras, we received samples of two of Canon's premium RF lenses made for the EOS R cameras and ideal for astrophotography.

The RF 15-to-35 mm f/2.8 L
This new zoom lens has a focal length range and speed perfect for nightscape photography. At 15 mm and wide-open at f/2.8, the lens was clean across the frame with low aberrations at the corners. Off-axis aberrations became more pronounced at the longer focal lengths but were still well-controlled at 35 mm. While vignetting was significant, that can be fixed in RAW processing with Lens Correction functions.




RF 15-to-35-mm lens at 15 mm, f/2.8.


RF 15-to-35-mm lens at 35 mm, f/2.8.

The RF 85 mm f/1.2 L
Razor-sharp on-axis, even wide open, this short telephoto showed very low off-axis aberrations even at f/1.2, allowing it to grab lots of nebulosity in short exposures and at low ISO speeds. This test shot is with the stock EOS R camera. This is one of the best 85-mm lenses on the market, providing a fine focal length for Milky Way star fields.


RF 85-mm lens at f/1.4.

◀ Blow-ups of the North America Nebula taken at ISO 1600 show the EOS Ra with lower noise than the decade-old Canon 5D MkII, despite the latter's larger pixels, and similar or slightly lower noise than the Canon 6D MkII and 60Da.

would expect, Canon's own *EOS Utility* desktop program controls both R models, either tethered or wirelessly via the camera's Wi-Fi connections.

With its mirrorless cameras, Canon introduces a new CR3 format for its RAW files. *Adobe Photoshop*, *Adobe Lightroom*, and competitor programs from ACDSee, Affinity, DxO, and ON1 can open these CR3 files, as can *PixInsight* as of v1.8.8. But *AstroPixelProcessor* (v1.075) and *Raw Therapee* (v5.7), two programs popular with astrophotographers, could not.

With all mirrorless cameras the "flange distance" from the lens mount to the sensor is very short; there is no mirror to flip in and out of the light path as there is in a DSLR. In Canon's case their EOS R cameras have a flange distance 24 mm less than in their DSLRs. Plus, with their mirrorless R cameras Canon introduces a new wider-format RF lens mount. Adapting older EF and EF-S Canon lenses is possible with one of Canon's EF-EOS R lens adapters. One is also needed to attach an EOS R to a telescope via your existing camera adapter/field flattener and its Canon T-ring.

The version of the EF-EOS R lens adapter that accepts drop-in filters provides the opportunity to insert light-pollution filters into the light path well ahead of the sensor. They will work better with wide-angle lenses than do clip-in filters, which can vignette the image on the sensor.

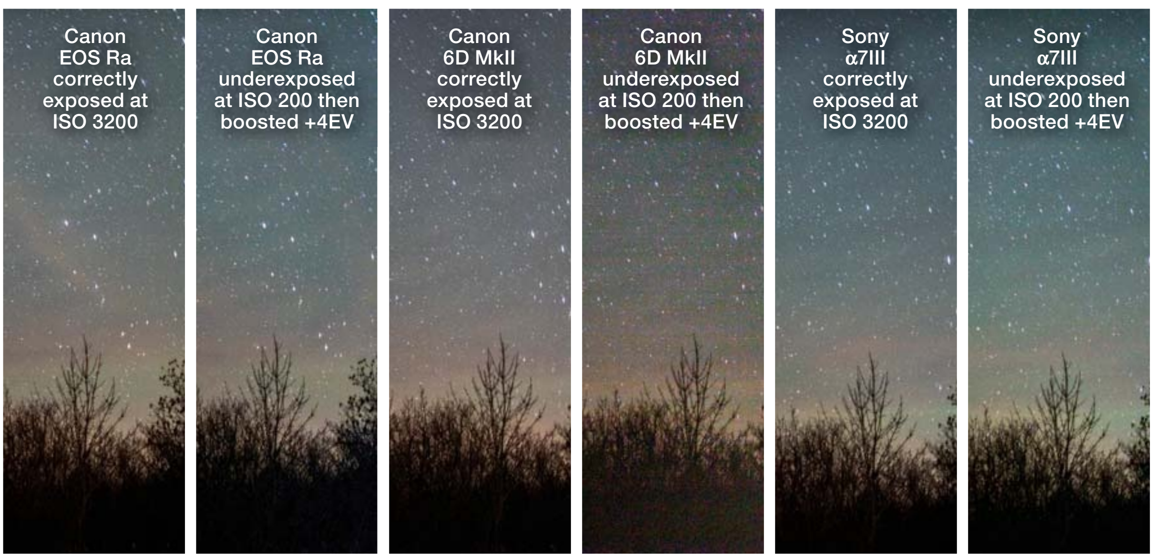
On the Down Side

The EOS R cameras offer HD and 4K movie recording at ISO speeds up to 102,400 and with shutter speeds as slow as ⅛-second. Those specs allow either EOS R to record movies of night scenes.

However, when recording in 4K the frame is cropped by factor of 1.8×. The severe crop will make it difficult to capture real-time 4K movies of sky-spanning aurorae, even with wide-angle lenses. On the other hand, the crop factor has a benefit when shooting eclipses in 4K. The Sun can fill the frame with a shorter focal length lens or telescope than would otherwise be the case, much like when shooting with APS-format cameras.

When using Long Exposure Noise Reduction (LENR) to reduce thermal noise, Canon's full-frame DSLRs have a unique buffer that allows you to take three to five images in quick succession (the number varies with the model), before the dark frame kicks in with LENR turned on. One internal dark frame gets applied to several images, speeding up image acquisition.

However, this feature does not work if you control the camera through its



◀ Pairs of images properly exposed at 0 EV and underexposed by -4 EV, then brightened later in processing, demonstrate how the Canon 6D MkII (center) is unforgiving of such underexposure. By comparison, while not quite as good as the ISO invariant Sony α7III (right), the EOS Ra (left) performs very well.

USB port with software on a computer. Nor does it work with a DSLR if you have Live View activated. Unfortunately, due to the nature of mirrorless cameras, the EOS R and Ra have Live View always on and lack this dark frame buffer. Pity!

Recommendations

If you are looking to upgrade to a full-frame camera and stay within the Canon lens ecosystem, then an EOS R camera gets you the image quality of a 5D Mark IV at lower cost, and with a brighter Live View screen.

The stock EOS R will also work very well for general-purpose nightscape and time-lapse shooting, and for deep-sky imaging of constellations, star clusters, and galaxies, as well as solar and lunar eclipses.

But if it's rich emission nebulosity you're after, consider the EOS Ra for its extended red sensitivity. Keep in mind it will be slightly compromised for day-time photography.

▲ *Left:* An EF-EOS R lens adapter provides the required spacing that allows the camera sensor to sit at the correct distance from field-flattener lenses often used with telescopes. This ensures they perform properly, as most of these optics are designed for the longer flange distance of a DSLR. *Right:* The EOS R cameras use Canon's E3 sub-mini jack for the remote shutter (top). Also included are headphone and microphone jacks, plus USB-C and HDMI ports.

I was impressed with the EOS R, and even more so with its astronomical variant, the Ra. Kudos to Canon for recognizing our niche use and for providing us with a superb camera for capturing the cosmos. I just might have to retire my decade-old modified EOS 5D Mark II!

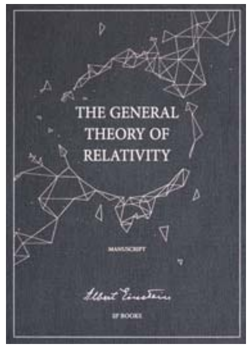
■ Contributing Editor **ALAN DYER** maintains his blog at **amazingsky.net** with tales of image-taking, time-lapse videos, tutorials, and test reports.

The arcs of the Heart Nebula, IC 1805, are nicely recorded by the EOS Ra in a stack of eight 6-minute, ISO 1600 exposures through the 105mm f/6 refractor.

Magna Carta of Modern Physics

THE GENERAL THEORY OF RELATIVITY

Albert Einstein
SP Books, 2019
80 pages, ISBN 979-10-95457-05-3
Limited edition, hand-numbered 1–1,000
US $140, hardcover.



"I AM GLAD THAT I GOT RID OF THE MANUSCRIPT," Einstein wrote in late April 1925 to his wife, Elsa, "and thank you for doing me this favor of love." Elsa had solved a problem that her famous husband, who was then traveling in South America, had been unable to solve: what to do with the original manuscript of his magnum opus, "The Foundation of the General Theory of Relativity." At the time, Einstein was helping establish the Hebrew University of Jerusalem, and Elsa had given the document to a university official who ensured that it later ended up there. The manuscript has been a treasured part of the Hebrew University's collection since it opened on April 1st of that year.

Einstein ended the sentence quoted above with a few words that would trigger heart palpitations in historians of science: "better than burnt or sold." *Burnt?!* One might as well burn Magna Carta, to which Hanoch Gutfreund, director of the university's Albert Einstein Archives and author of this facsimile edition's foreword, likens Einstein's masterwork. For this 46-page handwritten paper, published on May 11, 1916, in the journal *Annalen der Physik*, represents as great a watershed.

One doesn't have to read German, much less understand the complicated mathematics in Einstein's paper, to appreciate its beauty. In his foreword, which also appears in French and German, Gutfreund gets to the core of Einstein's chef d'oeuvre when he writes, paraphrasing the theoretical physicist John Wheeler, "An almost poetic formulation of the essence [of general relativity] is: matter tells space how to curve and curved space tells matter how to move." Einstein's theory, Gutfreund notes, is a hugely complex mathematical formulation of this simple-sounding statement. That formulation finds its apotheosis in the equation labeled "(53)" on the opposite page.

What *didn't* this paper transform in our modern understanding of the universe and its workings? Many of the phenomena astrophysicists study today are natural consequences of GR (as the theory is often abbreviated): Black holes, which according to GR will form whenever the ratio of an object's mass to its radius becomes sufficiently large. Gravitational time dilation, in which events occur more slowly near a massive body than they do farther away. The bending of starlight and associated time delay as light follows the curvature of spacetime that a massive object creates.

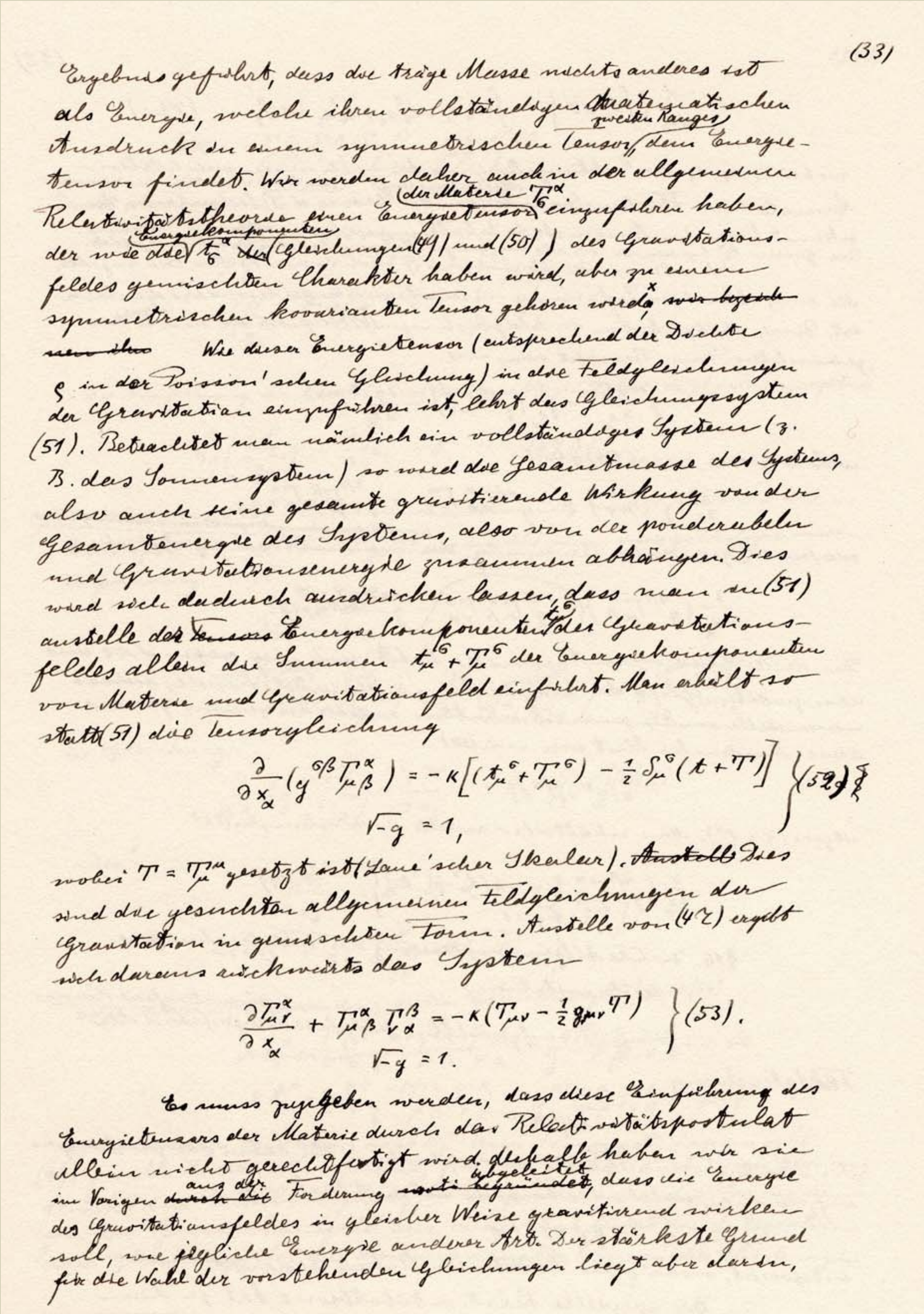
There's more — much more. Another consequence of GR, for example, is gravitational lensing. As illustrated most aptly by Einstein's Cross, a strongly lensed quasar in Pegasus, lensing allows astronomers to study distant celestial objects that intervening matter (in this case, a foreground galaxy) multiplies and magnifies. The theory also augured gravitational waves. These ripples in the fabric of spacetime arise from violent gravitational events such as the merging of two black holes. Scientists first detected these waves, which have ushered in a new era of astronomy, a century after Einstein's paper saw print (*S&T:* May 2016, p. 10).

As revolutionary as GR has been, it's not the be all and end all. Two significant issues in particular dog the theory. One is how to reconcile the smooth geometric description of spacetime that GR presumes with the "grainy" description that quantum mechanics calls for. The other concerns singularities, where our understanding of physics breaks down. GR posits singularities at the center of black holes and at the start of the Big Bang. But do they actually exist? Or does GR require rejiggering?

Neither of these open questions need diminish our wonder at this priceless manuscript. Few documents in human history have upended their field as utterly as GR has physics. One feels reverential sliding this book out of its charcoal-gray, nearly 10-by-14-inch slipcase. You turn the pages slowly, in part out of respect for how long it took its author to work out the theory (eight years). We merely ordinary types glom onto signs that Einstein was as human as the rest of us: His cross-outs, insertions, and other last-minute corrections before publication speak to us in ways we can all sympathize with. One surprise, considering our collective mental image of his famously messy hair, is his neat, quite legible handwriting.

We're extremely fortunate to have this original document. Einstein typically tossed his working papers once pieces appeared in print; no early drafts, for instance, survive from his "miracle year" of 1905. So thank you, Elsa, for ensuring the safekeeping of this seminal work in Einstein's own hand.

■ Editor in Chief **PETER TYSON** wishes he understood general relativity as well as Einstein did.



(33)

Ergebnis geführt, dass die träge Masse nichts anderes ist als Energie, welche ihren vollständigen mathematischen Ausdruck in einem symmetrischen Tensor zweiten Ranges, dem Energietensor findet. Wir werden daher auch in der allgemeinen Relativitätstheorie einen Energietensor der Materie T_σ^α einzuführen haben, der wie die Energiekomponenten t_σ^α der Gleichungen (49) und (50) des Gravitationsfeldes gemischten Charakter haben wird, aber zu einem symmetrischen kovarianten Tensor gehören wird.

Wie dieser Energietensor (entsprechend der Dichte ρ in der Poisson'schen Gleichung) in die Feldgleichungen der Gravitation einzuführen ist, lehrt das Gleichungssystem (51). Betrachtet man nämlich ein vollständiges System (z. B. das Sonnensystem) so wird die Gesamtmasse des Systems, also auch seine gesamte gravitierende Wirkung von der Gesamtenergie des Systems, also von der ponderabeln und Gravitationsenergie zusammen abhängen. Dies wird sich dadurch ausdrücken lassen, dass man in (51) anstelle der ~~Tensors~~ Energiekomponenten t_μ^σ des Gravitationsfeldes allein die Summen $t_\mu^\sigma + T_\mu^\sigma$ der Energiekomponenten von Materie und Gravitationsfeld einführt. Man erhält so statt (51) die Tensorgleichung

$$\left.\begin{aligned}\frac{\partial}{\partial x_\alpha}\left(g^{\sigma\beta}\Gamma^\alpha_{\mu\beta}\right) &= -\kappa\left[\left(t_\mu^\sigma + T_\mu^\sigma\right) - \frac{1}{2}\delta_\mu^\sigma\left(t + T\right)\right] \\ \sqrt{-g} &= 1,\end{aligned}\right\} (52)$$

wobei $T = T_\mu^\mu$ gesetzt ist (Laue'scher Skalar). ~~Anstelle~~ Dies sind die gesuchten allgemeinen Feldgleichungen der Gravitation in gemischter Form. Anstelle von (47) ergibt sich daraus rückwärts das System

$$\left.\begin{aligned}\frac{\partial \Gamma^\alpha_{\mu\nu}}{\partial x_\alpha} + \Gamma^\alpha_{\mu\beta}\Gamma^\beta_{\nu\alpha} &= -\kappa\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T\right) \\ \sqrt{-g} &= 1.\end{aligned}\right\} (53).$$

Es muss zugegeben werden, dass diese Einführung des Energietensors der Materie durch das Relativitätspostulat allein nicht gerechtfertigt wird. Deshalb haben wir sie im Vorigen ~~durch die~~ aus der Forderung ~~nicht begründet~~ abgeleitet, dass die Energie des Gravitationsfeldes in gleicher Weise gravitierend wirken soll, wie jegliche Energie anderer Art. Der stärkste Grund für die Wahl der vorstehenden Gleichungen liegt aber darin,

▲ **IN A NUTSHELL** The equation above that Einstein hand-labeled "(53)" encapsulates his general theory of relativity.

A Telescope Made with a Paintbrush

Here's how to fabricate a carbon-fiber tube.

▲ A homemade carbon-fiber OTA is a fitting companion to this homemade mount.

LAST SEPTEMBER I WROTE about Tom Bartol's massive equatorial mount. He made it to carry his home-built 10-inch f/5.6 Newtonian telescope, which used a traditional cardboard Sonotube OTA. After the mount was finished, the scope seemed a bit shabby compared to its shiny new support. One of Tom's friends, Cary Thomas, noted that discrepancy and offered to help him make a carbon-fiber tube to replace it.

You'd think Tom would jump at the chance, but he had to think about it for a while. His reason? "I'm a precision metal-working machinist — to me, epoxy and floppy fabric are the ingredients for a drippy, runny, sloppy mess!" But Cary is as accomplished at working with composite materials as Tom is with metal. Eventually he convinced Tom that they could make a beautiful, lightweight, rigid tube worthy of his machined metal masterpiece.

The pair worked out a simple procedure for wrapping layers of carbon-fiber fabric around a cardboard tube that served as an internal form. They started with an 11¾″-diameter tube and wrapped two overlapping layers of duct tape around it to act as a release agent (epoxy doesn't bond well to duct tape). Next, they made plywood disks that fit snugly inside the tube to keep it round and ran a length of PVC pipe through holes in the middle of the disks to act as a rotisserie spit. They rested the pipe on two sawhorses so they could spin it, slowly drawing the fabric onto the tube a little at a time while they wet it with epoxy.

◀ The carbon-fiber fabric is wetted with epoxy (applied with 3-inch brushes) as it's slowly wound onto the form. Pictured left to right are Bryan Paquette, Kevin Winchell, and Tom Bartol.

To test their methods, the pair first made a prototype that had the full 11¾″ diameter but was only 4″ long. They wrapped 12 layers of 3k carbon fabric (0.01″ thickness) onto the tube, using 3″-wide paintbrushes to soak it with epoxy as they wound it up. By being careful with the epoxy and winding slowly and evenly, squeezing out air bubbles as they went, they got a strong and beautiful ring that required neither external form nor vacuum bagging to finish out. The prototype wound up (literally!) with a 0.15″ wall thickness, and even though it weighed only 10 ounces it was strong enough to support Tom's weight (150 pounds) and only flex an inch.

And the biggest surprise for Tom: The process was neat and clean.

Buoyed by that success, they went into full production. The cardboard QuickTube they purchased at Home Depot only came in 48″ lengths, but the final tube needed to be 53″, so they had to splice two pieces of tube together. They used ten yards of 60″-wide carbon fiber fabric, which gave them ample extra width and also gave them factory edges to work with. (Cut edges easily unravel, complicating the wrapping process.)

With the help of two more friends, Bryan Paquette and Kevin Winchell, they rolled up a 9-layer core in about three hours. While that was still wet, they applied a layer of polyester peel-ply to top it off. They used a heat gun to kick-start the curing process and let it finish overnight, then stripped off the peel-ply to reveal a rough-textured outer surface.

Rough textured? Why didn't they want it smooth? Because the original telescope was deep blue and the mount was named "BlueShift" in its honor, yet carbon fiber is black. That clearly wouldn't do. So the peel-ply's rough texture created a good bonding surface for another layer of carbon with blue Kevlar in the weave. They wound this

TOM BARTOL (4)

final layer onto the tube using the same technique as before, then added several more coats of clear epoxy to create a beautiful, high-gloss finish.

They carefully measured their finished product and cut the ends square to 53″ with a hacksaw, then soaked the whole works with a garden hose. The cardboard tube disintegrated and was easily pulled out, and the duct tape peeled away easily as well, leaving a beautiful finished tube that Tom painted on the inside with 3% reflective theater flat black paint.

Tom admitted that "It was a bit unnerving, to say the least, to drill holes and use a 2¼″ hole saw (!) on this wonderful piece to fulfill its metamorphosis from a spool of fabric and jug of liquid epoxy into a fabulous telescope." But drill he did, with the result you see here. BlueShift is now complete, beautiful, and homemade right down to the core.

For more information, contact Tom at **t.m.bartol@gmail.com**.

Contributing Editor **JERRY OLTION** welcomes your project submissions. Contact him at **j.oltion@gmail.com**.

▲ *Top:* The finished tube seen above before being removed from the form. *Bottom:* The final exterior layer has blue Kevlar woven into it for a wonderfully attractive finish.

MIRROR LAKE

Brian Roth

The heart of the Milky Way with bright Jupiter (right) reflects off the still surface of Summit Lake in Lassen Volcanic National Park, California.

DETAILS: *Sony α7II mirrorless camera with Zeiss 25-mm f/2 lens. Total exposure: 30 seconds at ISO 3200.*

◁ GHOSTLY ATTENDANTS

Daniel Hightower

The faint emission nebulae IC 59 and IC 63 (top left and center, respectively) are slowly dissipating due to ionizing radiation from the star Gamma (γ) Cassiopeiae at top right.

DETAILS: *Takahashi FSQ-106EDX4 astrograph with ZWO ASI1600MM-Pro CMOS camera. Total exposure: 25 hours through O III, Hα, and S II narrowband filters.*

▽ HORNED SUNRISE

Aref Banaee

On December 26, 2019, the partially eclipsed Sun rises over the warm waters of the Persian Gulf off Qeshm Island, Iran.

DETAILS: *Nikon D3200 DSLR with 55-to-300-mm lens set to f/5.6. Total exposure: 1⁄400 second at ISO 100.*

△ INFLUENTIAL BLACK HOLE

Kent Wood

Relativistic jets from the stellar-mass black hole Cygnus X-1 collide with the surrounding interstellar medium to produce the blue bow shock seen faintly at right.

DETAILS: *16-inch Ritchey–Chrétien telescope with Atik 16200 CCD camera. Total exposure: 18 hours through color and narrowband filters.*

△ THROUGH THE WITCH HEAD

Kfir Simon

Several galaxies including NGC 1752 (left of center) appear through the bluish reflection nebulosity and brownish dust of the Witch Head Nebula, IC 2118, in Orion.

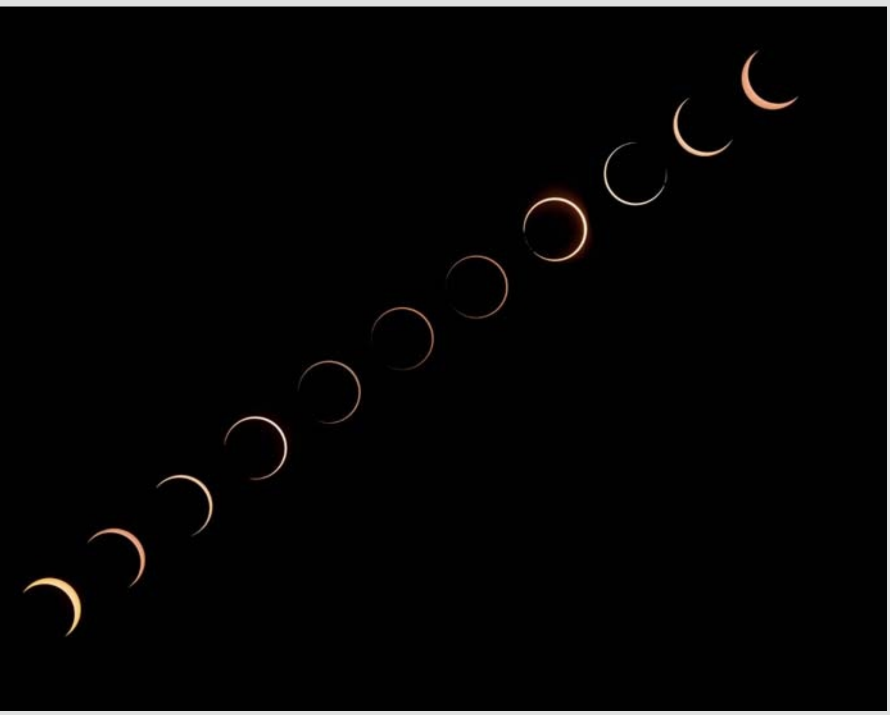
DETAILS: *16-inch f/3.75 Dream Astrograph with Apogee Alta U16M CCD camera. Total exposure: 4 hours through LRGB and hydrogen-alpha filters.*

STELLAR ANNULUS

Ethan Wong

The Moon passes in front of the Sun during the eclipse of December 26, 2019. Since the Earth is so close to perihelion, the Moon cannot completely cover the solar disk, resulting in an annular, rather than total, solar eclipse.

DETAILS: *William Optics Zenithstar 61 f/5.9 refractor with Canon 60D DSLR camera. Composite of 11 exposures captured at ISO 100.*



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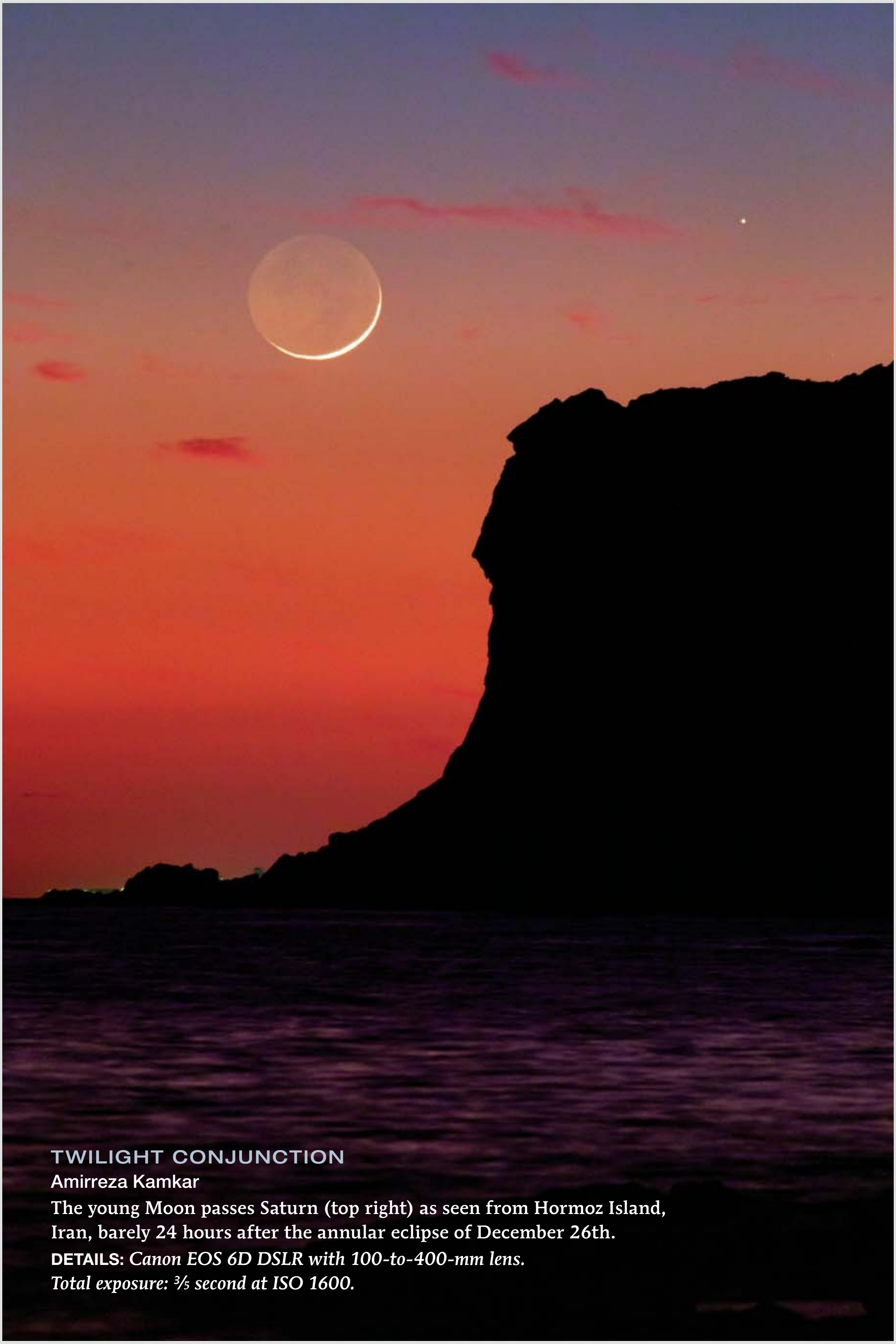

TWILIGHT CONJUNCTION

Amirreza Kamkar

The young Moon passes Saturn (top right) as seen from Hormoz Island, Iran, barely 24 hours after the annular eclipse of December 26th.

DETAILS: *Canon EOS 6D DSLR with 100-to-400-mm lens. Total exposure: $\frac{3}{5}$ second at ISO 1600.*

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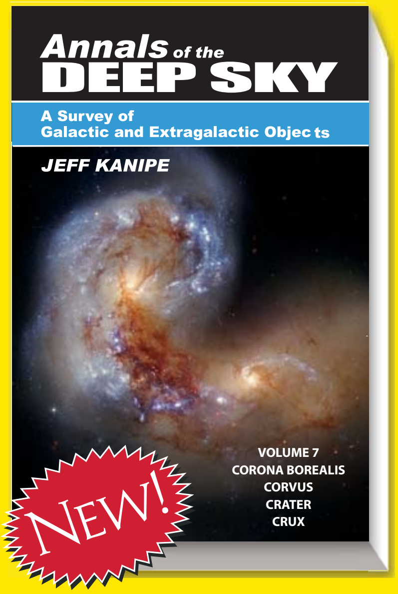

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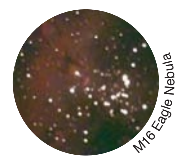

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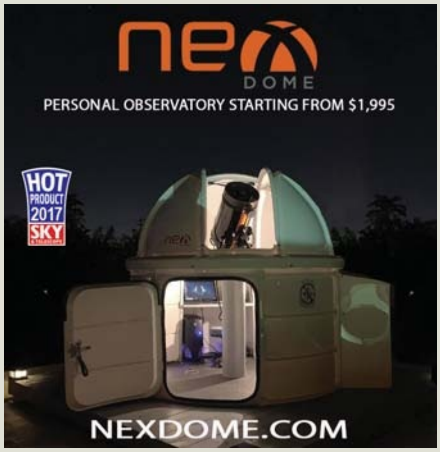

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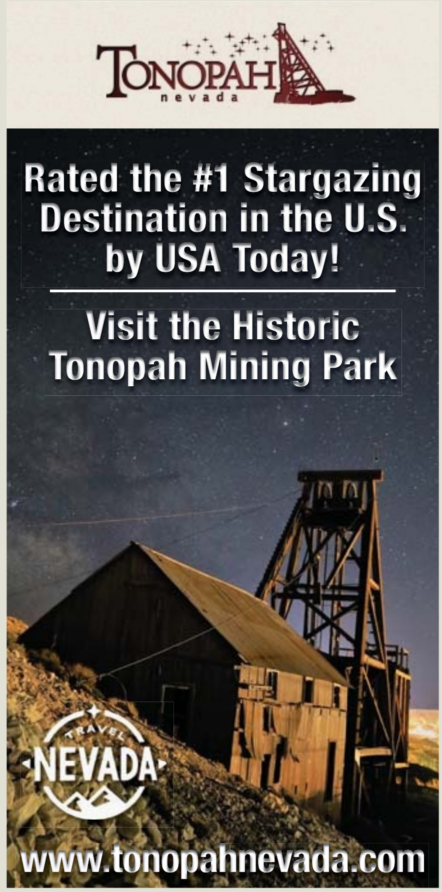

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My Immense Journey

When it comes to distance traveled in my lifetime, I leave even the Voyagers in the dust.

IN MY NEARLY 76 YEARS on this planet, I've traveled a total of 2.8 trillion kilometers (1.7 trillion miles). *Trillion?* Incredible. But you have, too, or with luck and good health you will.

Let's start by counting those 76 voyages around the Sun. Any mileage we might have accumulated on the surface of our planet is tiny in comparison. Frequent-flyer miles don't count here!

Earth's orbital speed averages about 108,000 km per hour, so in one year our planet travels 946 million km around the Sun. Multiply that distance by your age. For me, that's a total of 72 billion km.

But there's more. (Following estimates vary according to source.) Our Sun orbits the center of the Milky Way Galaxy at 810,000 km/hr, carrying us along with it. One year adds another 7.1 billion km to our total. And the Milky Way itself is speeding toward the Andromeda Galaxy, our nearest large neighbor, at about 360,000 km/hr, or 3.2 billion km/yr.

Then there's the motion of the Local Group of galaxies toward the Virgo Cluster: 792,000 km/hr, or 7 billion km/yr. Finally, at the largest scale, there's the motion of the Laniakea Supercluster toward the Great Attractor and beyond it to the Shapley Attractor: an amazing 2,157,000 km/hr or 18.9 billion km/yr.

So, in my 76 years, all these motions add up to 2.8 trillion km.

Have you felt it? Neither have I, and I've been only occasionally aware of the fact. But altogether I've traveled a lot farther than the distance that the Voyager 1 space probe, launched in 1977, now lies from the Sun. Having left our solar system in 2012, Voyager 1 is currently (in mid-December 2019) about 22.2 billion km from Earth — less than 0.8% of the distance I've traveled. On the other hand, my journey has brought me about 7% of the distance that Earth lies from our nearest neighbor star system, some 41.8 trillion km away. At this rate, I'll match Alpha Centauri's distance from us around the year 3090.

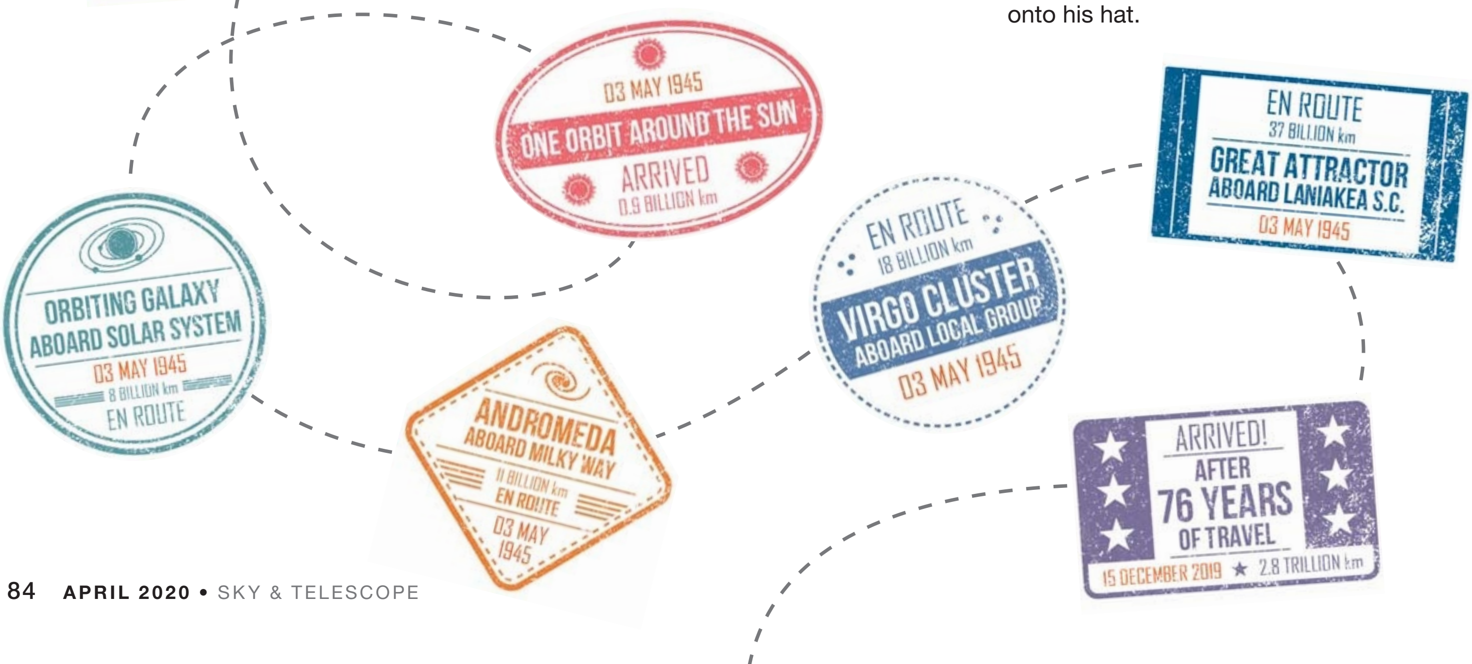
But what about other motions I've ignored? Well, there's mileage gained from the daily turning of our planet. That's 40,000 km/day if you live at the equator, or zip if you're standing on either pole. (I live halfway between.) Doesn't add much to the total. Then there's the "wobble" motion of the solar system above and below the galactic plane. Again, chump change. I'll stick to my back-of-the-envelope calculation of 2.8 trillion km.

Hold your horses, you'll say if you're among the mathematically inclined. All these motions are not independent of one another, and they move in different directions. Obtaining an accurate combined total requires a complicated vector field analysis.

Fortunately, that's arguably been done. Relative to the Cosmic Microwave Background, it's a combined motion of 1.3 million km/hr, or, for a geezer of my years, it's 865 billion km — in the direction of the constellation Crater.

In sum, at this moment you and I are traveling *very* fast, at a wide variety of speeds and in a number of different directions. What can I say? *Bon voyage!*

■ **DAN RINNAN** is a member of the Eugene Astronomical Society. Whenever Oregon weather permits, he's out under dark skies, hitching rides and holding onto his hat.



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