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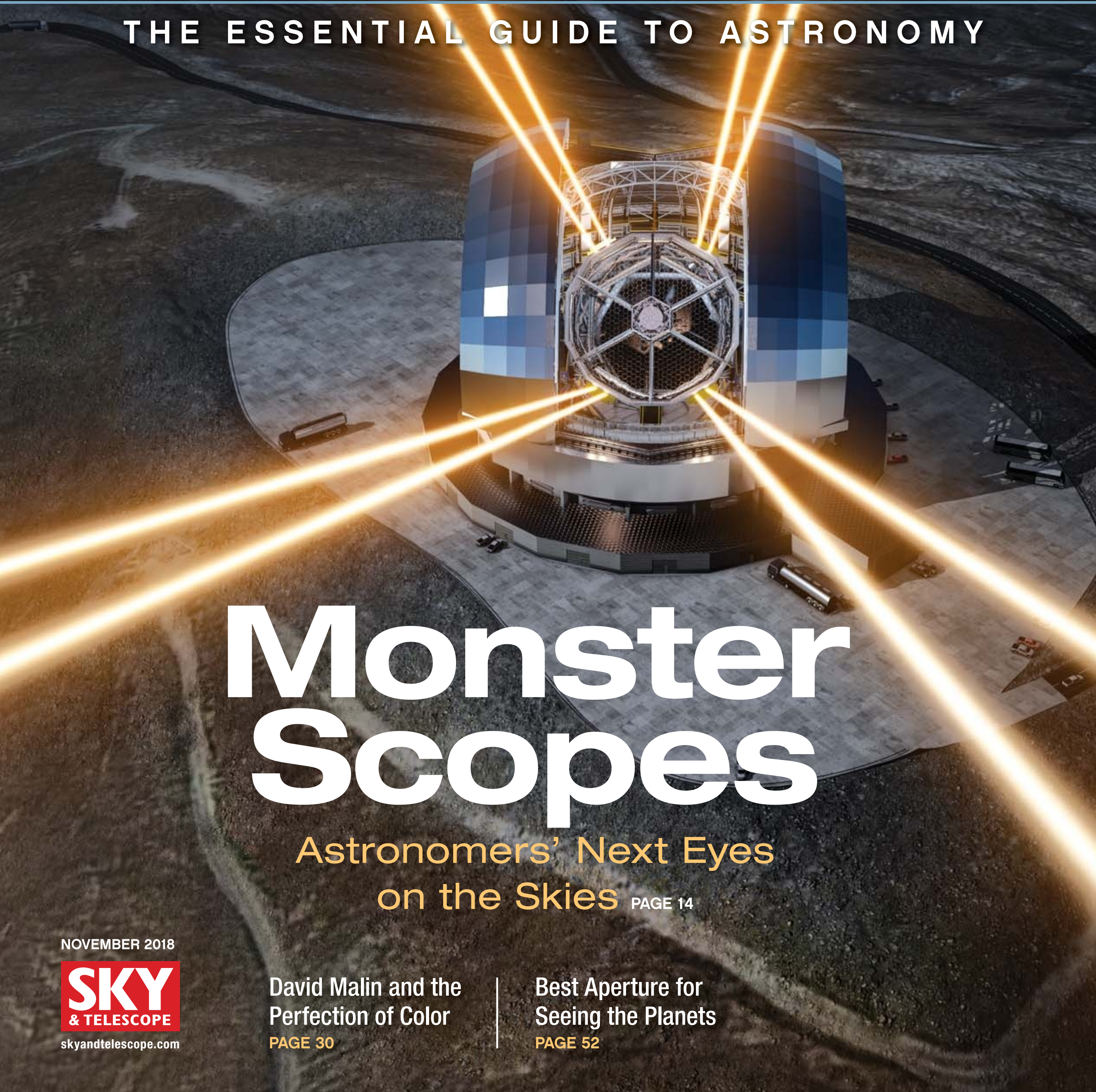
THE ESSENTIAL GUIDE TO ASTRONOMY



Monster Scopes

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November 2018 VOL. 136, NO. 5

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Supersize Me

PROFESSIONAL ASTRONOMERS, just like amateurs, suffer from that widespread affliction known as aperture creep. *If only we had a scope twice that size*, they fantasize, *think what we'd discover.*

Chile's Las Campanas Observatory already hosts the twin Magellan Telescopes, each bearing a 6.5-meter (21-foot) mirror. But soon it will boast the Giant Magellan Telescope. This behemoth will combine seven 8.4-meter mirrors for an effective aperture of 24.5 meters (80 feet). The two 10-meter Keck telescopes atop Mauna Kea in Hawaiʻi do phenomenal science. Yet astronomers hope eventually to add another telescope just steps away with a mirror effectively 30 meters in diameter.

European pros might have the most pronounced aperture creep of all. The four unit telescopes (8.2 m each) that make up the European Southern Observatory's Very Large Telescope have conducted groundbreaking astronomy for more than a decade. But the ESO is now building the Extremely Large Telescope (39.3 m). If European astronomers had had their way, the ESO instead would be erecting the Overwhelmingly Large Telescope (100 m).

I'm not making these names up. One wonders what they'd dub the next iteration: The Astronomically Large Telescope? The Unimaginably Large Telescope? Suitable adverbs would run out long before their lofty notions.

This ever-bigger tendency is not limited to single-object observing. Large survey projects like the Sloan Digital Sky Survey (2.5 m) will pale, at least in terms of total data collected, beside next-gen survey instruments like the Large Synoptic Survey Telescope (8.4 m). The SDSS total data volume is about 40 terabytes; LSST will gather 15 terabytes of raw data *every night* (*S&T:* Sept. 2016, p. 16).

Nor does "bigger is better" confine itself to optical and near-infrared astronomy. The Arecibo Observatory (305 m), for instance, recently ceded the distinction of world's largest single-dish radio telescope to China's Five-hundred-meter Aperture Spherical Radio Telescope, or FAST (500 m). Even space telescopes creep. The James Webb Space Telescope (6.5 m) will explore far more deeply than is possible with either the Spitzer Space Telescope (0.85 m) — which focuses on the infrared as JWST will — or the Hubble Space Telescope (2.4 m).

Creep is a good thing for astronomy, of course. Those three monster optical telescopes alone — the Giant Magellan, the Thirty Meter, and the Extremely Large — will revolutionize our understanding of the universe. So huge are they in significance that we're devoting two articles to them. The first, on page 14, describes the telescopes in general; the second, in next month's issue, goes into their instrumentation and the key science questions they'll help us address.

Amateurs: Isn't it reassuring to know you're not alone in your predicament?

Editor in Chief

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More Balloon Astronomy

Laura Fissel's "Science in the Stratosphere" (*S&T:* Feb. 2018, p. 14) brought to mind another noteworthy balloon flight. On May 6, 1958, astronomer Alfred Mikesell and Navy pilot Malcolm Ross ascended in an open gondola to measure he twinkling of stars to determine where in the atmosphere this phenomenon occurs. Mikesell thought it occurs at the tropopause rather than in the stratosphere. To prove this idea he brought a photoelectric photometer attached to a small telescope with an electronic recorder.

They began their flight from an open-pit iron mine near Brainerd, Minnesota. Launching below ground level let them avoid the strong afternoon winds while filling the balloon with helium. As an extra precaution, Ross overfilled the balloon to ensure a rapid vertical ascent out of the pit.

▲ Sixty years ago, Navy pilot Malcolm Ross (pictured) and astronomer Alfred Mikesell flew a balloon into the stratosphere to study the scintillation of starlight.

JOHN MIKESELL

Unfortunately, two problems resulted. First, the vertical speed was well over 1,000 feet per minute, which took them to the target elevation of 40,000 feet in just 30 minutes, much too fast for making scintillation measurements at intermediate elevations. Second, the balloon rose in a spiral that twisted the support straps, which in turn caused the 2,500-pound gondola to revolve like a giant torsion pendulum throughout the entire 12-hour flight. It was impossible to aim the telescope at a star long enough to record data.

Even though the primary purpose of the mission failed, Mikesell made an important discovery that would later benefit the space program. He and Ross were wearing standard-issue Navy cold-weather clothing with lots of fabric layers. Previously they had worn this clothing in a test chamber down to temperatures of −77°C (−107°F), yet the instant they reached the stratosphere they felt cold far more intense than they had encountered in the test chamber. At that altitude, their suits couldn't adequately prevent the heat loss from their bodies. Researchers later discovered that a thin layer of aluminum covering the fabric significantly slows the loss of body heat. Thus we have the familiar shiny suits worn by today's astronauts.

Darryl Davis • Albany, Oregon

For more details about this flight, visit www.mikesell.info.

Costs of Mission Hardware

I was struck by the contrast in cost-effectiveness between the Mars helicopter described in David Dickinson's News Note (*S&T:* Aug. 2018, p. 8) and the Transiting Exoplanet Survey Satellite (TESS) reported in the same section by Elizabeth Howell.

TESS was reported to have cost under $200 million to develop and build, which seems a bargain considering that its 360-kg mass probably has many components for which no prior technology or off-the-shelf hardware existed to draw on. That's 800 pounds of custom-designed, purpose-built, ultraprecise scientific hardware meant to operate for 20 years in space, fabricated at a cost of $250,000 per pound.

By contrast, the 1.8-kg drone helicopter for the Mars 2020 rover mission is stated to have been funded at $23 million — a seemingly large sum, given our collective experience with professional and military drones as the basis for a machine that wouldn't need much customization to operate in Mars's environment — harsh for sure, but not deep space by a long shot. That's 4 pounds of hardware for an eye-watering *$6 million per pound*.

I won't discount the rigorous testing that both sets of hardware must undergo to become space-rated. Still, the helicopter's development cost seems disproportionately high. That money could pay the salaries of 40 engineers, technicians, machinists, and so forth at over $100,000 a year each for five years. So how is it that equipping what is essentially an off-the-shelf device with faster motors and larger rotors can be so costly?

Howard L. Ritter, Jr.
Fuquay-Varina, North Carolina

David Dickinson replies: *I asked space-policy expert Casey Dreier (The Planetary Society), who said that the $23 million was provided for fiscal year 2018, and another $15 million was appropriated in FY 2017, for a total of at least $38 million. But since off-the-shelf hardware can't be assumed to function flawlessly on Mars, it's a technology demonstration project, and that means a lot of testing and validation (and engineering hours), not to mention the processing and planning to integrate the helicopter onto the rover itself.*

Staying Cool

I would imagine that binary stars exist within globular clusters. I've read where some binaries can be close enough to be touching. Binaries can also be rather far apart and still be gravitationally related.

When you get out into space the temperature is quite frigid. So my question is: In globulars, where stars are close together, is there a lot of heat between them, or are they still far enough away from each other that it's still cold in between?

Bill Schultz
Cincinnati, Ohio

Monica Young replies: *That's an interesting question to ponder when you see those thousands of stars within your telescope's field of view! Both light and heat follow the inverse-square law, which means they decrease at a rate proportional to the* square *of the distance from their source. So even though stars are immensely hot, their heat and luminosity fall off quickly. Even in the tightly packed centers of globular clusters, where there might be up to 1,000 stars per cubic parsec (a cube 3.26 light-years on a side), the average distance between stars would still be 0.1 parsec, or about 21,000 astronomical units. Compare that to the size of our solar system, which is typically given as 100 a.u. or so.*

So, long answer short: Yes, stars in globular clusters are still far enough apart for it to be cold between them. (Or as Douglas Adams writes in The Hitchhiker's Guide to the Galaxy*: "Space is big. Really big. You just won't believe how vastly, hugely, mind-bogglingly big it is.")*

Star Reporter

Regarding the online article "IceCube Neutrino Offers New Eyes on the Cosmos" by Ben Skuse (posted on July 23rd), I've lost count of all the articles about this result that I've read, from sources ranging from world-class news media to top-shelf physics and math publications. But — as is so often the case — *Sky & Telescope*'s is by far the most in-depth and explanatory of the lot. It's not just a cut-and-paste of the press release, and it manages to avoid getting bogged down in intellectual weeds without dumbing down to the point of scientific-sounding fluff.

I'm continually impressed with how often your science reporting is the best of the bunch, and not just on stories dealing directly with astronomy.

Glen Stephan
Estes Park, Colorado

Expanding Vocabulary

Camille Carlisle's excellent article, "Near the Pit" (*S&T:* Sept. 2018, p. 22), introduced me to two words with which I was not previously familiar: *peribothron* and *bumfuzzling*. Now I just have to find a way to use them in conversation.

Mark Holm
Monroeville, Pennsylvania

FOR THE RECORD

- The large observatory pictured at far left atop Haleakalā (*S&T:* Aug. 2018, p. 66) is not the Advanced Electro-Optical System Telescope, which actually sits inside the squat silver enclosure at center right as part of the Air Force MSSC. The structure looming over the Pan-STARRS telescopes houses the newly constructed 4-meter Daniel K. Inouye Solar Telescope.

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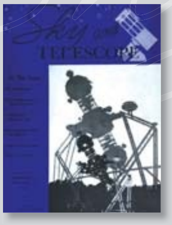
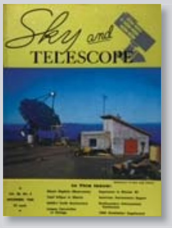
75, 50 & 25 YEARS AGO by Roger W. Sinnott

1943



1968



1993

◖ November 1943

Wartime Astronomy "A cablegram from K. Lundmark in Sweden was received at Harvard, asking for observations of both the Diamaca comet and the Hoffmeister nova. Astronomers [here] had heard about the comet, but what nova and where?

"Further telegraphic procedure then brought the news [that] C. Hoffmeister, director of the Sonneberg branch of the Berlin-Babelsberg Observatory, had discovered a 12th-magnitude nova in the constellation Aquila. . . . Searching earlier photographs of the region, he found that the star had attained a maximum brightness of about 7th magnitude between April 13th and May 2nd, nearly five months before. . . .

"In view of events abroad, it is a bit surprising that it should have been a German astronomer who first discovered [Nova Aquilae 1943]."

◖ November 1968

Lunar Transients "[Near] Las Cruces, New Mexico, is Corralitos Observatory, operated by Northwestern University with NASA support for the primary purpose of detecting transient changes on the moon. J. Allen Hynek [reports] the results of three years systematic surveillance . . . with a 24-inch Cassegrain reflector in conjunction with an image-orthicon tube. The observer sits in a room below the telescope floor, seeing an area of the moon on a monitor screen. . . .

"More than 3,000 hours of lunar surveillance have been logged [but] no localized lunar events were detected. . . . This negative result is in sharp contrast to the numerous reports by amateur astronomers in recent years of bright flashes, colorations, and large-area brightenings lasting a few seconds."

Reports of such changes are still controversial, but occasional flashes due to meteoroid impacts have been confirmed by independent observers and videos.

◖ November 1993

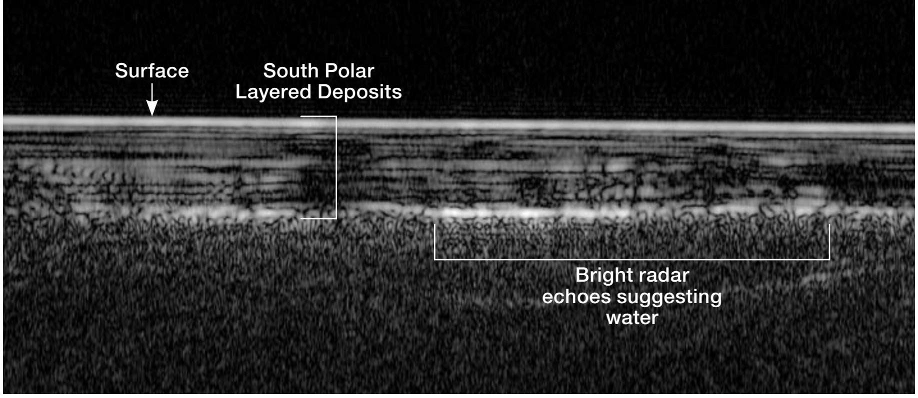
Magnified Quasars "Our view of the very distant universe is distorted by gravitational lensing a lot more than anyone thought, according to two University of Washington astronomers. Liliya Rodrigues-Williams and Craig J. Hogan studied the distribution of quasars brighter than magnitude 18.5, and between redshifts 1.4 and 2.2, in various areas of the sky. They found that if there's a galaxy cluster in the foreground . . . it boosts the number of quasars seen in the background by a remarkable 70 percent. In effect, the combined gravitational field of the cluster's galaxies acts as a giant magnifying glass. . . .

"This finding may come as a rather hollow vindication to the supporters of astronomer Halton C. Arp and others who have claimed for years that high-redshift quasars cluster around low-redshift galaxies. . . . It appears they really do."

Gravitational lensing can also produce multiple images of a single remote quasar.

SOLAR SYSTEM

Water Lake Discovered on Mars



▲ An example radar profile for one of 29 orbits over the 200 × 200 km study region in the south polar region of Mars shows layers of ice and dust to a depth of about 1.5 km. The bright horizontal feature at the top corresponds to the icy Martian surface. The brightest reflections from the base layer — close to the center of this image — are centered around 193°E / 81°S in all intersecting orbits, outlining a 20-km-wide anomaly that Roberto Orosei and colleagues interpret as a pond of liquid water.

THE SECOND-OLDEST OPERATIONAL Mars orbiter, the European Space Agency's Mars Express, has discovered evidence of stable, present-day liquid water on Mars.

How is this discovery of water on Mars different from past announcements of the same? For one, the data come from a different instrument examining a new location on Mars. But most importantly, it's the first time the observations support a present-day body of water that *stays* liquid.

The results, which appear in the August 3rd *Science*, come from the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) instrument. This radar sounder emits radio waves using a pair of 20-meter-long (66-feet-long) booms that extend on either side of Mars Express and measures the time it takes for the radio waves to travel to Mars, bounce, and travel back to the spacecraft.

The long radio waves from the instrument's 40-meter antenna can penetrate as far as 5 kilometers (3 miles) down. Subsurface boundaries between layers with different properties each reflect the radio signal, so MARSIS may detect multiple echoes from each pulse. As the instrument tracks along the ground, it builds up a 2D slice of the subsurface called a *radargram*.

For many of its 15 years at Mars, MARSIS has detailed the interior structure of the planet's *polar layered deposits*, layers of dust and water ice that exist at both poles. More recently, the instrument team picked a region of the southern deposits where the surface looks especially bland, making it easier to study the base of the deposits in detail without interference from overlying features. MARSIS scanned this region intensely from May 29, 2012, to December 27, 2015, collecting 29 criss-crossing radargrams.

In one particular location, where many radargrams cross over a region about 20 km wide, the scans kept hitting an especially bright bottom-most boundary about 1,500 meters beneath the surface. This unusually reflective spot, which persisted over a period of three years, suggests a material very different from the ice above it or the rock below it. Roberto Orosei (National Institute of Astrophysics, Italy) and colleagues argue that the most likely explanation is a briny lake (or a layer of very sludgy, liquid-water-rich sediment).

Why is it briny? The predicted temperature at the base of the southern polar layered deposits is −68°C (−90°F), and pure liquid water can't exist at such low temperatures. On Earth, where subglacial lakes in Antarctica can have temperatures as low as −13°C, the freezing point of their water is depressed by the presence of large amounts of salt — much more than is present in Earth's oceans. Mars has salts of sodium, magnesium, and calcium, not to mention a plethora of chlorine-based *perchlorates*, all of which — if concentrated enough — could depress the freezing point of water to as low as −75°C. So it is physically possible that a very salty lake persists beneath the southern polar cap.

Higher-resolution data would help confirm the lake's presence: The radar images' resolution is about 5 km, providing a fuzzy look at the 20-kilometer width of this putative lake. Future missions could more precisely map its contours — and perhaps discover detail beyond the capabilities of MARSIS. There's every reason to think we could discover many more such briny spots deep underneath the Martian south polar cap.

■ EMILY LAKDAWALLA

The ExoMars Trace Gas Orbiter captured this view of part of Mars's south polar ice cap on May 13, 2018.

EXOPLANETS

First Direct Image of Newborn Planet

ASTRONOMERS USING A NEW instrument on the Very Large Telescope (VLT) in Chile have directly imaged the youngest planet known to date. The data suggest that giant planets come together quickly and, once formed, regulate further growth of their host star.

The star PDS 70 is only about 5 million years old and is still growing, accreting mass from a surrounding disk of gas and dust. Within the gaseous swirl, researchers had previously found a dark gap. But while disk gaps are often taken to be the signature of a newborn planet, other processes can create gaps, too (*S&T:* Oct. 2013, p. 12).

To explore further, Miriam Keppler (Max Planck Institute for Astronomy, Germany) and colleagues used VLT's

▲ The SPHERE instrument on the Very Large Telescope in Chile imaged PDS 70b after blocking the light from its host star (dark central disk).

SPHERE adaptive optics system, discovering a point source dubbed PDS 70b within the disk's gap. The astronomers estimate the object to have an upper limit of 5–14 Jupiter masses. Revisiting observations taken in 2012 with the Gemini South telescope's Near-Infrared Coronagraphic Imager, the team concludes that PDS 70b orbits its star every 120 years. The result will appear in *Astronomy and Astrophysics*.

In a follow-up study to appear in the same journal, the team went a step further, taking additional observations to examine the planet's atmosphere. Applying several models to the observations, the team found a temperature in the range of 1000–1600K (1400–2400°F) and a high likelihood of clouds of evaporated metals and minerals.

The young planet is still slowly accumulating material, but new observations with the 6.5-m Magellan Clay Telescope, to be published in *Astrophysical Journal Letters* by Kevin Wagner (Steward Observatory) and colleagues, show that it has probably already acquired most of its gas. The planet may have cleared out the wide gap during an earlier period of runaway gas accretion.

■ **JULIE FREYDLIN**

SUN

Parker Solar Probe Launches to "Touch the Sun"

TOUTED AS THE "mission to touch the Sun," the Parker Solar Probe is the first to be named after a living person, solar physicist Eugene Parker (University of Chicago, emeritus). The spacecraft will carry a suite of instruments to study the origin of the solar wind and the dynamics of the solar corona, looping around the Sun 24 times in its seven-year mission.

After its launch on August 12th, the probe is due to swing by Venus on September 28th, entering an initial, 150-day-long orbit around the Sun. Passing 34.7 solar radii from the Sun on November 1st, it will complete six additional Venus flybys to further decrease its period to 88 days. Ultimately, the spacecraft will reach it closest approach, passing within 9 solar radii of the Sun's surface, on December 19, 2024.

Engineers designed the Parker Solar Probe to survive temperatures that can reach 1600K (2500°F). To take the heat, the craft is equipped with a heat shield made of reinforced carbon composite 11.4 cm (4.5 inches) thick. The majority of the probe's four instrument suites will remain behind this shield, where temperatures will be a comfortable 85°F. But a couple of key pieces — namely, the Solar Probe Cup (SPC) and the niobium-alloy antennas of the FIELDS experiment — will extend past the shield to directly examine the Sun. The SPC will scoop up samples of charged particles in order to measure their flux and flow, while the FIELDS experiment will measure the electric and magnetic fields around the Sun. Visit **https://is.gd/ParkerSolarProbe** to learn more about the instruments the probe carries.

The probe will be the first mission to go past the *Alfvén point*. Within this boundary, *Alfvén waves* — oscillations of charged particles and the magnetic fields they travel along — tie the solar wind to the Sun's surface, but particles beyond it escape into the solar system. Studying the plasma within the Alfvén point for the first time, scientists will explore the solar wind's origin, hopefully improving space weather forecasts. Close-in measurements will also help scientists find out what heats the million-degree solar corona.

■ **DAVID DICKINSON**

▶ NASA's new solar probe launched August 12th from Cape Canaveral aboard a Delta IV Heavy rocket.

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PARTICLES

IceCube Neutrino Linked to Cosmic Source

FOLLOW-UP OBSERVATIONS ACROSS the electromagnetic spectrum have helped scientists pinpoint the source of a single high-energy neutrino — a barely-there particle that has no electrical charge and almost no mass. The IceCube collaboration announced the probable birthplace of the neutrino, dubbed IceCube-170922A, in the July 13th *Science*.

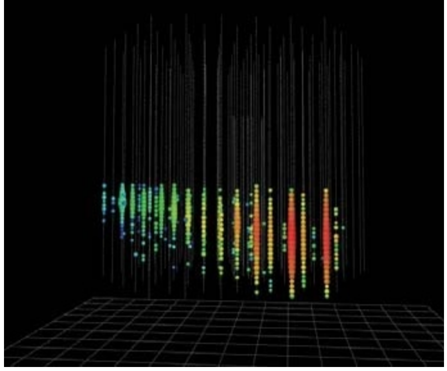
The neutrino ghosted through our planet on September 22, 2017, before crashing into an atom in the Antarctic ice. The collision produced a heavy cousin of the electron called a *muon*, which left a track of dim, bluish light in the IceCube detector. Backtracking from the muon's trajectory, a computer cluster calculated the source's location on the sky and sent an automated alert to telescopes around the world just 43 seconds after the event.

Within hours the space-based Neil Gehrels Swift Observatory had identified the particle's possible source: the blazar TXS 0506+056, whose light and particles travel 3.8 billion light-years to reach Earth. This supermassive black hole sends out twin jets of high-energy radiation, one of which happens to be aimed at Earth. The Fermi Gamma-ray Space Telescope reported that this blazar was flaring at the time of the neutrino event. Observations from more than 20 telescopes confirmed the flare across the electromagnetic spectrum.

With a known object for reference, IceCube scientists searched the archive and discovered that the blazar was associated with a larger-than-expected number of neutrinos detected between 2014 and 2015. Both the neutrino energies and the light collected from the blazar are characteristic of a cosmic particle accelerator.

Oddly, scientists haven't detected neutrinos from flaring blazars much closer to Earth, such as Mkn 425 and Mkn 501. However, the authors calculate the chance of a coincidental alignment between the single neutrino detection and the flare of TXS 0506+056 to be only one in a thousand. Still, Kohta Murase (Penn State) urges caution: "If we look at history, there have been many claims for which such a level of significance eventually went away," he explains. "Definitely, we need more events to establish that blazars are sources of neutrinos."

■ BENJAMIN SKUSE



◀ The neutrino recorded on September 22, 2017, smashed into Antarctic ice, creating a muon that left the track shown here. Color encodes the time of arrival (red is sooner, blue is later), and the size corresponds to the brightness recorded by individual sensors.

MARS

Source of Present-Day Dust on Mars Found

NEW RESULTS SHOW that the Medusae Fossae Formation (MFF), a set of broad and enigmatic plains straddling the planet's equator, has provided most of the fine dust found everywhere on the Martian surface.

By one estimate, some 3 billion tons of dust cycle between the planet's surface and atmosphere each year. These particles must be extremely small to become airborne, microscopic motes no more than 50 to 100 microns across. For decades researchers have struggled to find geologic processes on Mars that operate efficiently enough and long enough to generate all that silty grit.

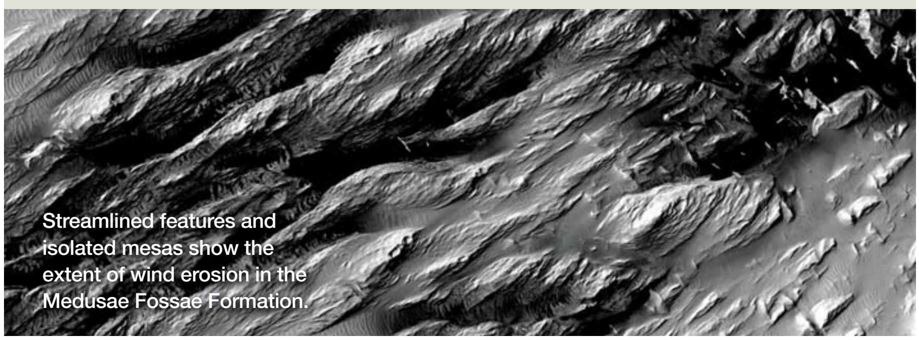
Now, researchers think they know the answer: Ever since the MFF's formation after a supervolcano erupted 3 billion years ago (*S&T:* Oct. 2018, p. 11), its gradual but incessant erosion has created most of the present-day dust on Mars, say Lujendra Ojha (Johns Hopkins University) and colleagues. Ojha's team explores this possibility July 20th in *Nature Communications*.

Unlike on Earth, where bodies of water trap most dust, Martian dust floats in the atmosphere or settles on the ground. Data collected by Mars rovers show that all this dust, if spread out evenly around the planet, would create a layer about 3 meters thick.

Ojha's group finds that the MFF might originally have covered 2½ times more of the Martian landscape than it does now. Wind-driven erosion of such extensive plains could have produced enough dust to mantle the whole planet to a depth of 2 to 12 meters, in agreement with the actual 3-meter thickness.

The kicker comes from chemistry: Previous rover data have shown that Martian dust is extremely rich in sulfur and chlorine, with a distinct sulfur-to-chlorine ratio. When Ojha's team used a gamma-ray spectrometer on NASA's Mars Odyssey orbiter to deduce the MFF's chemical composition, they found the exact same abundances. No other region on Mars has these same chemical characteristics.

■ JULIE FREYDLIN



Streamlined features and isolated mesas show the extent of wind erosion in the Medusae Fossae Formation.

NEUTRINO DETECTION: THE ICECUBE COLLABORATION; MEDUSAE FOSSAE: NASA / JPL / UNIV. OF ARIZONA

GALAXIES

Andromeda's Encounter with a Galactic Sibling

OUR NEIGHBOR GALAXY ran into a large companion billions of years ago, astronomers claim July 23rd in *Nature Astronomy*.

Richard D'Souza and Eric Bell (both at University of Michigan) examined independent, large-scale simulations to understand how Andromeda-size galaxies form. To reproduce our neighbor's massive and metal-rich stellar halo, the simulations require a major collision within the past 5 billion years, with disrupting effects continuing until 2 billion years ago. The researchers conclude that M32, Andromeda's satellite, is the most likely remnant of the encounter. The parent galaxy, dubbed M32p, was likely similar in mass to the Milky Way.

The collision explains many of the galaxies' characteristics, D'Souza says. A gravitational encounter could have triggered Andromeda's bout of star formation 2 billion years ago, when the merger ended. It could also have ripped away M32p's disk, creating the giant stream of metal-rich stars in Andromeda's halo and explaining M32's compact structure.

▲ The oddly compact satellite galaxy M32 might be the remnant of a past merger.

But Puragra Guha-Thakurta (University of California, Santa Cruz), who wasn't involved in the study, doubts M32's involvement. If M32 were the remnant of a major merger, then it ought to have a stream of tidal debris both ahead of and behind it, he says — but while a giant stream of stars and gas trail the satellite, nothing lies in front of it.

Nevertheless, D'Souza and Bell maintain that their work makes a strong case that *something* massive interacted with Andromeda. More observations of stellar motions and composition might help bolster the case.

■ ELIZABETH HOWELL

STARS

Gap in Gaia Data Reveals Stellar Interiors

ASTRONOMERS WORKING with data from the European Space Agency's Gaia mission (*S&T:* Aug. 2018, p. 9) have discovered a new feature due to a change in the structures of low-mass stars.

Astronomers often use the century-old Hertzsprung-Russell diagram to determine stars' properties based on their color and brightness. Now, a team of astronomers led by Wei-Chun Jao (Georgia State University) has announced the discovery of a narrow but distinctive gap in this diagram in the July 1st *Astrophysical Journal Letters*. While most stars follow a smooth continuum, a tiny hiccup appears in the luminosities of low-mass *M* stars.

The gap in luminosities corresponds to the mass where *M* stars transition from a fully convective interior to a structure more like the Sun's, with a convective envelope surrounding a denser, radiative core.

Most theoretical models of stellar structure don't predict this hiccup. Yet James MacDonald and John Gizis (both at University of Delaware) suggest in the October 21st *Monthly Notices of the Royal Astronomical Society* that the gap *is* a feature of existing theory.

The gap, they explain, comes from changes in the efficiency of the stars' power source. The boiling motions in the cores of lower-mass stars help mix intermediate products of fusion reactions, allowing them to fuse hydrogen more efficiently. When the core becomes too dense for convection, that steady increase in efficiency stops. This sudden change creates a dearth of stars at a particular brightness; however, some questions remain. Clearly, the HR diagram still has secrets to reveal.

■ MONICA YOUNG

IN BRIEF

Small Satellite to Answer Big Question

HaloSat, a CubeSat deployed from the International Space Station on July 13th, is on the hunt for the universe's missing mass. While the identity of dark matter remains a mystery, even "normal" baryonic matter isn't all accounted for: Astronomers tallying up stars, planets, galaxies, gas, and dust only come up with about half of the expected mass. Some of this missing matter may reside in million-degree gas that surrounds galaxies, but the temperatures are so extreme that observational signatures are faint. HaloSat detects X-rays with energies between 400 and 2,000 electron volts, which enables it to find emission from ionized oxygen associated with superhot halo gas. With a 100-square-degree field of view, HaloSat will efficiently survey the entire sky to determine the extent of the Milky Way's gaseous halo. The satellite will avoid a major source of noise, created as the solar wind interacts with Earth's atmosphere, by only taking observations during its 45-minute passes over Earth's nightside. HaloSat is expected to operate for a year. Read more about the mission at **https://is.gd/halosat**.

■ DAVID DICKINSON

Sea Meteorite Recovered

On the evening of March 7th, a fireball lit up skies along western Washington and Oregon. The object responsible, later estimated to be 2 metric tons, broke apart some 25 km (16 miles) off the coast of Washington state. Now, a team of scientists has announced the possible recovery of fragments from the fall. The first sonar-based search effort with *Exploration Vessel Nautilus* didn't turn up anything, but the team had better luck with a seven-hour visual search using a pair of remotely operated vehicles named Argus and Hercules. Using a suction hose sampler, magnetic plate, and sediment scoop, the researchers attracted and sorted out meteoritic debris. A preliminary analysis by Marc Fries, Cosmic Dust Curator at NASA's Johnson Space Center, revealed two small fragments characteristic of the smooth fusion crust that forms during a bolide's plunge through Earth's atmosphere. If verified, the find will mark the first meteorite recovery from the seafloor after an observed fall.

■ DAVID DICKINSON

▲ Ultraviolet image of Venus taken by the Pioneer Venus Orbiter

A Nebulous Existence

For both Venus and Earth, life's last refuge might lie in the clouds.

BEFORE THE SPACE AGE, it was common to regard Venus as a planet stuck in a state resembling Earth's deep past — perhaps a carboniferous swamp world with tree ferns and giant reptiles. Now we know that our nearest planetary neighbor is actually a vision of our likely future.

When Venus and Earth were both young, their surface conditions were probably very similar, sporting warm, organics-rich oceans and active geology. They were the kind of places where we think life could easily have formed, if our current understanding of both the origin of life and of Venus are correct.

Yet the Sun gradually brightens as it ages, causing the inner edge of the *habitable zone*, where surface water can exist on rocky planets, to slide inexorably outward. Some time in the remote past it swept past Venus, and her seas evaporated. Some time in the future the same thing will happen to Earth.

What became of Venusians (if any existed) when the oceans vanished and the surface became too scalding for organic life? Is it possible that some organisms found sanctuary up in the atmosphere? For more than 20 years I've promoted the plausibility of a cloud biosphere on Venus. My mentor Carl Sagan floated this idea even earlier, and some colleagues have elaborated upon it in a recent paper published in the journal *Astrobiology* (see **https://is.gd/venusclouds**).

Conditions in the cloud deck are moderate — roughly the same temperature and pressure as at Earth's surface. Moreover, plenty of nutrients and energy sources exist there, even liquid water in the form of concentrated sulfuric acid. Also, there are some stubborn riddles concerning the clouds and upper atmosphere that make us wonder. These include unidentified structures inside some of the larger cloud particles, and unidentified material that absorbs most of the solar energy striking the planet, both of which could conceivably have a biological explanation.

Thanks to the discovery of extremophile organisms on Earth, which thrive in strong acid, along with the persistence of those cloud-deck mysteries, interest in the life-in-the-clouds proposal has increased lately. When NASA or another space agency next launches a mission to explore Venus's atmosphere, astrobiological prospecting surely will be among the goals.

One compelling reason to explore Venus and to reconstruct its past is to understand the far future of Earth. This is true about climate: If we can grasp the mechanism and timing of the runaway greenhouse that destroyed Venus's surface oceans, we'll know better what lies ahead for our world when the Sun inevitably warms it to the point that Earth can no longer hold its water (*S&T:* Oct. 2017, p. 22).

It may be true about geology as well: Plate tectonics, so vital to the functioning of our home world, seems to have ceased on Venus (if it ever operated there at all). We're not sure why, but it might have to do with the drying out of the interior that accompanied the loss of surface water.

Finally, Venus may even give us a glimpse of our planet's old age in terms of its biology. If life on a dying oceanic world can migrate to the clouds, as might have taken place on Venus, then that might be the long-term fate of Earth's biosphere. The clouds may be our planet's final habitable zone.

■ **DAVID GRINSPOON** is author of *Venus Revealed: A New Look Below the Clouds of Our Mysterious Twin Planet* (1997), in which he first hypothesized about microbial life in Venusian clouds.

NASA

 by Govert Schilling

MONSTE SCOPES

Astronomers and engineers are boldly building a generation of telescopes like none that has gone before.

I was driving a sturdy 4WD pickup truck up a steep and winding gravel road in the Chilean Atacama Desert. It was hard to keep the car under control on the bumpy track. My passengers must have been terrified at every hairpin curve. Only by stopping the truck every now and then could I enjoy the surreal beauty of the surrounding landscape, with the white enclosures of the European Southern Observatory's (ESO's) Very Large Telescope on the horizon, some 20 kilometers away. Our goal: the barren summit of Cerro Armazones, a conical mountain in the Sierra Vicuña Mackenna range.

The day before, we had been filming at the Very Large Telescope (VLT) for the ESO documentary *Europe to the Stars*. But we also wanted to take a look into the future and to show viewers the site of the organization's next monster instrument, the 39.3-meter *Extremely* Large Telescope (ELT). At the time — more than six years ago now — the summit of Cerro Armazones carried little more than a weather station, some site-testing equipment, and a microwave communications antenna. Driving up the mountain was a challenge.

Standing at the summit, I couldn't help thinking back to the spring of 1999, when I attended an international workshop on future telescopes at Bäckaskog Castle in southern Sweden. The 10-m Keck II Telescope at Mauna Kea, Hawai'i, had only been in operation for three years, and the European VLT was still very much under construction. But at Bäckaskog, ESO scientists and engineers bravely presented the design of a humongous *100*-meter telescope, called OWL (for Overwhelmingly Large). I remember team leader Roberto Gilmozzi bluntly stating: "There are no known technological showstoppers. We could start building this right away."

Well, it turned out there were *financial* showstoppers, and the OWL Telescope never materialized. But right now, three smaller monster telescopes are taking shape, set for first light in the 2020s. International partnerships led by U.S. institutions are planning the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT). Meanwhile, most of the original design studies for OWL found their way into ESO's ELT. Together, these three instruments are destined to revolutionize our view of the universe. We are really standing on the threshold of a new era of astronomical discovery.

New Technologies

Just over a century ago, on November 1, 1917, the 100-inch (2.54-m) Hooker Telescope at Mount Wilson Observatory near Los Angeles gathered its first light. Using this revolutionary instrument, noted cosmologist Edwin Hubble (after whom the Hubble Space Telescope is named) discovered the true nature of "spiral nebulae" — individual galaxies comparable to our own Milky Way — and the expansion of the universe. For more than 30 years, the Hooker Telescope remained the largest in the world. When the 200-inch (5.1-m) Hale Telescope at Palomar Mountain in southern California was dedicated on June 3, 1948, many astronomers believed that they had reached the limits of technical feasibility.

In two feature articles, S&T Contributing Editor Govert Schilling looks into the future of optical and near-infrared ground-based astronomy. This month's story describes the three next-generation telescopes that are planned for the 2020s; next month's article will focus on instrumentation and science.

R

EXTREMELY LARGE TELESCOPE This illustration shows the upcoming European behemoth in operation. Lasers will create artificial stars high in the atmosphere to reveal turbulence patterns, enabling adaptive optics to compensate.

ESO / L. CALÇADA

In subsequent decades, however, most of the limiting factors in constructing much larger instruments have been overcome. One of the developments that made this possible was the return, in the late 1970s, to small and relatively cheap alt-azimuth telescope mounts, as opposed to the bulky, asymmetric equatorial mounts of the past. The big advantage of an equatorial mount is that the diurnal rotation of the night sky can be tracked by rotating the telescope at a constant speed around just one axis, parallel to the axis of the Earth. But today's computer-controlled stepping motors no longer have an issue with moving a huge telescope around two axes at the same time, with continuously varying speeds, as required for a much more compact alt-azimuth mount. A smaller and more symmetrical mount leads to huge cost savings for both the telescope construction and the enclosure, which can also be much smaller.

Even more important was the advent of thin-mirror technology. Older generations of mirrors had to be thick enough to withstand gravity, wind load, and temperature changes without losing their shape. But thanks to active support by computer-controlled actuators, which compensate for possible deformations by these environmental changes, today's telescope mirrors can be as thin as 10 to 20 centimeters without losing their required curvature stability. Moreover, telescope builders successfully started to experiment with large, jigsaw-like mirrors, consisting of relatively small interlocking hexagonal segments, which are easier and cheaper to produce (and transport!) than a single monolithic mirror.

As a result of these new technologies, quite a number of 8- to 10-m class optical telescopes are operational right now, including the twin 10-m Keck Telescopes at Mauna Kea and the four 8.2-m Unit Telescopes of ESO's VLT in Chile. By using laser-produced artificial guide stars in the upper atmosphere, wavefront sensors to precisely measure the incoming light, and thin, rapidly deformable mirrors in the telescope's light path, even atmospheric turbulence can be compensated for in a technique known as adaptive optics (*S&T:* May 2016, p. 30). Evidently, the venerable 200-inch Hale Telescope was not an end point, but just another milepost along the road to astronomy's ever-larger eyes on the skies. The same is now true for Keck and the VLT.

▲ **FUTURE ELT SITE** Taken in early 2018, this image shows the early foundations for the dome and telescope structure of ESO's Extremely Large Telescope (ELT), which will perch at an altitude of some 2,500 meters (8,300 feet) on Cerro Armazones in the Chilean Atacama Desert.

ESO / G. HÜDEPOHL

Seven-Eyed Magellan

If you want to see an example of what's next, you need to drive to Arizona Stadium in Tucson, home field of the Arizona Wildcats. Unknown to most of the visiting football fans (and probably to quite a number of players), the University of Arizona's Richard F. Caris Mirror Laboratory is located underneath the stadium's east wing. Here's where five of the seven thin 8.4-m mirrors for the future Giant Magellan Telescope (GMT) have already been spun-cast in a giant rotating oven (*S&T:* Mar. 2014, p. 24). The first segment has been polished to its final surface accuracy, while the next four mirrors are currently being worked on.

"With a focal length precision requirement of 300 microns, it's a big challenge," says GMT Organization vice president Patrick McCarthy (Carnegie Observatories), "but we steadily keep on moving forward."

At Cerro Las Campanas in northern Chile, construction work for the new telescope started earlier this year. The mountain's summit was already leveled in 2012, and when Miguel Roth (who was the observatory director at the time) drove me up to the plateau in the spring of 2013, the outline of the GMT enclosure was marked with white boulders. Since then, the road has been graded, and residence buildings for construction workers have been erected. "The site is big enough to accommodate a second GMT," Roth proudly told me. Who knows what the future will bring? The W. M. Keck Observatory on Mauna Kea also consists of two identical telescopes, and the Las Campanas Observatory is already home to the twin 6.5-m Magellan Telescopes.

Megascope Partnerships

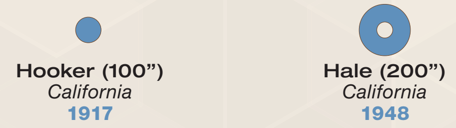
EXTREMELY LARGE TELESCOPE

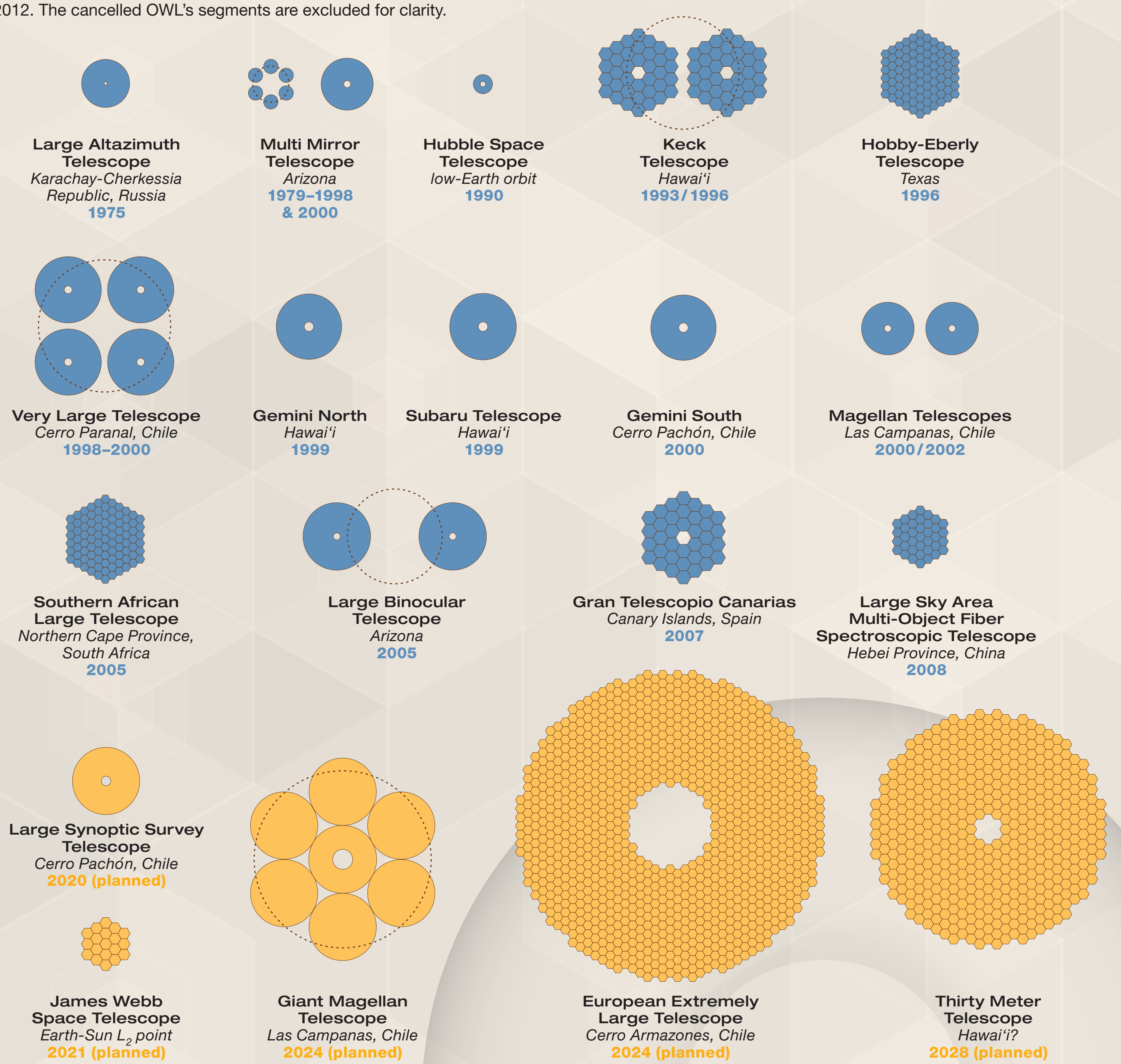
European Southern Observatory (ESO) member states:
Austria • Belgium • Czech Republic • Denmark • Finland • France • Germany • Italy • The Netherlands • Poland • Portugal • Spain • Sweden • Switzerland • United Kingdom

GIANT MAGELLAN TELESCOPE

Arizona State University • Astronomy Australia Limited • Australian National University • Carnegie Institution for Science • FAPESP: the São Paulo Research Foundation (Brazil) • Harvard University • Korean Astronomy and Space Science Institute • Smithsonian Institution • Texas A&M University • University of Arizona • University of Chicago • University of Texas at Austin

APERTURE AMBITION Limited only by their imaginations (and budgets), astronomers have developed increasingly gargantuan telescopes, exemplified by this selection of primary mirrors from the last century. Dotted circles indicate effective collecting area. In 2000, a single mirror replaced MMT's six smaller ones, and the Keck Interferometer operated from 2003 to 2012. The cancelled OWL's segments are excluded for clarity.

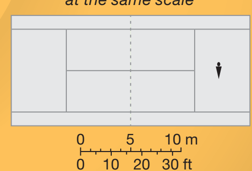




THIRTY METER TELESCOPE

California Institute of Technology • Department of Science and Technology (India) • National Astronomical Observatories of the Chinese Academy of Sciences • National Institutes of Natural Sciences/National Astronomical Observatory of Japan • National Research Council (Canada) • University of California • Association of Universities for Research in Astronomy (associate member) • Gordon and Betty Moore Foundation (observer)

Tennis court and human at the same scale



GIANT MAGELLAN TELESCOPE

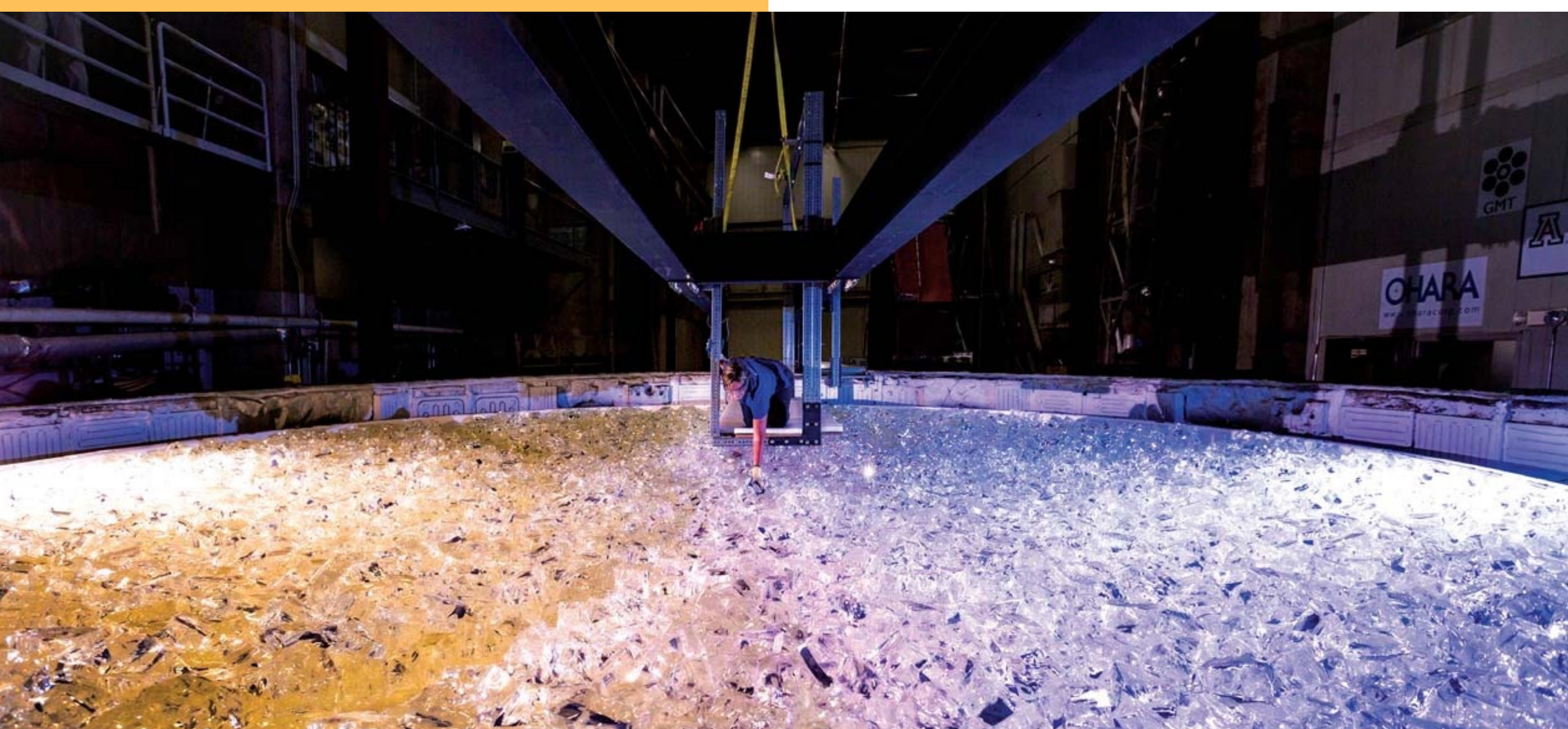
However, for now, building just one Giant Magellan Telescope is challenging enough. The instrument explores a novel design, never before used in a large professional telescope. Surrounding a central parabolic 8.4-meter mirror — the largest monolithic blank the Arizona Mirror Lab can produce — are six similar-sized asymmetric siblings, each weighing more than 15 metric tons and all mounted on the same telescope structure. Together, the seven mirrors constitute a giant 24.5-m paraboloidal primary. Because of the gaps between the individual mirrors, the GMT has the light-gathering power of a 22.5-m telescope. By 2024, astronomers hope to put the first mirrors in place and achieve first light.

Just like the primary, the secondary mirror of the GMT, with an effective diameter of 3.2 m, will consist of seven smaller (1.1-m) mirrors. These concave ellipsoidal mirrors are an integral part of the GMT's adaptive optics system. Six sodium lasers will be used to create artificial guide stars. Hundreds of times per second, atmospheric wavefront distortions will be measured and corrected for by subtle "shape shifting" of the ultra-thin (2.4-millimeter) secondary mirrors by means of 672 actuators per segment. Eventually, the plan is to produce one additional segment for both the primary and secondary mirrors: That will enable astronomers to continue observations when one of the mirrors has to be removed temporarily to be recoated.

Thanks to financial commitments from a long list of partner institutions in the U.S., Australia, Brazil, and South Korea, about half of the necessary $1.05 billion has been secured, according to McCarthy. "Fundraising remains one

◀ **MOPPING UP** Arizona mirror lab staff clean the glass for GMT's fourth mirror after opening the oven.

▼ **CREATING GMT'S PRIMARY MIRROR** Lab staff member Linda Warren places the last piece of glass into the mold for the GMT's fifth mirror, which was cast in 2017 and is now cooling.



of our many activities," he says. In 2024, the Giant Magellan Telescope may start science operations as a half-grown giant, with a primary made up of only a few "eyes" instead of the full seven. That would hardly compromise the angular resolution of the observations, but it would of course reduce the sensitivity of the instrument: With four mirrors, for example, the GMT would have the same light-gathering power as an imaginary 17-m telescope. However, barring unexpected setbacks, McCarthy remains confident: "No way the GMT will end as a four-mirror telescope."

Thinking Big

For the Carnegie Institution for Science, a founding partner in the GMT project, it made a lot of sense to construct the new telescope close to where they already are operating the two original Magellan Telescopes. After all, GMT could be described as Magellan on steroids. Likewise, the Thirty Meter Telescope (TMT) is a pumped-up version of Keck, and it should come as no surprise that the California Institute of Technology (Caltech) and the University of California want to build their new monster telescope at Mauna Kea, Hawaiʻi — close to their original 10-m Keck twins.

The Thirty Meter Telescope is going to be huge. While the primary mirrors of the two Keck Telescopes consist of just 36 hexagonal segments (a design pioneered by the late astronomer Jerry Nelson), TMT will have no fewer than 492 segments. Together, they constitute a 30-m wide hyperboloidal mirror. Measuring 1.44 m across, each segment is stiff enough to resist deformations due to gravity, wind load, or temperature changes. Still, active support systems are needed to keep the segments precisely positioned with respect to one another under all circumstances.

Because of the overall shape of the TMT mirror, the segments come in 82 different types (six of each), their asymmetric curvature depending on the distance from the center. They are produced using a technique known as *stressed mirror polishing*. Carefully calculated external stresses are applied to each mirror blank, so that it can be polished into a spherical shape, which is much easier than changing the techniques to match 82 different shapes. Upon release of the external forces, the mirror springs back to the desired off-axis, asymmetric shape. Every work day, two of the 492 segments will be recoated in a giant coating plant next to the telescope, switched out of the primary with spares every two weeks. After about a year, each and every segment will have received a new reflective layer (probably silver).

The TMT's 3.1-m convex secondary mirror is also a hyperboloid. The secondary is 20% larger than the primary mirror of the Hooker Telescope, which was the world's largest reflector until just 70 years ago. Even the flat tertiary mirror is larger, with a 3.5-by-2.5-m elliptical shape. Thanks to its optical design, the TMT has a surprisingly large field of view of almost 20 arcminutes, two-thirds of the apparent diameter of the full Moon. Another impressive feature of the telescope is its elegant, spherical enclosure, which will reach as high as an 18-story building. Known as a *calotte dome*, it has a tilted moving structure and a large circular opening.

At almost 700 square meters, the light-collecting area of the TMT will be some 80% larger than that of the GMT. Of course, the Thirty Meter Telescope will also be outfitted with adaptive optics, using multiple lasers. Unfortunately, just as with the GMT, the necessary funds — estimated at some $1.4 billion — are not yet fully secured, says TMT International Observatory (TIO) board member Thomas Soifer (Caltech), despite a generous $200 million grant from the Gordon and Betty Moore Foundation. "We really need a major new partner, like the National Science Foundation," he says. A descope plan is available, if necessary.

Pacific Protest

There have been many issues regarding the TMT's location. A planned groundbreaking ceremony on October 7, 2014, was disrupted by Native Hawaiians who protested against yet another large telescope on the summit of their sacred mountain. "It was a surprise," recalls TIO's executive director Edward Stone (Caltech). "We had spent eight years on environmental impact studies and listening to the community." In late 2015, the Hawaiian Supreme Court vacated the original building permit on procedural grounds. After many public hearings, the state's Board of Land and Natural Resources granted a fresh construction permit in September 2017, but opponents filed a notice of appeal with the state Supreme Court. "You'll be amazed by all the things lawyers can do," says Soifer.

Meanwhile, the TIO board started to develop Plan B, just in case. Instead of building the TMT at Mauna Kea, the new instrument could find a home at the Roque de los Muchachos Observatory, on the Spanish island of La Palma, off the coast of Morocco in the Atlantic Ocean. La Palma already hosts the 10.4-m Gran Telescopio Canarias — a near-identi-

THIRTY METER TELESCOPE

GMTO CORPORATION (3); TMT: TMT INTERNATIONAL OBSERVATORY cal copy of Keck. "Mauna Kea has always been our preferred choice," says Stone, "but La Palma is an excellent alternative." Nevertheless, he admits that the lower altitude and the higher average temperature make it a less ideal site for studying the longer-wavelength part of the infrared spectrum, which is important for many astronomical research topics, from the origin of stars and planets to the evolution of the first galaxies in the universe.

In the fall of 2017, after three years of delay, the TMT board decided it really needed to start constructing the telescope in the spring of 2018. "We were wrestling with how many additional years — and money — it would be worth it to be at Hawai'i," says Soifer. "We want to achieve first light in 2028." But as this issue went to press, a formal decision had not yet been made. "We continue to assess the ongoing situation," said Stone in a prepared statement in April. The board still remains hopeful of court decisions that will allow construction to resume on Mauna Kea. One concern is that Japan — a major partner in the TMT project — has always been opposed to moving the telescope to La Palma, given the country's special astronomical connections to Hawai'i.

As for the financial issues: In May 2018, the National Science Foundation's National Optical Astronomy Observatory (NOAO) announced the development of a U.S. Extremely Large Telescope (US-ELT) Program, together with both the GMT Organization and the TMT International Observatory. By working together in one program and by focusing on complementarity instead of competition (after all, one instrument is in the Northern Hemisphere and the other in the Southern Hemisphere), the hope is that NSF will eventually cough up the necessary funds.

Going to Extremes

Financial issues appear to be relatively minor, and location issues non-existent, for the third — and largest — monster telescope, ESO's 39-m Extremely Large Telescope (ELT). According to former ESO Director General Tim de Zeeuw (Leiden University, The Netherlands), the project is on schedule for completion in 2024. "Construction costs will be highest in 2019 and 2020," he says, "but ESO's member states have given the Board permission to take out a loan, if necessary."

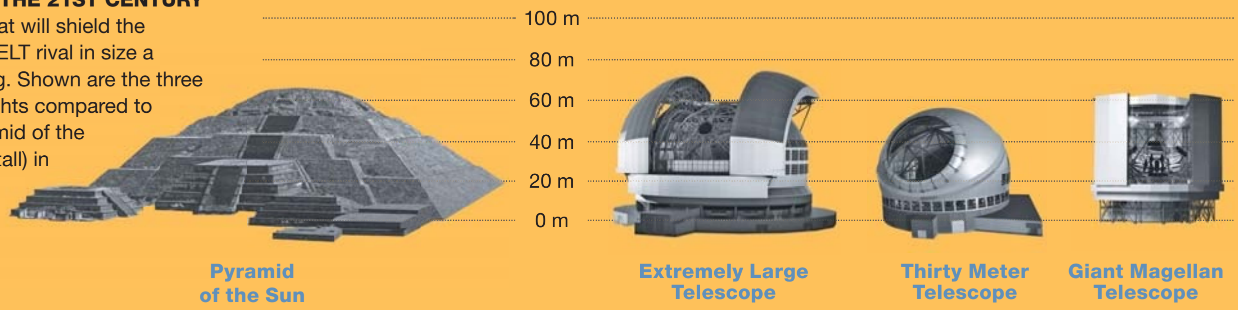
▲ **HAWAIIAN CONCERNS** TMT opponents gather in 2015 to pray atop Mauna Kea, which native Hawaiians consider sacred. Preschool teacher Kaho'okahi Kanuha (at right) told Hawai'i Public Radio at the time, "Curiosity should not supersede the values and the traditions of the host people and the host culture."

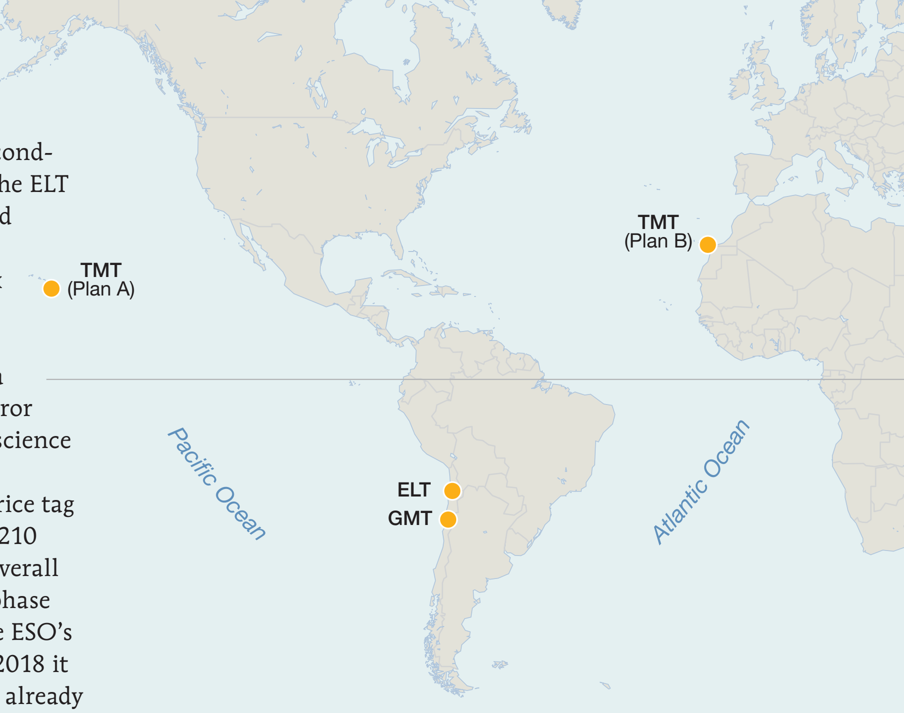
Cerro Armazones in northern Chile was selected as the location for the ELT in April 2010 (the site had also been considered for the TMT). Road construction commenced in June 2012, a few months after I drove my pickup truck up the old gravel track. The mountaintop was leveled in June 2014, and on May 26, 2017, Chilean president Michelle Bachelet Jeria ceremonially laid the first stone for the future observatory. Armazones is close to Cerro Paranal, home to ESO's Very Large Telescope. As a result, the ELT will be able to make use of much of the same infrastructure, including the control room and residential and technical facilities.

Originally, the ELT was designed as a 42-m giant. Not so much because 42 is "the answer to life, the universe, and everything," as in Douglas Adams's cult science-fiction book *The Hitchhiker's Guide to the Galaxy*, but because (the rumor goes) it would give the European project exactly twice the light-gathering power of the Thirty Meter Telescope. However, the original plan had to be descoped in 2011. Paring back from 42 to 39.3 meters doesn't sound like a big difference, but the number of 1.45-m segments could be reduced from 984 to a "mere" 798. Their precise positions are measured and controlled by 4,608 edge sensors and 2,394 actuators.

The ellipsoid primary is made up of 133 different types of segments (six of each, just as in the case of the TMT). Com-

PYRAMIDS OF THE 21ST CENTURY
The buildings that will shield the GMT, TMT, and ELT rival in size a 20-story building. Shown are the three enclosures' heights compared to that of the Pyramid of the Sun (66 meters tall) in Mexico.





bined with the telescope's extremely convex 4.2-m secondary and a slightly concave 3.8-m tertiary, it provides the ELT with a perfect image quality over its 10 arcminute field of view. Laser guide-star adaptive optics will be performed using a 2.4-m flexible mirror, consisting of six "petals." At just 2 mm thick and controlled by some 8,000 actuators, this will be by far the most complex adaptive optics mirror ever produced. Finally, there's a thin elliptical, 2.6-by-2.1-m flat mirror. This fifth mirror stabilizes the image and steers the beam towards the science instruments.

In the telescope's first construction phase, with a price tag of some $1.3 billion, the inner five rings of segments (210 in total) will remain empty, compromising the ELT's overall sensitivity. Additional funds for the second and final phase would have already been available if Brazil had become ESO's 16th member state by now. However, in the spring of 2018 it became clear that the accession agreement, which had already been ratified by the Brazilian Congress in May 2015, will not be signed by the president. "But," says de Zeeuw, "Poland — home country of famous astronomer Nicolaus Copernicus — did join ESO in 2015, and Ireland will probably follow in late 2018. Moreover, Australia has entered a strategic partnership with ESO in July 2017, and I'm confident that they will become a full member eventually."

It's hard to imagine how impressive the Extremely Large Telescope will be, when completed. At almost 1,000 square meters (over twice the size of a basketball court), its main mirror will be larger than all previous professional telescopes combined. The ELT has a total moving mass of more than 3,000 metric tons. The Nasmyth instrument platforms on either side of the huge telescope structure will be large enough to accommodate a single 8.2-meter VLT Unit Telescope. The double shutter of the enclosure measures 45 m in width, and at 74 m, the giant 5,000-ton dome is higher than the ancient Pyramid of the Sun near Mexico City.

Astronomy has come a long way since Galileo Galilei trained his small, home-built telescope at the Moon, the planets, and the stars. Some four centuries ago, his observations ushered in a whole new view of the universe we live in. The same will no doubt be true for the GMT, TMT, and ELT, which are by far the largest eyes on the sky ever built by humans. I can't wait to take in the revolutionary cosmic vistas they are going to yield.

■ *S&T* Contributing Editor **GOVERT SCHILLING** lives in The Netherlands but has paid multiple visits to most major astronomical observatories worldwide.

Monster Telescopes at a Glance

	Giant Magellan Telescope (GMT)	Thirty Meter Telescope (TMT)	Extremely Large Telescope (ELT)
Partnership	International partnership (U.S., Australia, Brazil, South Korea)	International partnership (U.S., Canada, China, India, Japan)	European Southern Observatory (15 member states, see page 16 for list)
Aperture	24.5 m	30 m	39.3 m
Primary mirror design	Paraboloid (seven 8.4-m monoliths)	Hyperboloid (492 1.44-m hexagonal segments)	Ellipsoid (798 1.45-m hexagonal segments)
Total moving mass	1,500 metric tons	1,430 metric tons	3,000 metric tons
Enclosure	Cylindrical (56 m diameter, 63 m high)	Calotte dome (66 m diameter, 56 m high)	Shuttered dome (86 m diameter, 74 m high)
Location (altitude)	Cerro Las Campanas, Chile (2,520 m)	Mauna Kea, Hawai'i (4,210 m) or Roque de los Muchachos (La Palma, Canary Islands), Spain (2,400 m)	Cerro Armazones, Chile (3,050 m)
Estimated cost	$1.05 billion	$1.4 billion	$1.5 billion
First light	2024	2028	2024

Altitudes rounded to the nearest 10 meters (3,000 meters is about 10,000 feet).

PROTESTORS: MOLLY SOLOMON / HAWAI'I PUBLIC RADIO; SIZE COMPARISON: SCOPES: ESO, PYRAMID: DANIEL CASE / CC BY-SA 3.0; MAP: LEAH TISCIONE / *S&T*; SOURCE ESO

Return to the Iron Planet

An ungainly stack of satellites is set to double the number of spacecraft that have visited Mercury.

▲ **IRON PLANET** This 66-image Messenger mosaic is roughly centered on the rayed crater Kuiper, just south of Mercury's equator. Long rays striate the globe, many tracing back to Hokusai along the limb at upper right.

MERCURY FAST FACTS ▶

Axial tilt	Mean distance from Sun	Surface temperature
0.01° (Earth: 23.5°)	58 million km (0.39 astronomical unit)	–223°C to 427°C (coldest in shadowed polar craters) (Earth range: –88°C to 58°C)

MERCURY: NASA / JHU APL / CARNEGIE INST. FOR SCIENCE / JASON PERRY; DIAGRAMS: GREGG DINDERMAN / S&T; GLOBE MAPS: NASA / JHU APL / CARNEGIE INST. FOR SCIENCE

It's small and gray and covered with craters — and, no, it's not the Moon. At first glance, Mercury looks a lot like Earth's natural satellite. Both have lava plains and rugged cratered terrain, with bright streaks radiating out from powerful impact scars on their drab, airless surfaces. But the Sun-scorched innermost planet is a very different place, from its inside out.

In contrast to the Moon's puny core, Mercury's iron heart takes up some 80% of the planet's radius. It's still at least partially molten and generates a weak, global magnetic field. Moreover, the planet's ongoing, slow solidification affects its surface: As the core freezes, it shrinks, and the crust wrinkles like a drying plum, creating ridges that cut right across big craters.

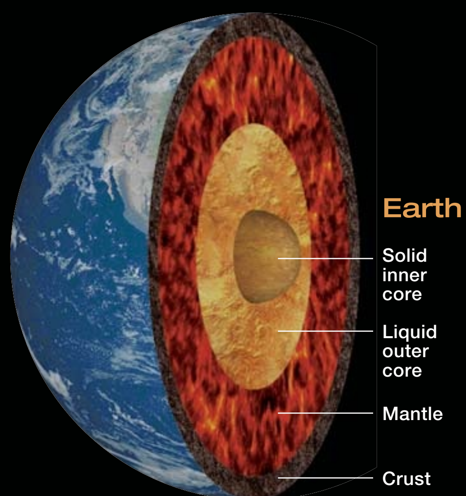
Look closely at those craters, and you'll find some have inexplicably dark rays, rather than bright ones. The floors and peaks of others appear to be moth-eaten, with "hollows" of missing rock. Mercury's dayside might be baked by the Sun to temperatures reaching 427°C (800°F), but even that isn't hot enough to evaporate its surface rock.

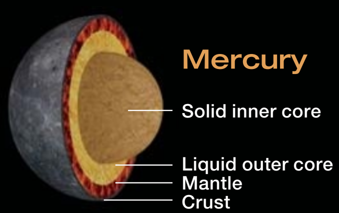
These hollows, like so many other features of Mercury, remain an enigma. All of what we know about this world comes from Earth-based observations and a couple of spacecraft. More than 50 years into the age of interplanetary travel, only two missions have targeted Mercury: NASA's Mariner 10, which flew past the planet three times in 1974 and 1975, and NASA's Mercury Surface, Space Environment, Geochemistry, and Ranging (Messenger) spacecraft, which also zoomed by three times before settling into a highly productive orbital mission from 2011 to 2015 (*S&T:* Apr. 2012, p. 26). Messenger's data upended scientists' theories for how the planet formed and left scientists grappling with its results. In October or November of this year, the joint European-Japanese BepiColombo mission will launch to pick up where Messenger left off, beginning a 7-year journey to the innermost planet to solve some of Mercury's persistent mysteries.

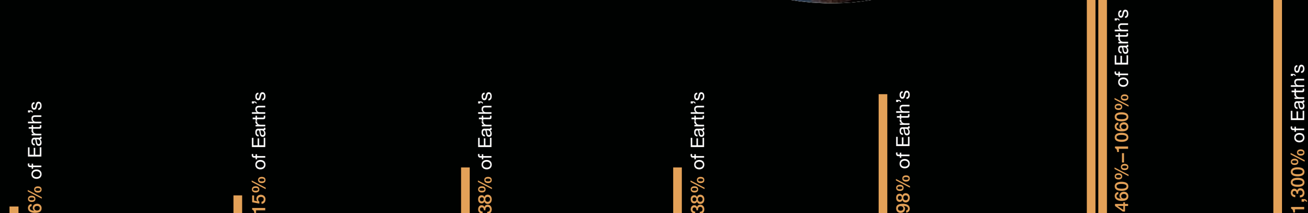
Under New Scrutiny

Mercury hasn't been as high a priority for exploration as other places, such as Mars. That's partly because it's harder to put an orbiter around Mercury than it is to get to Pluto: The tiny planet is deep in the Sun's gravity well, and it takes numerous flybys of Earth, Venus, and Mercury itself to reduce a spacecraft's velocity enough to settle it into a Mercurian orbit.

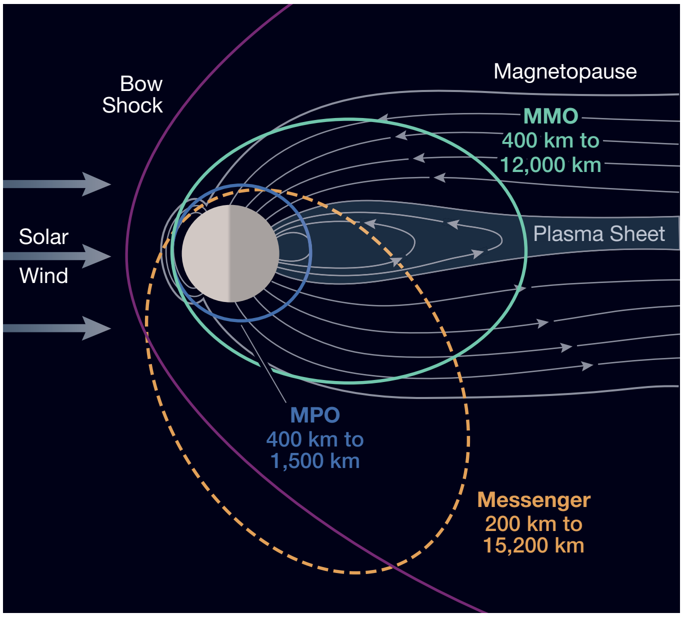
▼ **ALL HEART** Mercury's solid-iron inner core and liquid outer core of iron, sulfur, and silicates together dominate the planet's interior. In comparison, Earth's inner and outer cores take up far less of our world's total volume. Cutaways are roughly to scale.







Mass	Surface area	Diameter	Surface gravity	Mean density	Solar irradiance	Orbital eccentricity
3.3×10^{23} kg	74.8 million km^2	4,879 km	3.7 m/s^2	5.43 g/cm^3	6,272–14,448 watts/m^2	0.21



◀ **MESSENGER VS. BEPICOLOMBO** BepiColombo's components will follow polar orbits, as Messenger did, but they won't fly as far from the planet and will be oriented differently to the planet's spin axis.

Two space agencies are taking on the challenge together. Their joint mission will deliver two spacecraft into orbit at Mercury: Europe's Mercury Planetary Orbiter (MPO), and Japan's Mercury Magnetospheric Orbiter (MMO, nicknamed Mio). The pair will loop around Mercury in polar orbits, as Messenger did, but with crucial differences that will give the BepiColombo mission a much more thorough view.

Unlike Messenger's path, which took it close to the north pole and far from the south one, MPO's orbit will be nearly circular and close to the planet, giving its imagers and spectrometers a detailed look at all latitudes. MMO will follow a more elongated orbit that takes it out farther than MPO to sample more regions of the magnetic field. Both spacecraft will always orbit in the same plane, enabling scientists to coordinate observations.

The set of instruments that BepiColombo will bring to bear at Mercury is broadly similar to Messenger's, only more capable. MPO has color cameras, infrared spectrometers, a laser altimeter, and particle detectors. MMO has a magnetometer, two instruments to study plasma in the magnetic field, plus an exosphere imager and a dust monitor. What will these spacecraft learn that Messenger could not?

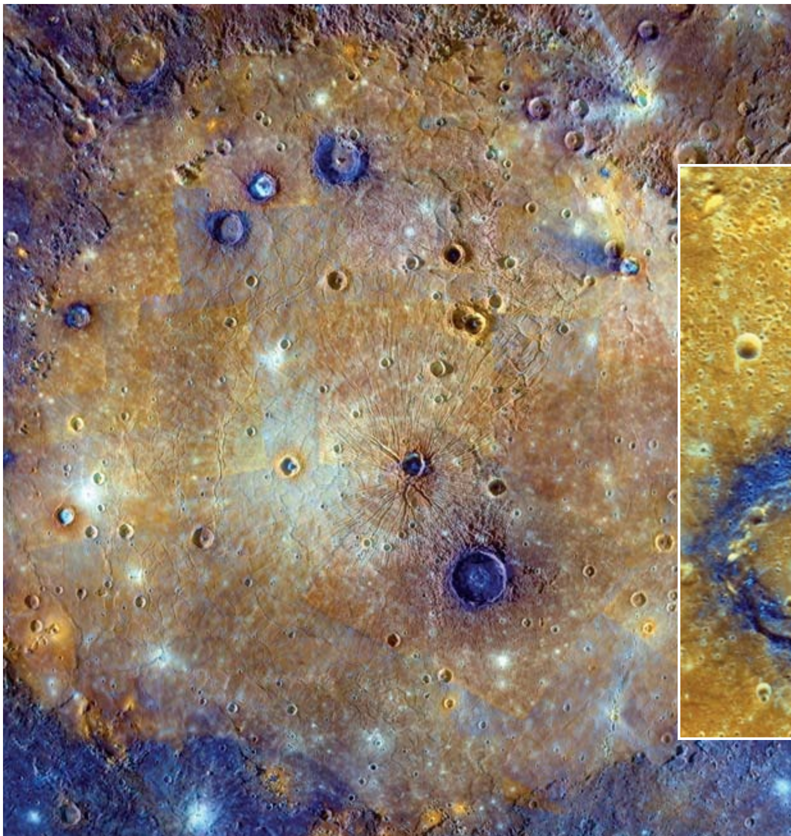
Dark Surface, Light Elements

The most surprising discovery made by Messenger is Mercury's surface composition. It took the orbiter's gamma-ray and neutron spectrometers until the end of the mission to accumulate enough data for quality compositional maps. The result: Mercury's crust is about 5% sulfur by mass. This is roughly 100 times sulfur's abundance in Earth's crust and was totally unexpected. The crust is also 1.4% carbon. The abundance of these two elements directly contradicts formerly favored ideas about how Mercury's bulk composition could be so very metal-rich.

Sulfur and carbon are both relatively "volatile" elements and were not expected to condense in the hottest, innermost portion of the solar nebula as our solar system formed. Prior to Messenger, some scientists had hypothesized that modern-day Mercury is little more than the core of a preexisting larger planet whose mantle was blasted off by a large oblique impact, or perhaps that its lighter materials were blown away by an early, hot Sun. But sulfur and carbon should have been scarce in the aftermath of either scenario. Their abundance confounded mission scientists.

Messenger did confirm ground-based studies that the surface contains little iron or titanium. These are the elements that make the Moon's basalt-filled maria dark, and without them, scientists had difficulty explaining why Mercury's surface is so dark. The unexpectedly high abundance of carbon offers a clue: It might be that graphite (a crystalline form of carbon), not iron, darkens Mercury, mixed among the silicate rocks of its crust.

Mercury has patches of what's been dubbed *low-reflectance material* that's even darker than the usual crust. It's generally exposed by impacts, which dig into the crust and exca-



▶ **CALORIS BASIN** This mosaic of Mercury's signature, 1,500-km-wide impact structure combines enhanced-color and topographic data to reveal differences in geologic features. Lava flows appear orange. Several smaller, subsequent craters have punched through the surface lava to expose what geologists term *low-reflectance material* (blue). This material is likely part of the original basin floor (see close-up in center). Based on the craters, the volcanic layer appears to be between 2½ and 3½ km thick.

ORBITS: LEAH TISCIONE / S&T; CALORIS BASIN: NASA / JHU APL / CARNEGIE INSTITUTION FOR SCIENCE vate deep material, throwing it onto the surface. Mercury likely once had a magma ocean, as the just-formed Moon did after its violent birth (*S&T:* Aug. 2018, p. 26). But whereas the Moon's magma ocean developed a crust of floating low-density silicates, some planetary scientists suggest that Mercury developed a crust of buoyant graphite. After more than 4 billion years of impacts and volcanism, that primordial crust is now buried or disrupted (perhaps, blending with other crustal rocks to darken them). But surviving patches occasionally make themselves known when impacts punch through to a remnant.

The surface's low iron content hampered Messenger's ability to discern the composition of Mercury's rocks in fine detail. Near-infrared spectroscopy relies on the presence and positions of spectral features associated with iron to separate rocks by composition. So BepiColombo's instrument suite includes a thermal emission spectrometer, MERTIS, which is more sensitive to variations in surface composition beyond iron content. The hope is that MERTIS can determine exactly what Mercury's enigmatic dark material is. The instrument's ability to see in the dark — imaging the surface using the heat emitted by its rocks during Mercurian night — will produce a whole new kind of data for the planet and reveal some of the secrets of its poles. And, maybe, better compositional information will help scientists solve the mystery of why Mercury's core is so disproportionately big.

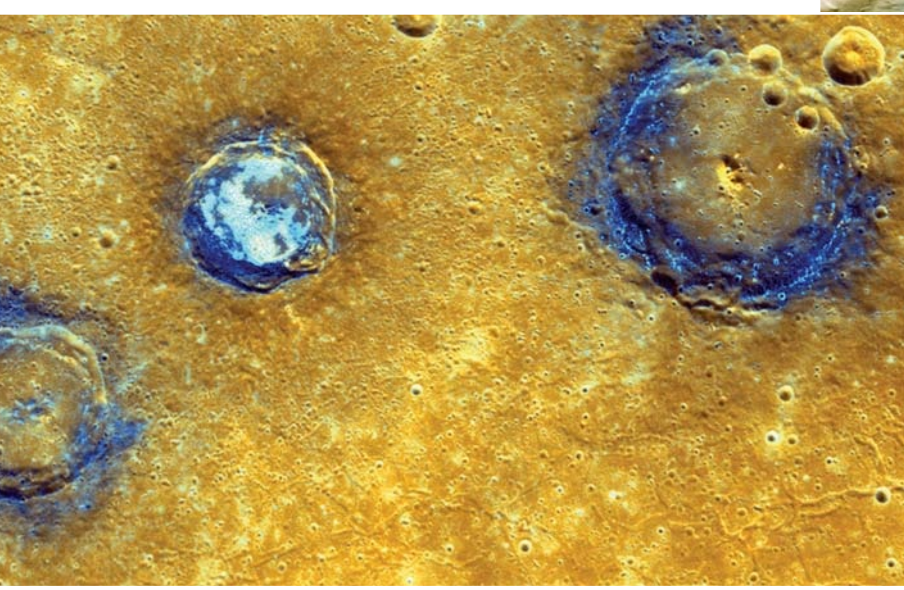
Puzzling Geology

Planetary scientists determine the ages of surface units by counting the numbers and sizes of craters that they have accumulated, but geologic processes can reset that clock. Mercury has fewer small craters than the Moon does, suggesting a major "resurfacing event" at some point early in its history. Geologists intentionally employ the bland word "resurfacing" to avoid attributing a cause, because we don't know if the resurfacing was caused by volcanism, impacts, tectonism, some combination, or none of the above.

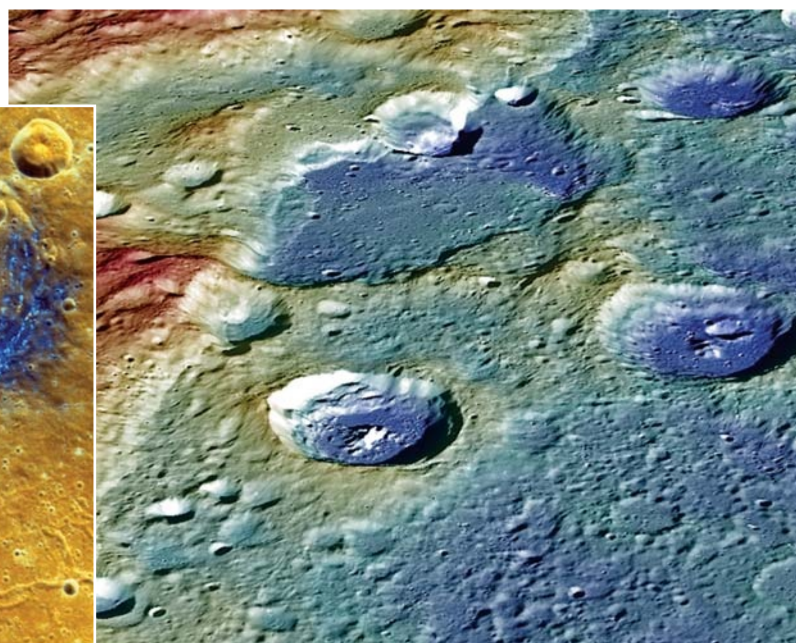
Of particular interest are the relatively flat plains interspersed between the large craters (called, appropriately, *intercrater plains*). They appear to be volcanic flows, but are they? Are they all the same age, or is there a lengthy history recorded in the rock? Messenger couldn't tell. Maybe BepiColombo will. It will deliver much finer-scale pictures of much more of the planet, particularly the southern hemisphere. The more smaller craters that geologists can count, the better they can estimate the ages of small surface areas — and the finer distinctions they will be able to draw between the histories of different parts of the surface.

Higher-resolution pictures will also enable geophysicists to track Mercury's global shrinkage to smaller scales. Mercury shrinks because it has a partially molten interior that is slowly solidifying, and solid rock is denser than liquid rock and thus occupies less volume. Mariner 10's distant images of Mercury showed scarps that recorded 1 to 2 kilometers (about 1 mile) of planetary shrinkage. After Messenger, we now think that all of Mercury contracted by as many as 9 km (6 mi). If there are more scarps at finer scales than Messenger could see, there may have been even more shrinkage. Mercury is still cooling, so there should still be compression along

▼ **MYSTERIOUS DARK STUFF** This enhanced-color mosaic shows three craters within much larger Caloris Basin: Munch (left), Sander, and Poe. Sander, the smallest of the three, is about 50 km across. They've excavated *low-reflectance material*, oddly dark stuff that might be rich in graphite. The same craters lie toward the top of the image at left.



▼ **SHRINK MARKS** The giant thrust fault Carnegie Rupes slashes through the 132-km-wide crater Duccio, the wall it creates rising nearly 2 km above the lower terrain. Scarps like these form as Mercury's interior cools, causing the planet to contract. By tallying up all the planet's known scarps, researchers calculate that the planet's circumference has shrunk by at least 7 km — and perhaps 2 km more before its crust was solid enough to form wrinkles.



NASA / JHU APL / CARNEGIE INSTITUTION FOR SCIENCE (2) those faults even today. Can BepiColombo find evidence for geologically recent fault motion? Can it map different amounts or types of crustal crumpling in rocks of different ages to discover how Mercury shrank with time?

A Hot Planet's Ice

We know that the planet closest to the Sun has deposits of nearly pure water ice at its poles. This seems outlandish, given how strongly the Sun beats down on Mercury's surface (up to some 10 times more intensely than at Earth). Even more amazing is that we first discovered that polar ice in 1991 using radio telescopes on Earth, which detected deposits near the pole that looked bright in radar images (*S&T:* Jan. 1992, p. 35). Messenger proved that the round radar features near the north pole all lie inside deep impact craters whose floors and north-facing slopes never see the Sun, and whose interiors plummet to about –200°C (–330°F).

Later in the mission, Messenger scientists commanded its camera to shoot long-exposure images of those permanently shadowed crater floors. Using light reflected off the sunlit south-facing rims, the spacecraft was able to reveal the radar-bright deposits. Unexpectedly, these images showed some of them to be as black as coal, while others are bright. The interpretation: The cold, shadowed craters contain ice deposits that are tens of meters thick at most, mantled with a varying amount of dark, carbon-rich material.

How does this stuff get to Mercury's poles? Water and most carbon-containing organic molecules are both highly volatile at Mercury — once delivered by asteroids or comets, they don't sit around on the hot surface; instead, they turn into gas and float off. Gravity might bring them back down, but they can't remain stuck to the planet's hot surface. However, any volatile molecule floating in Mercury's thin atmosphere that happens to touch down on the incredibly cold surface of a permanently shadowed floor can become trapped there forever, unless it's disturbed by an impact.

The Moon also has polar ice deposits, but they are patchy and impure. So why are these two worlds' polar ices so different? Could it be that Mercury's ice looks cleaner because it's fresher, delivered recently in a single impact event?

If that's the case, then the impact should have left a crater we can see. You can tell which craters are relatively young on Mercury (or the Moon, for that matter) by the presence of bright rays. And there is no more impressive rayed crater in the solar system than Mercury's Hokusai, a 114-km-wide scar near 60°N with bright rays stretching across the face of the planet, making Mercury look like a gray watermelon.

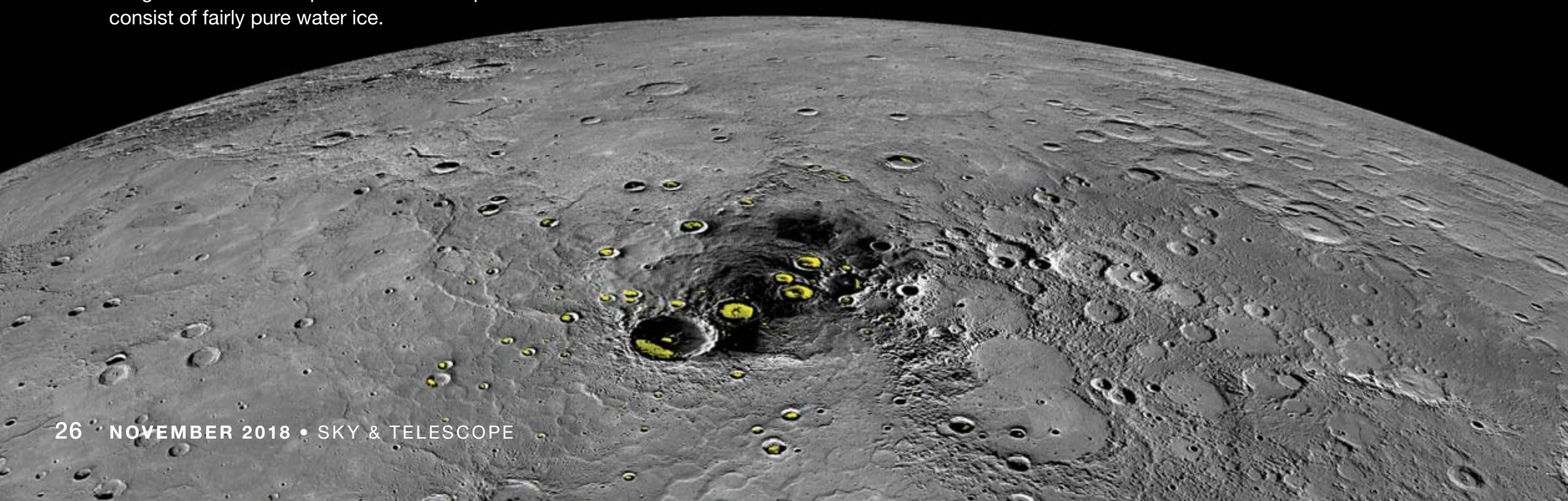
A team led by Carolyn Ernst (Johns Hopkins University Applied Physics Laboratory) has calculated what kind of impacting body would create Hokusai. Observing its horseshoe-shaped peak ring and the large volume of formerly molten rock that fills its floor, they calculated that a reasonable-sized comet or asteroid impactor (25 km) traveling a reasonable speed (less than 30 km per second) could have produced Hokusai and easily delivered sufficient water to account for everything now at Mercury's north pole.

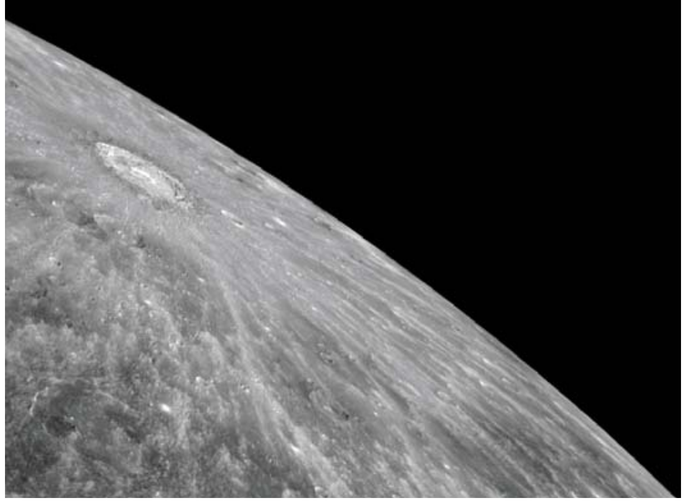
As for the south pole, recent Arecibo observations suggest that radar-bright deposits there cover roughly double the area that their northern counterparts do. Moreover, the southern pole region is more heavily cratered. We don't know what surprises might still hide there, but BepiColombo will get the first close views of this region.

Embedded in the Stellar Wind

Much of Messenger's mission focused on the environment around the planet — particularly its magnetic fields and the charged and neutral particles residing there. No other world in the solar system has the intense relationship with the Sun that Mercury does. At Venus and Earth, the solar wind's interactions are primarily with their ionospheres, far above the ground. But at times the solar wind can interact directly with Mercury's rocky surface. One bizarre implication is that,

THERE'S ICE IN THEM CRATERS Radar observations made from Arecibo Observatory reveal bright deposits (tinted yellow) in several shadowed craters at Mercury's north pole, which have been revealed by long-exposure Messenger images. Scientists suspect that these deposits consist of fairly pure water ice.





▶ **HOKUSAI** During a flyby of Mercury in 2008, Messenger recorded this prominent 114-km-wide crater and its bright splash pattern. The impact that created Hokusai might have delivered water that migrated to the planet's poles and formed ice deposits on the floors of permanently shadowed craters there.

while aurorae appear high in the atmospheres of Earth and Venus, there could be aurora-like emissions at ground level on Mercury, at least at X-ray wavelengths.

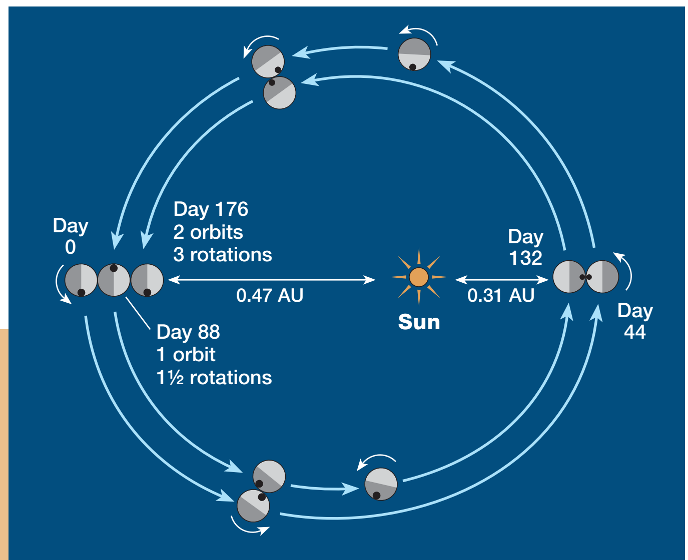
Mercury's churning molten outer core generates a global magnetic field, albeit one that's only 1% as strong as Earth's at the surface. A weird (and still unexplained) aspect of Mercury's magnetic field is its offset toward the north pole by roughly 500 km, some 20% of the planet's radius. The planet's weak magnetosphere can hold off solar radiation — sometimes. But when coronal mass ejections blast toward Mercury, the incoming plasma can compress the field drastically enough to let solar radiation smash directly into Mercury's surface. The south pole gets bombarded more because of the northward offset of the field.

When solar wind particles slam into Mercury's surface, they knock atoms from surface rocks and into Mercury's tenuous *exosphere*. It's not a proper atmosphere — individual atoms rarely encounter each other, so it has no wind or weather — and spacecraft like Messenger and BepiColombo can fly directly through it unimpeded, tasting atoms that until recently were part of the planet's surface.

Solar wind, intrinsic magnetic field, and neutral and charged particles are all interlinked and dynamic on very short time scales. For example, when the solar wind's magnetic field lines connect with a planet's dayside magnetic field, the latter's field lines peel back around to the planet's nightside, where they reconnect. On Earth, this process takes about an hour; on Mercury, magnetic field lines can shift from one side of the planet to the other in a matter of minutes. It's so dynamic that it's difficult to understand all the interactions with only one spacecraft in one location at one time, especially because many of the relevant measurements are performed in situ, with the spacecraft directly measuring field strength or ion composition. With two spacecraft in different orbits, BepiColombo will be able to measure the magnetic field and particle environment at two points simultaneously. MPO will operate at a distance where the planet's influence is stronger, while MMO will explore a region where the solar wind takes over. Together, they'll watch how the whole system responds to solar storms.

BepiColombo's Odyssey

To get MPO and MMO to Mercury, ESA built a third spacecraft, the Mercury Transfer Module (MTM). The MTM has huge solar arrays to power ion thrusters that will accomplish the hard work of setting up BepiColombo's rendezvous with Mercury. This is the first time that ESA will use solar electric propulsion on an interplanetary mission. MTM employs the full power-generating capability of its solar panels only when it's farther from the Sun than Venus's orbit; once it passes inside Venus's distance, it has to tilt its solar panels at an angle to the Sun to avoid overheating and also to limit damage from solar energetic particles.

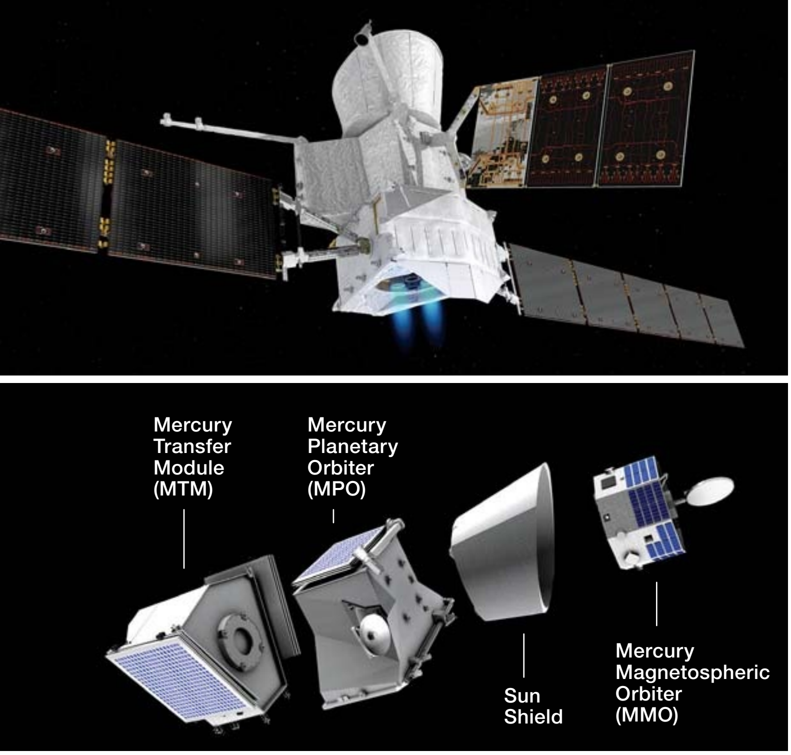


▲ **A DAY ON MERCURY** The innermost planet takes 58 Earth days to turn once around its axis, and 88 Earth days to orbit the Sun. But as seen from the planet's surface, the Sun takes far longer — 176 Earth days — to return to the same point in Mercury's sky. Thus the planet experiences one "day" every two "years."

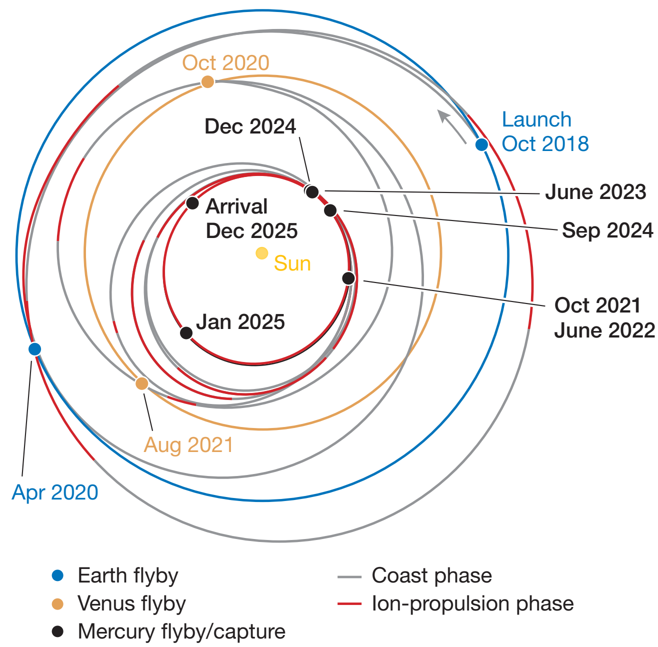
Bepi Colombo, the Man

Giuseppe "Bepi" Colombo (1920–84) was an Italian mathematician and engineer who discovered that the time it takes Mercury to rotate around its axis is two-thirds as long as its year. Before his work, astronomers had thought the planet's day was the same length as its year, 88 days. He also proposed putting NASA's Mariner 10 spacecraft in a 176-day-long solar orbit that would bring it past Mercury repeatedly, enabling the mission's three flybys.

NASA / JHU APL / CARNEGIE INSTITUTION FOR SCIENCE (2); ORBIT AND DAY DIAGRAM: SUE LEE / *THE NEW SOLAR SYSTEM*, SOURCE: ROBERT STROM (UNIV. OF ARIZONA)



▲ **COMBO SPACECRAFT** *Top:* Artist's impression of BepiColombo in cruise configuration. *Bottom:* An expanded view of BepiColombo's components. The Mercury Planetary Orbiter and Mercury Magnetospheric Orbiter (nested in the sunshield) will ride to the innermost planet with the ion-powered thrust of the Mercury Transfer Module.



▲ **SCENIC ROUTE?** To reach the innermost planet, BepiColombo has to lose orbital energy — a lot of it. The spacecraft will use gravity assists with Earth, Venus (twice), and Mercury itself (six times) to slow down enough to gently enter orbit around the iron planet in 2025.

Spacecraft propulsion alone won't be enough. BepiColombo will perform one flyby of Earth, two of Venus, and six of Mercury to tweak the shape, size, and orientation of its heliocentric orbit before settling in at Mercury in December 2025. The MTM will be dropped two months before the combination craft enters orbit. On arrival, MPO will hit the brakes so that Mercury can capture the paired craft. After many smaller maneuvers, the duo will reach MMO's desired orbit. MMO will separate, and MPO will drop to its own low-altitude circuit of the planet in March 2026. The science mission is planned to begin shortly thereafter.

▲ **HOLLOWS** Strange pits pockmark Mercury's surface, sometimes appearing in clumps several kilometers across. Individual hollows can be as small as a couple of hundred meters wide. Scientists think that the vaporization and escape of volatile compounds in the surface might explain the marks.

Unfortunately, the stacked spacecraft structure limits BepiColombo's science capability during the long cruise. MMO in particular will be hidden beneath a European-built heat shield and unable to employ its instruments. It won't be able to do any science at all until it's been captured by Mercury, where it will jettison the shield and spin up to a 4-second rotation period, using that spin to deploy its booms and redistribute heat so that it can bear the high temperatures close to the Sun.

The use of ion propulsion also constrains science observations during the voyage. The engine has to operate nearly continuously for months on end. The thrust direction and solar-panel orientation dictate the direction that the spacecraft points, so there's no possibility of pointing instruments to do observations — except when the engine is off and the craft is coasting (see diagram above).

The next seven years will not just be a waiting game, though. BepiColombo's science teams are particularly eager to test their instruments at Venus. MPO's remote-sensing instruments mostly have their eyes pressed firmly against the transfer module, but a couple of instruments (notably MERTIS) have sideways-pointed channels that will be able to take some data. And measurements of fields and particles — by the magnetometer, neutral and ion spectrometers, radio science experiment, accelerometer, and others — can be made even while the spacecraft remain stacked. Perhaps, when BepiColombo passes Venus, it will be able to do coordinated observations with another Japanese mission, Akatsuki, training its senses on one enigmatic world en route to another.

■ *S&T* Contributing Editor **EMILY LAKDAWALLA** is Senior Editor and Planetary Evangelist for The Planetary Society, and author of the recent book *The Design and Engineering of Curiosity: How the Mars Rover Performs Its Job*.

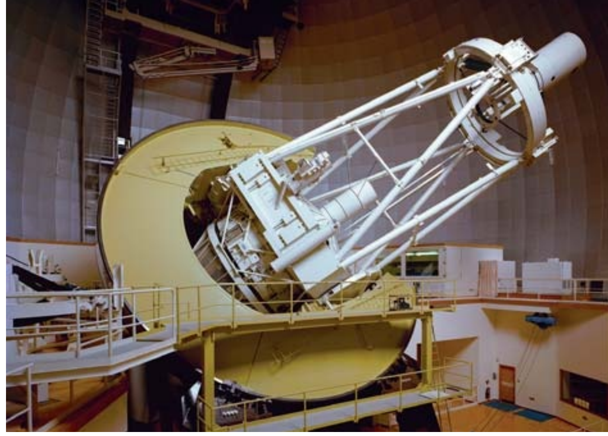
 by Antonio Peña

COLOR FROM B+W The three spectroscopic plates at left recorded with the UK Schmidt Telescope on B, V, and R spectroscopic film were combined to produce the color image of the Rho Ophiuchi nebula complex below.

When Color Came from Down Under

Astronomy had to wait nearly 100 years before one astronomer popularized the color of the universe.

The Internet makes it easy for us to enjoy impressive images of planets, nebulae, star clusters, and galaxies with just a few mouse clicks. Virtually any Messier or NGC object can be found online, usually shown with plenty of color and detail. But it wasn't always so easy. After Henry Draper and others pioneered astrophotography in the late 1800s, it took nearly a century before one individual developed a reliable technique for producing color astrophotographs that still is in use in the digital age.

▲ **GOOD OLD DAYS** *Left:* David Malin is seen in the prime focus cage of the 4-meter f/3.3 Anglo-Australian Telescope. *Right:* The AAT with its massive horseshoe equatorial mount.

New Eyes Down Under

Since most of the planet's population lives north of the equator, it's not surprising that many of the world's largest telescopes were located there until the end of the 20th century. By the 1960s, huge instruments such as the 200-inch Hale Telescope were in regular use studying the northern skies, while gems of the Southern Hemisphere such as the Magellanic Clouds and the most interesting areas of the Milky Way were inaccessible to first-class telescopes.

The need for a large telescope to scrutinize the southern skies was clear, so in 1967, the UK and Australian governments agreed to join forces to build a 4-meter-class telescope at Siding Spring, Australia. The cost to construct the Anglo-Australian Observatory (AAO) was shared by both partners, and when in operation, the telescope would be shared equally between astronomers of the two countries.

To save on development time and cost, the design of the Anglo-Australian Telescope (AAT) was based on the 150-inch telescope at Kitt Peak National Observatory in Arizona. In 1969, the AAT's 3.9-meter main mirror was cast in the U.S. and was polished one year later in the UK. The mount that would support the telescope was a huge equatorial. Today, it remains one of the largest equatorial mounts in the world.

Officially, first light for the AAT was on April 27, 1974, but the first "good" plate with the telescope was made earlier when Ben Gascoigne took a 60-minute exposure of Omega Centauri before the mirror was even aluminized. Gascoigne was responsible for much of the telescope's optical design and, later, its commissioning.

The AAT commissioning continued for more than a year, and, while there was still much to be done, it was declared ready for observing in early 1975. Routine, scheduled operation began in June.

While the AAT was in development, another instrument, the UK Schmidt Telescope (UKST) was built at Siding Spring in 1973, as an updated copy of the Palomar (now Oschin) Schmidt Telescope in California. The UKST is essentially an f/2.5 wide-field telescope with a focal length of 3 meters and an aperture of 1.2 meters. It was operated by the Royal Observatory, Edinburgh, until 1988, when AAO took over.

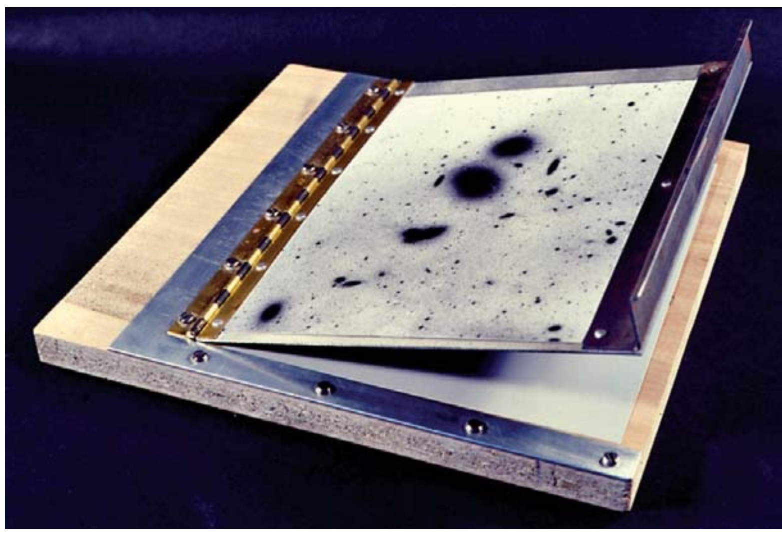
The availability of these two instruments under the southern sky had been a dream for generations of both British and Australian astronomers. A new window to a relatively unknown area of the sky had been opened.

South of the Equator

In November 1974, the journal *Nature* published an opening for staff at the AAT, including a photographic specialist. At that time, the Englishman David Malin was working in the chemical industry with optical and electron microscopes. Malin obtained many beautiful images of crystalline materials while developing his photographic prowess. When denied the position to head the lab at what was then the Geigy Company, Malin took note of the classified listing in *Nature*. Despite being woefully ignorant about the techniques of astronomical photography, he applied for the position. There was enough overlap between microscopy and astrophotography that he was offered the job. He accepted and moved his family to Australia to work as scientific photographer at AAO.

The first two years at the AAT were mainly focused on setting up the photographic support facilities. Malin was also

▼ **PLATE REGISTRATION** Malin constructed a custom superimposition frame to precisely align the individual color plates under the enlarger. A print is attached to the hinged lid to act as a positional reference for each image, which is projected through it and combined onto a sheet of unexposed film or photographic paper beneath.



ALL PHOTOS BY DAVID MALIN

responsible for establishing the *film-hypersensitizing* processes (already initiated at the UK Schmidt) to improve the sensitivity of the photographic plates. Hypersensitization reduces *reciprocity failure* of photographic materials. Reciprocity failure is a well-known characteristic of photographic emulsions, which can be understood as the effective speed of the emulsion falling dramatically during long exposures. When exposure times are in minutes (rather than the fractions of a second for snapshots), raw film does not record double the photons on the negative if it's exposed for twice the time. In the late '70s, this failure was found to be reduced by baking the plates in an oven for a few hours in nitrogen gas and then soaking them in hydrogen gas. Once hypersensitized, the plates acquire a brief shelf life and have to be exposed as soon as possible (within just a few hours!) and developed quickly to obtain optimum results.

During the mid-'70s, professional observatories collected most of their photons using photographic plates, though some electronic detectors were used for recording spectra. These plates, manufactured by Kodak, were glass sheets coated with a thin emulsion layer that was sensitive to a broad wavelength range, making them suitable for astronomy. They were very rigid and stable, though expensive, and didn't curl or buckle during long exposures like commercial film acetates. Their large size allowed them to cover 6.6° × 6.6° on a 356-mm (14-inch) square plate when exposed in the UKST. The AAT used smaller plates covering one square degree of sky.

Once exposed and developed, the plate became a negative image where the stars appear as black dots, galaxies and nebulae are gray smudges, and the sky background is a uniform gray. Astronomers preferred to study original plates, as creating a positive image does not add scientific value to an exposure, and any additional process tends to degrade the original quality. Additionally, human vision can pick out faint structures more easily on a negative image than on a positive.

All this work occurred in the black-and-white domain, but sometimes filters were employed to isolate a particular region of the visible spectrum. In general, however, the main purpose of photography with a large telescope was to study faint objects. Exposing plates directly at the focal plane of a telescope created nice monochrome images with very little information regarding an object's color.

From his earliest days working with the AAT, however, Malin was interested in obtaining color images. But telescope time for these experiments was difficult to find. He first tried to jury-rig a Hasselblad roll-film holder at AAT's prime focus in May 1976. Two months later, he stuck large sheets of color negative film onto blank glass plates to make color exposures.

Unfortunately, color film had some characteristics that made it inefficient for astronomical use — the lack of contrast and non-uniform spectral response being the most obvious. Also, color films intended for daylight snapshots suffered from reciprocity failure and did not work well with long exposures.

The tests with color film were interesting, but the low contrast and weird color balance convinced Malin that this was not the correct approach. The solution, it turned out, had already been proposed more than a century earlier.

In 1861, the Scottish scientist James Clerk Maxwell had presented the fundamentals of color synthesis and photography in a famous lecture at London's Royal Institution. In trying to understand the process of color vision, he showed that color pictures could be made by registering three positive, monochrome images on a screen that were projecting through the same color filters used to take the images. The most realistic images were those taken and projected through red, green, and blue filters. Maxwell had established the basis of both color photography and color vision, and is considered to be the father of color photography. Now Malin had to apply it to astrophotography.

Tricolor Photography

Malin realized that the most promising option to extract color from the objects in the universe was to use a modification of Maxwell's additive three-color process in the astronomical arena. This required three plates of the object (and

▶ **TECHNICOLOR GLORY** Before the 1980s, color photographs of deep-sky objects were a rare treat to come across. It wasn't until David Malin perfected the technique of combining B, V, and R spectroscopic plates as blue, green, and red images that dazzling color pictures of objects became possible, like this portrait of the Zeta Orionis region in Orion captured with the UK Schmidt Telescope.

three times more telescope time than what was required for a monochrome image). As this was unachievable with the limited telescope time available, Malin decided to use as much archival material as possible. This approach took advantage of monochrome plates made for photometric work using the standard astronomical B, V, and R photometric system to create a realistic RGB color image. The decision enabled the acquisition of plates to fit into the normal routine of the telescopes. This meant that plates obtained for variable-star photometry or supernova studies could also be used to produce color images. As a bonus, there were already many previously exposed B and V plates; only an additional R-band plate was required to complete a color composite. These could often be obtained in twilight at both ends of the night.

The original plates were obtained using Kodak spectroscopic emulsions and Schott glass filters. Going forward, all the plate batches were tested to characterize their long-exposure sensitivity to establish the best exposure time for each color band, typically between 40 and 60 minutes for each type of hypersensitized photographic emulsion.

After some time experimenting with darkroom procedures, Malin established a technique to make positive copies of the plates by controlling contrast, density, and dynamic range during the chemical processing. Then, the three copies were overlaid sequentially by projection on color-sensitive photographic paper using an enlarger with red, green, and blue filters for the appropriate exposures. A simple frame permitted aligning the projections. The process could be performed in less than 15 minutes.

Malin successfully applied Maxwell's tricolor composition technique using monochrome plates from one of the best astronomical telescopes in the Southern Hemisphere. And he did it more than 100 years after Maxwell presented his theory about color photography.

The technique allowed Malin to create a number of images from the late '70s through the mid-'80s when he had access to the AAT and plates from UKST. Nebulae and galaxies were shown in their natural colors, and a chromatic explosion began appearing in magazines. Color images also made it possible to visualize some astrophysical processes for the first time.

The photographs were not only useful for science, but also in promoting the beauty of astronomy. Color psychology did its work, and suddenly, everybody wanted color photographs of the universe. People unconnected to astronomy felt attracted to those images, combining familiar color and distant splendor.

All this extraordinary dynamism of color developed in the analogue processes of chemical photography in the late '70s, converging just before an emerging technology rose to the forefront. The charge-coupled device (CCD) and computerized image processing were on the horizon, which together would change photography and astronomy forever. Chemical processing, glass plates, and a lot of hypersensitization gear were leaving observatories as the digital age ushered in a new order where color images are much easier to obtain and process.

However, some things haven't changed. Tricolor imaging through red, green, and blue filters is still the preferred system for recording the best deep-sky images by amateur astrophotographers and professional astronomers alike.

Malin's images played a big part in popularizing astronomy in the late '70s and '80s thanks to the enigmatic attraction of color over all of us. This is one major legacy of his work.

▶ **GALACTIC FIREWORKS** Because many B and V plates were recorded for spectroscopic studies, the R (red) plates needed to complete the color set were often recorded several months or even years later. The B and V exposures of this photograph of Centaurus A were recorded shortly after the discovery of a supernova in its dust lane, but poor weather delayed the exposure of the red plate until long after the star had faded, resulting in the odd blue-green star.

◀ **COLOR EXPLOSION** Recorded over several months in 1979 with the UKST, this deep image of M20 (top), M8 (right), and NGC 6559 (left) was the best natural color photo of the field at the time.

■ **ANTONIO PEÑA** is an engineer working in the European aerospace industry. In his free time, he images the night sky with a Ritchey-Chrétien telescope and DSLR camera with lenses. He is grateful to Dr. Malin for his help and support while researching this article.

In Search of Extragalactic Globulars

What's the farthest star ball you can see with an amateur telescope? Start your hunt outside the Milky Way.

The Milky Way is home to roughly 160 globular clusters, spread around the galactic halo and toward the central bulge. These densely packed stellar spheres formed roughly 10 billion years ago and contain tens to hundreds of thousands of gravitationally bound stars. As ancient relics of the Milky Way, they offer important astrophysical clues to stellar evolution and dynamics, as well as to galactic formation and later accretion events. And, of course, they're among the most breathtaking sights in the sky.

The number of globular clusters in a host galaxy correlates strongly with the galaxy's luminosity. The supergiant elliptical M87 boasts an estimated 12,000 clusters while ubiquitous low-luminosity dwarf galaxies contain at most a few. Within the more than 100 nearby galaxies that comprise our Local Group, M31 commands the largest collection, with more than 500 confirmed globulars. But how many of these can you see with an amateur scope? Let's head outside the Milky Way and explore some of the globulars in our galactic neighbors.

A few words of caution: Extragalactic globulars lack the optical impact of familiar ones in the Milky Way so are best appreciated with your mind as well as your eyes. Consider M13, arguably the Northern Hemisphere's finest globular. If it were located at the distance of the Andromeda Galaxy, it would appear as a 16th-magnitude speck! So as you observe, take time to contemplate the astrophysical importance and true grandeur of these globulars — it will make the hunt much more enjoyable.

Our first stop is the well-studied Large Magellanic Cloud (LMC), which lies at a distance of 165,000 light-years. It boasts 16 ancient metal-poor globulars along with 100 "intermediate-age" (1–3 billion years) massive clusters. You'll need to observe these from the Southern Hemisphere, but if you have the opportunity, exploring the cluster- and nebula-rich fields of the LMC is an unforgettable experience. My observations were made under dark transparent skies in rural Australia.

▲ **SMALL SPARKLER** In amateur scopes, extragalactic globular clusters like NGC 1835 remain unresolved. This Hubble Space Telescope image reveals the 11th-magnitude cluster's core. NGC 1835 is the brightest globular in the Large Magellanic Cloud.

NASA / ESA / HUBBLE LEGACY ARCHIVE

Scottish-born astronomer James Dunlop spied **NGC 1835** in 1826 using his homemade 9-inch speculum metal reflector at Parramatta, near Sydney, Australia. He called it "a small round pretty well-defined nebula, bright at the centre." Dunlop's copper-tin alloy mirror was equivalent in light-gathering to a modern 6.5-inch telescope, but his description applies to most of the LMC globulars — they appear compact and unresolved, with strongly concentrated cores and faint smooth envelopes. NGC 1828 and NGC 1830, both smaller and fainter open clusters, lie in the same field of view, a common occurrence in the LMC.

Eight years later John Herschel began a monumental survey of the southern sky from Cape Town, South Africa, and discovered **NGC 1916** along the central bar of the LMC. This compressed globular sports a prominent central hub and a 40″ halo.

Although relatively bright, NGC 1916 is outclassed by **NGC 1903**, a gorgeous open cluster just 8′ to its northwest. NGC 1903 masquerades as a globular cluster, but studies yield a relatively youthful age of less than 100 million years. A 24-inch scope revealed a 20″ blazing core encased in a 1′ halo studded with nearly two dozen glittering stars. Northwest of NGC 1903 is NGC 1910, a large star cloud containing **S Doradus**, the prototype of a class of extremely massive, highly evolved stars called *luminous blue variables*. With a mean magnitude of approximately 9.5, S Doradus is the single brightest star in the LMC.

Argentinean astronomer José Luis Sérsic discovered the **Reticulum Cluster** in 1973 on plates taken with the 0.7-m Maksutov camera of the Cerro El Roble Observatory in Chile. He described it as a "Dwarf in Reticulum, probably a member of the Local Group." Later photometric investigations demonstrated it was a highly extended, low-luminosity globular. The LMC holds a tenuous grip on the Reticulum Cluster as it lies at the extreme limits of its halo. One day it may be snatched by the Milky Way's gravitational pull.

P. HORÁLEK / ESO

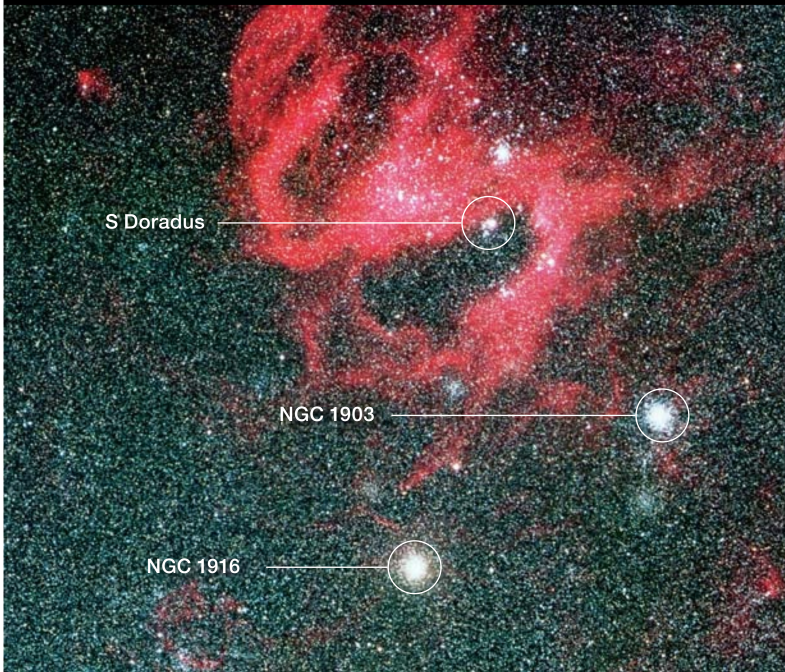
OUTLOOK CLOUDY As this view captured in the Atacama Desert of Chile shows, it's worth a trip to observe in the Southern Hemisphere. The Large and Small Magellanic Clouds are at the right of the frame. The bright star Canopus blazes above them.

Observing with a 14-inch scope, I found a large 3′ glow with a terribly low surface brightness and no noticeable concentration. As a bonus, the cluster is situated 1.3° west-northwest of NGC 1672, a showpiece barred spiral that lies far in the background at 60 million light-years.

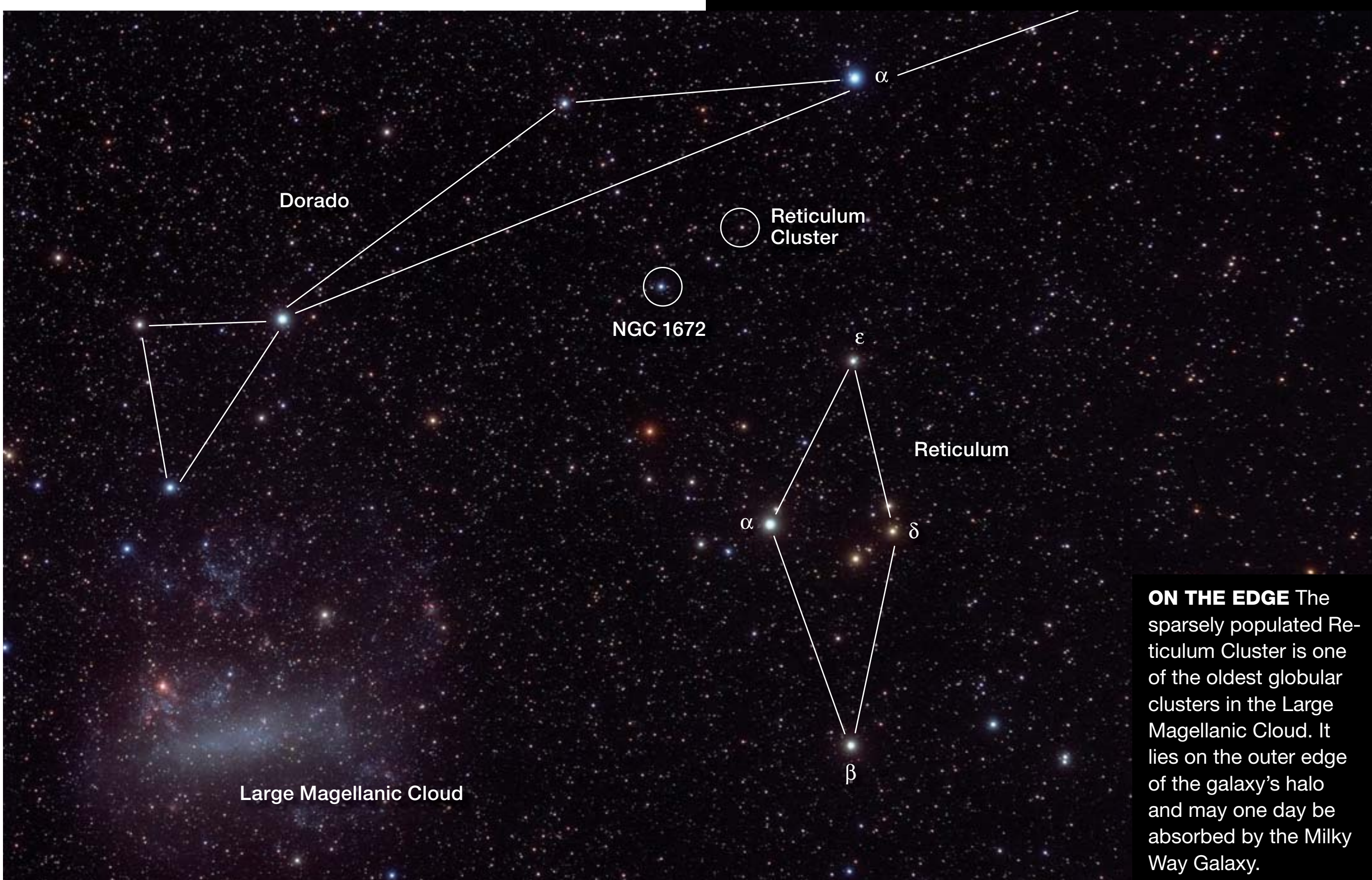
NGC 121 is the only classical globular cluster in the Small Magellanic Cloud, though its age is at least two billion years younger than its counterparts in the Milky Way and LMC. In 1998 it became the first extragalactic globular in which *blue stragglers* were detected by the Hubble Space Telescope (HST). These unusual stars are both bluer (hotter) and brighter than stars at the main-sequence turnoff point and are thought to be the result of a binary merger or mass transfer with a companion star.

Shining at a respectable 11th magnitude, NGC 121 stood out well through a 12-inch scope, with a 1′ oval halo that intensified to a conspicuous core. I found it nearly impossible, though, to pry my eyes off the spectacular globular **47 Tucanae** (NGC 104), just ½° south in the same low-power field. This duo provides a dramatic depth of field, with 47 Tucanae fifteen times closer than NGC 121!

Our next stop is the Fornax Dwarf Spheroidal Galaxy (Fornax dSph), a Milky Way satellite at a distance of 470,000 light-years. It escaped detection until 1938, when Harlow Shapley noticed it on a 24-inch Bruce astrograph plate taken at Harvard's Boyden Station in South Africa. Although the



▲ **SERPENTINE SETTING** N119, a twisted swath of ionized hydrogen associated with the star cloud NGC 1910, contains several luminous stars, including S Doradus, the brightest star in the Large Magellanic Cloud. Globular clusters NGC 1916 and NGC 1903 shimmer nearby.



ON THE EDGE The sparsely populated Reticulum Cluster is one of the oldest globular clusters in the Large Magellanic Cloud. It lies on the outer edge of the galaxy's halo and may one day be absorbed by the Milky Way Galaxy.

N119: ESO; RETICULUM CLUSTER: AKIRA FUJII integrated magnitude is an impressive 8.0, don't be misled; the light is spread out over ½° of sky and its anemic surface brightness, along with a low elevation (declination –34.5°), conspire to make the Fornax Dwarf a formidable visual target. My only convincing view was from the Southern Hemisphere when the galaxy was high overhead. Even then, I only noticed a subtle brightening confirmed by tracing around the galaxy's periphery.

The galaxy itself may be barely detectable, but four of its five globulars can be seen through a 10-inch scope (my comments are based on the view through a 13-inch). John Herschel found **NGC 1049** (Fornax 3), the brightest and most massive cluster, 103 years prior to Shapley's discovery. He reported seeing an object "pretty bright; small; round; like a star 12th magnitude a very little rubbed at the edges, a curious little object and easily mistaken for a star, which, however, it certainly is not." That reads pretty close to my own notes at 166×: "moderately bright, small (about 30″ diameter), very small bright core with a faint halo." Look for this 12.6-magnitude globular 15′ north of 8th-magnitude HD 16690.

While examining additional plates taken from Boyden Station, Shapley also discovered the globular clusters **Fornax 2** (visual magnitude 14.1) and **Fornax 4** (13.6). Fornax 2 is an easy 25′ star hop to the southeast of 5.8-magnitude Lambda^2 (λ^2) Fornacis, but it only appeared as a gauzy 20″ spot of uniform low surface brightness.

Fornax 4 is a strange beast. Although ancient stars dominate the other clusters, Fornax 4 is younger by 2 to 3 billion years. Furthermore, its central position suggests Fornax 4 may be the actual core of the Fornax Dwarf, but its radial velocity and population indicate it's a legitimate globular coincidentally in our line of sight to the center. I noted a hazy 20″ patch rising suddenly to a small, brighter core.

In the late 1950s Paul Hodge (University of Washington) added the outer halo globulars Fornax 1 and **Fornax 5** using plates taken in South Africa with the Armagh-Dunsink-Harvard (ADH) Baker-Schmidt telescope. Fornax 5 resembles Fornax 4, with a tight luminous core and a thin fainter halo. Look for it 13′ west of 7.3-magnitude HD 17060 and 10′ northeast of a string of four stars that point the way to the globular. With a visual magnitude of 15.6, Fornax 1 is easily the most challenging of the five globulars. Good luck!

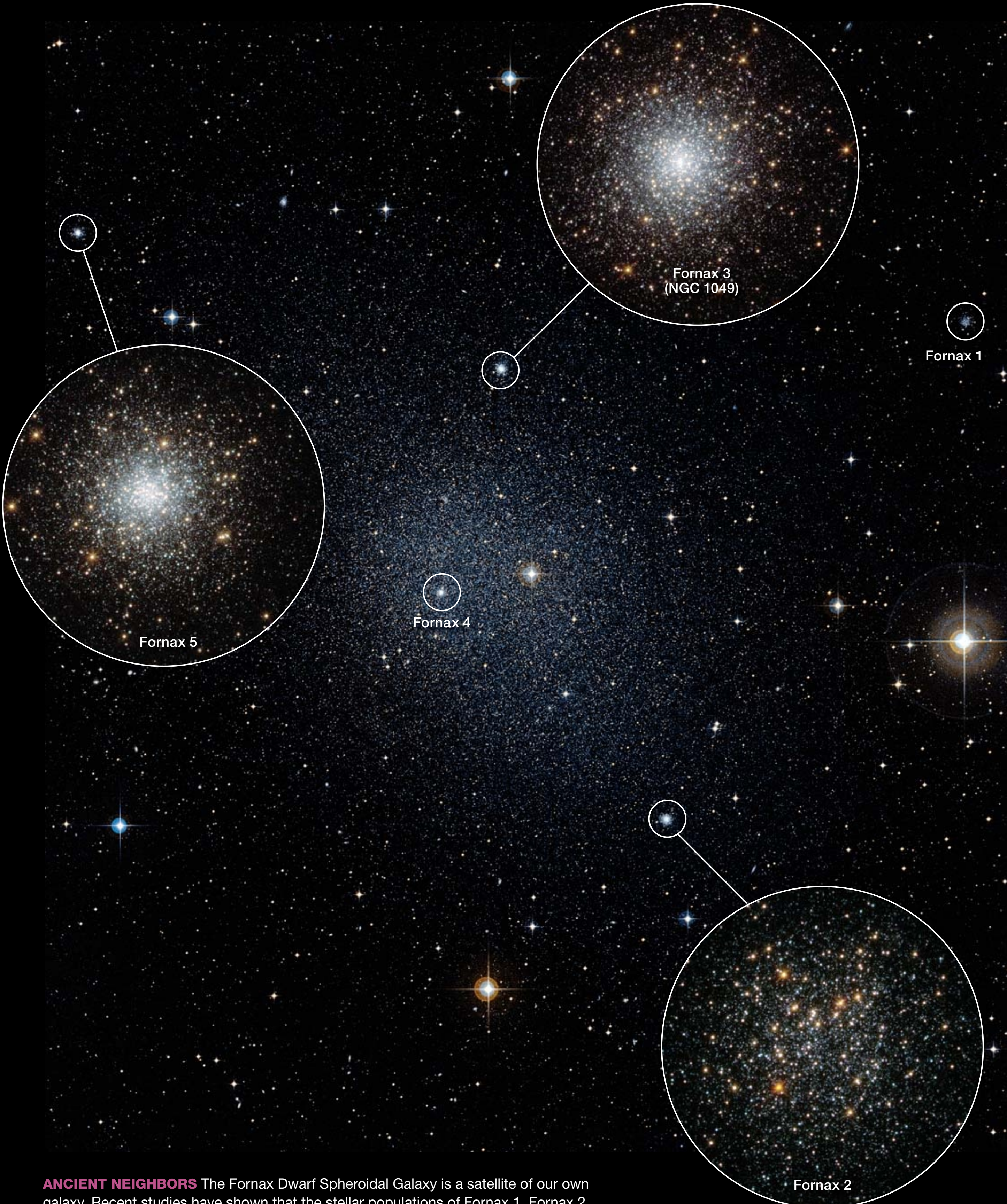
Legendary observer E. E. Barnard swept up **NGC 6822** (Barnard's Galaxy) in 1884 using his 5-inch Byrne refractor. The galaxy gained fame in 1925 when Edwin Hubble discovered 15 variable stars in it, including 11 Cepheids. Using Henrietta Leavitt's relationship between the period and luminosity of Cepheids, Hubble announced NGC 6822 as "the first object definitely assigned to a region outside the galactic system." Extragalactic astronomy was now firmly established. Modern studies place the distance at 1.6 million light-years, making it an isolated member of the Local Group.

While examining NGC 6822 Hubble also found 10 nebulous objects (five giant emission nebulae and five compact objects) that he labeled with Roman numerals I through X. He doubted any of these were globulars, but later studies proved **Hubble VII**, buried near the center, was a bona fide 16th-magnitude globular with an age of 10 to 11 billion years.

It took a painstaking search in 2010 using my 18-inch reflector in superb conditions just to glimpse Hubble VII as

NGC 121: NASA / ESA / HST / STEFANO CAMPANI; 47 TUCANAE: ESO / M.-R. CIONI / VISTA MAGELLANIC CLOUD SURVEY / CAMBRIDGE ASTRONOMICAL SURVEY UNIT

▲ **BLAZES OF GLORY** *Left:* The only classical globular cluster in the Small Magellanic Cloud, NGC 121 glitters with an abundance of hot, blue stars. NGC 121 lies about 200,000 light-years from Earth in the direction of the constellation Tucana. *Right:* Visually, the globular cluster 47 Tucanae appears to be a close neighbor to NGC 121; only ½° separates the pair in the sky from our point of view. But in fact, with a distance of about 13,500 light-years, 47 Tucanae is some 15 times closer to us than NGC 121.



FORNAX GALAXY: ESO / DSS2; NGC 1049, FORNAX 2, AND FORNAX 5: NASA / ESA / S. LARSEN (RADBOUD UNIVERSITY)

ANCIENT NEIGHBORS The Fornax Dwarf Spheroidal Galaxy is a satellite of our own galaxy. Recent studies have shown that the stellar populations of Fornax 1, Fornax 2, Fornax 3, and Fornax 5 are dominated by metal-poor stars more than 10 billion years old, while Fornax 4 is formed of younger, metal-rich stars.

a dim smudge. I thought Hubble VII would be my last globular sighting in the galaxy. But in 2011 a wide-field imaging survey with the Canada-France-Hawaii Telescope (CFHT) uncovered four new halo globulars in NGC 6822 designated SC1–SC4. Two years later, three more globulars (SC5–SC8) were identified using archival CFHT/MegaCam data. New globulars and a new challenge!

SC7 (not to be confused with Hubble VII) lies outside the visual boundary of NGC 6822, 22′ northeast of center, making a positive identification much easier. At 375× in my 24-inch, I immediately noticed a swollen 15th-magnitude "star" about 6″ to 8″ in diameter. The globular could be held steadily and seemed to have a brighter stellar nucleus.

SC6 is over a half-magnitude fainter than SC7 and a much tougher catch due to a brighter 14th-magnitude star at its north edge. I needed 500×, good seeing, and a healthy dose of patience to tease out an occasional stellar sparkle.

Hunting globulars in M31 is a popular project for seasoned deep-sky observers. I've tallied 45 (mostly with an 18-inch) along with 10 open clusters. Three of the brightest — G76, G78, and G280 — are close to magnitude 14.3 and readily accessible in a 10-inch under dark skies. Contributing Editor Alan Whitman covered these and many more in his article on M31 (*S&T:* Nov. 2013, p. 58).

In 1932 Hubble charted 140 nebulous objects in M31 found on 100-inch Hooker telescope plates and tentatively identified these as globulars based on "their forms, structure, colors, luminosities, and dimensions." Hubble missed **G1** (also called Mayall II), the most luminous globular in the Local Group, as it resides in M31's halo, 2.5° southwest of center at a projected separation of 130,000 light-years. A kinematic study of G1's nucleus in 2002 using the HST's Imaging Spectrograph provided strong evidence that it houses a 20,000-solar-mass black hole.

But is G1 a true globular cluster? With more than twice the mass of Omega Centauri (the Milky Way's heftiest globular), G1 may be the remnant core of a stripped dwarf galaxy that was digested by M31 earlier in its history.

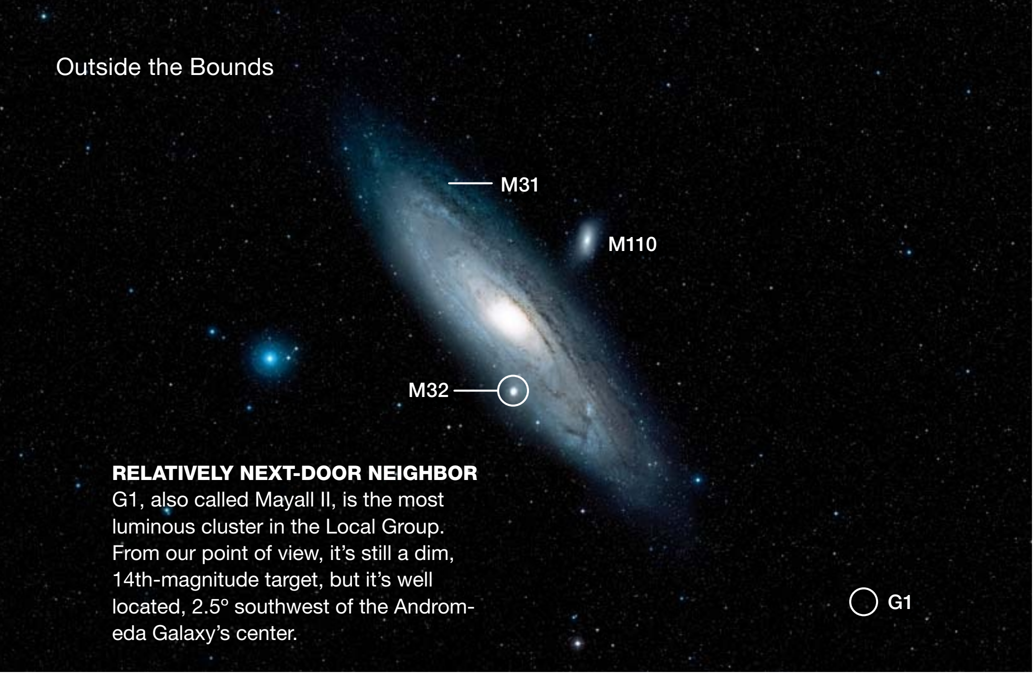
I've seen 13.8-magnitude G1 with only an 8-inch scope, though two 14th- to 15th-magnitude stars on the west edge confuse the view at low power. Using 323× in my 18-inch, G1 was easily visible as a 10″ puffball punctuated by a star-like nucleus, and the two nearby foreground stars form a cute pair of "Mickey Mouse" ears.

Recently, astronomers have found a cache of new globulars in the extreme outer halo of M31. **Martin-GC1** (MGC1) was discovered in 2006 during a CFHT/MegaCam survey, a whopping 8.6° south of M31 in the constellation Pisces! A 2009

Extragalactic Globulars & Friends

Galaxy	Galaxy Type	# of GCs	GC	Mag(v)	RA	Dec.	Notes
LMC	Irr	16	NGC 1835	10.2	$05^h 05.1^m$	–69° 24′	Milky Way satellite
			NGC 1916	10.4	$05^h 18.6^m$	–69° 24′	
			NGC 1903	11.9	$05^h 17.4^m$	–69° 20′	Open cluster
			S Doradus	8.6–11.5	$05^h 18.3^m$	–69° 15′	Variable star
			Reticulum Cluster	14.7	$04^h 36.2^m$	–58° 52′	
SMC	dIrr	1	NGC 121	11.2	$00^h 26.8^m$	–71° 32′	Milky Way satellite
Milky Way	SBbc	160	47 Tucanae	4.1	$00^h 24.1^m$	–72° 05′	
Fornax Dwarf	dSph	5	NGC 1049	12.6	$02^h 39.8^m$	–34° 15′	Milky Way satellite
			Fornax 2	14.1	$02^h 38.7^m$	–34° 49′	
			Fornax 4	13.6	$02^h 40.1^m$	–34° 32′	
			Fornax 5	13.6	$02^h 42.4^m$	–34° 06′	
NGC 6822	dIrr	8	SC 7	14.8	$19^h 46.0^m$	–14° 33′	Local Group Member
			Hubble VII	16.3	$19^h 44.9^m$	–14° 49′	
			SC 6	15.3	$19^h 45.6^m$	–14° 41′	
M31	Sb	> 500	G1	13.8	$00^h 32.8^m$	+39° 35′	Local Group Member
			Martin-GC1	15.5	$00^h 50.7^m$	+32° 55′	
			PAndAS-53/54	15.5	$01^h 18.0^m$	+39° 15′	
WLM	dIrr	1	WLM-1	16.1	$00^h 01.9^m$	–15° 28′	Local Group Member
Sgr Dwarf	dSph	4	M54	7.7	$18^h 55.1^m$	–30° 29′	Milky Way satellite

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.



RELATIVELY NEXT-DOOR NEIGHBOR G1, also called Mayall II, is the most luminous cluster in the Local Group. From our point of view, it's still a dim, 14th-magnitude target, but it's well located, 2.5° southwest of the Andromeda Galaxy's center.

▲ **CRYPTIC CLUSTER** G1 is the brightest globular cluster in the Local Group. It consists of more than 300,000 stars. Current research suggests that G1 could be a remnant galactic core and may have an intermediate-mass black hole at its center.

study using the Gemini Multi-Object Spectrograph found MGC1 was the most isolated globular in the Local Group at a galactocentric distance from M31 of 650,000 light-years.

Last year I tracked down this 15.5-magnitude globular using my 24-inch reflector at 260×. Upping the magnification to 500×, I held it continuously as a fuzzy 8″ glow. It was barely smaller than G1 and had a slightly bright pip at the center.

In 2014 the Pan-Andromeda Archaeological Survey (PAndAS) announced the discovery of 59 new outer halo denizens of M31, primarily by visual inspection of CFHT/MegaCam images. **PAndAS-53** and **PAndAS-54** form an exceptionally close 2′ pair, uncovered 7° east of M31. Both are quite dim at 15.5- and 16.0-magnitude and barely nonstellar in my 24-inch. These twin globulars either formed together at the fringes of M31 or more likely were captured from an accreted dwarf galaxy.

Our most remote target is in the Wolf-Lundmark-Melotte (WLM) Galaxy, discovered by German astronomer Max Wolf on a plate taken in 1909 at the Heidelberg-Königstuhl State Observatory. Knut Lundmark and Philibert Jacques Melotte independently found this dwarf galaxy 17 years later on Franklin-Adams plates and described it as "strikingly similar" to Barnard's Galaxy. WLM is located in western Cetus at the outskirts of the Local Group, 3.1 million light-years away. As a result of its isolation, the stellar population is probably in a pristine state, uncontaminated by galactic mergers and interactions.

In an early campaign to determine the Hubble constant, Milton Humason, Mount Wilson Observatory's mule-driver-turned-astronomer, measured the radial velocity of WLM as well as a nearby cluster with a similar velocity, **WLM-1**. In 1999 Paul Hodge obtained a color-magnitude diagram for WLM-1 using the HST and established it as a massive globular more than 13 billion years old. WLM-1's formation is surprising given the dwarf's very small intrinsic mass and low luminosity.

Visually, WLM is a challenging low-contrast galaxy. Sweeping 1° northeast of 6.3-magnitude 1 Ceti with my 18-inch, I found a large, very diffuse oval, extending 10′ × 5′ north to south. At high power a 15.5-magnitude Milky Way star was superimposed on the center, and just northwest lay a tiny H II region. The globular WLM-1 is situated just off the west edge of the galaxy and 40″ south of a 14.6-magnitude field star. At 16th magnitude, I found it a difficult quarry even through a 20-inch scope, though in rock-steady seeing it seemed slightly soft, a few arcseconds in diameter.

If observing such faint extragalactic globulars is daunting, consider instead **M54**, which is visible even in 50-mm binoculars. M54 is embedded at the center of our closest neighbor, the Sagittarius Dwarf Spheroidal Galaxy (Sgr dSph), which was discovered serendipitously in 1994 during a spectroscopic study of the Milky Way's bulge. The Sagittarius Dwarf lies at a distance of 80,000 light-years on the far side of the galactic center, covers a vast area of sky, and is in the process of being shredded by the tidal strain of the Milky Way Galaxy.

Three dim globulars — Arp 2, Terzan 7, and Terzan 8 — are members of the Sagittarius Dwarf, while NGC 5634, Palomar 12, and Whiting 1 are associated with two tidal streams of stars encircling the Milky Way that were ripped from the dwarf. M54 has been proposed as the actual nucleus of the galaxy, but a 2008 investigation using velocity and metallicity data concluded M54 formed independently and plunged to its current location at 87,000 light-years distant due to dynamical friction. The Sagittarius Dwarf Galaxy is much too large and dispersed to see visually, but M54 gains new luster once you know of its extragalactic origin.

■ Contributing Editor **STEVE GOTTLIEB** is willing to explore well beyond our galaxy's limits to bag the best star clusters.

FURTHER READING: For a complete list of globular clusters in the Local Group, as well as links to recent research on the topic, see **https://is.gd/extraglobs**.

M31 FAMILY: NASA / ESA / DSS2 / DAVID DE MARTIN; G1 CLOSE-UP: MICHAEL RICH / KENNETH MIGHELL / JAMES D. NEILL (COLUMBIA UNIVERSITY) / WENDY FREEMAN (CARNEGIE OBSERVATORIES) / NASA / ESA

3–6 EVENING: Mars glides past Delta (δ) Capricorni these four evenings, brushing past the star a mere ½° away on the 4th. Follow the Red Planet this month as it passes from Capricornus into Aquarius around the 10th and thereafter climbs farther into the Water Bearer.

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

11 DUSK: Look toward the southwest to see Saturn and the waxing crescent Moon, less than 4° apart.

12 EVENING: Algol shines at minimum brightness for roughly two hours centered at 8:10 p.m. EST; see page 51.

14 DAWN: Find the bedazzling pair of Venus, the Morning Star, and Spica, the brightest star in Virgo, in the east-southeast before sunrise. Only 1° will separate the planet and the star.

15 EVENING: After sunset, look south to see the just-past-first-quarter Moon hang 3° lower right of Mars.

17 ALL NIGHT: The weak Leonid meteor shower peaks in the early evening, but best chances for seeing meteors are in the early morning hours.

23 EVENING: The Moon, just past full, and Aldebaran rise less than 3° apart in the east-northeast. The distance between them grows as they rise higher into the sky.

29 MORNING: Regulus, Leo's front paw, will be about 2° lower right of the Moon, just shy of last quarter, in the hours before sunrise. Closer to dawn, Venus is retreating from Spica, but is still only 5° left of Virgo's brightest star.

29–30 NIGHT: Algol shines at minimum brightness for roughly two hours centered at 10:04 p.m. PST (1:04 a.m. EST).

Stephan's Quintet, a group of galaxies in Pegasus, is a bit of a misnomer: NGC 7320, the spiral in the upper left of the image, is a foreground galaxy some seven times closer than the other four.

NASA / ESA / SM4 ERO TEAM

NOVEMBER 2018 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	

NEW MOON
November 7
16:02 UT

FIRST QUARTER
November 15
14:54 UT

FULL MOON
November 23
05:39 UT

LAST QUARTER
November 30
00:19 UT

DISTANCES

Apogee	November 14, 16^h UT
404,339 km	Diameter 29′ 33″
Perigee	November 26, 12^h UT
366,620 km	Diameter 32′ 35″

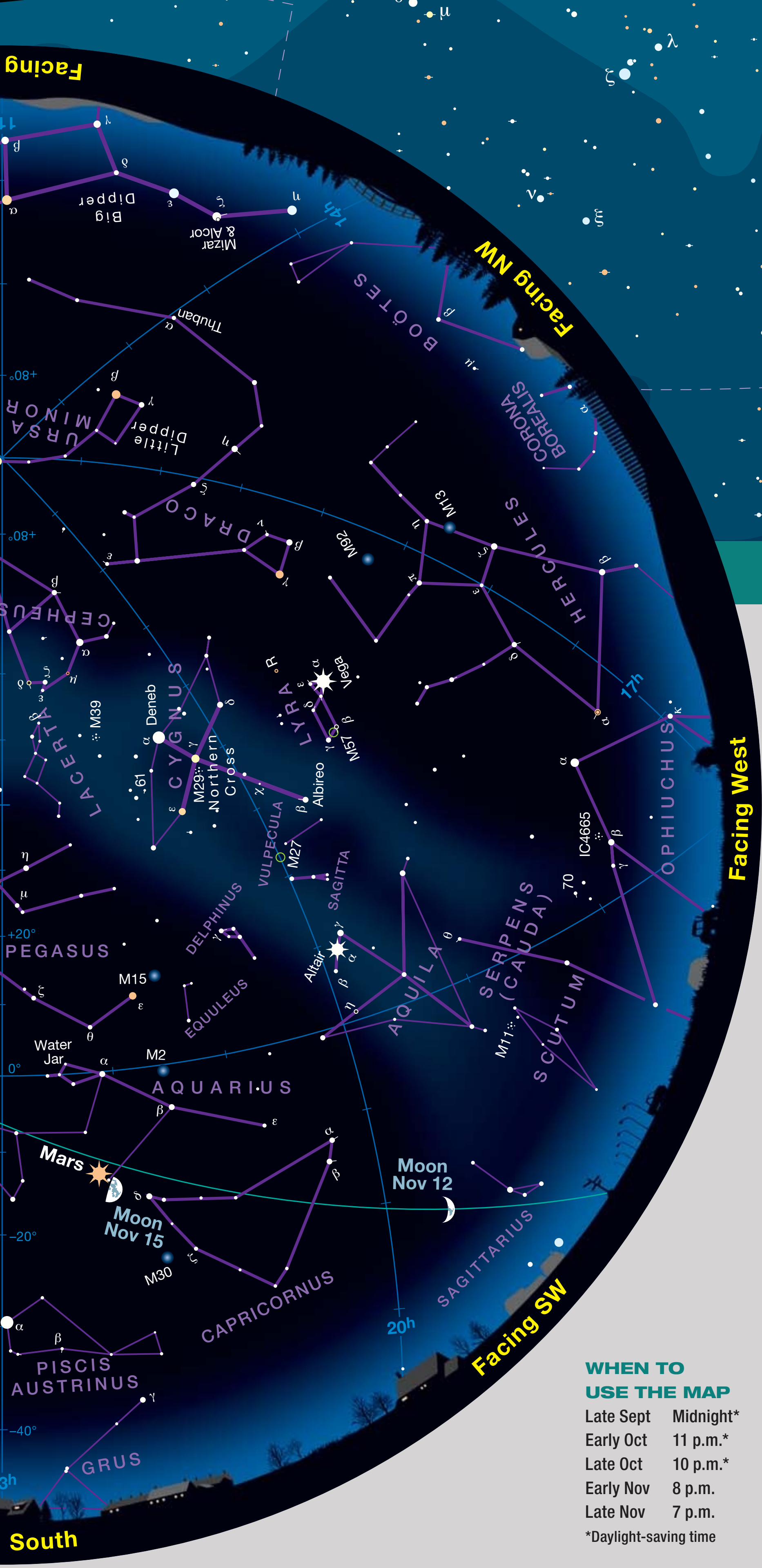
FAVORABLE LIBRATIONS

• Oken Crater	November 10
• Marinus Crater	November 11
• Galvani Crater	November 23
• Xenophanes Crater	November 24

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

*Daylight-saving time

Binocular Highlight by Mathew Wedel

Look Beyond

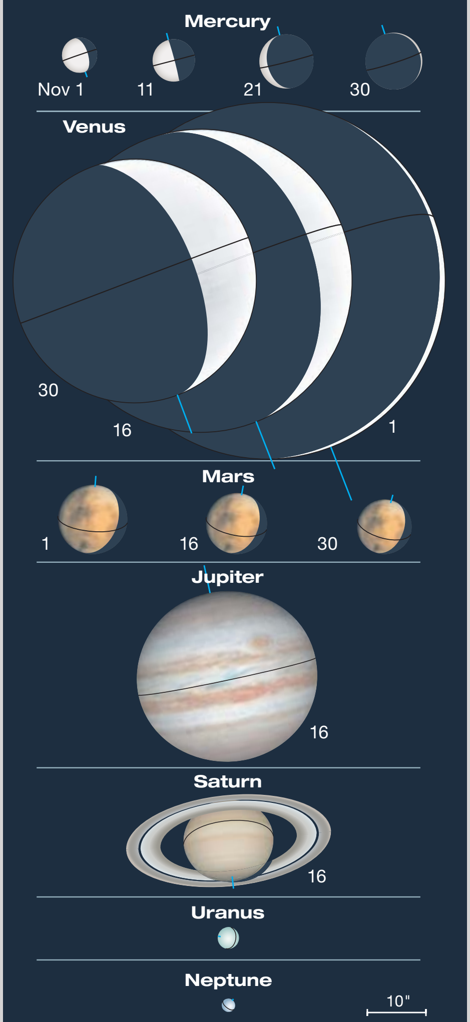
Here's a pretty puzzle to contemplate: the maybe-not-actually-a-cluster **NGC 7686**, in the far northwestern corner of the constellation Andromeda. Look for the short arc formed by the stars Iota (ι), Kappa (κ), and Lambda (λ) Andromedae. If you follow the arc to the north-northwest, about 3° past Lambda Andromedae, you'll find NGC 7686.

The first thing you'll see is a bright star with a slightly dimmer companion. The brighter one is HD 221246, a 6th-magnitude *K*-type orange-red giant, and its unrelated neighbor is HD 221203, an eighth-magnitude *G*-type yellow-orange giant. The two stars lie 900 and 1,300 light-years away, respectively. NGC 7686 lies behind them, about 5,000 light-years away. With a visual magnitude of 5.6, the cluster is brighter in total than both stars combined, but its light is spread across ¼°, or half the diameter of the full Moon. Depending on sky transparency and your level of dark adaptation, it might take a few minutes for NGC 7686 to swim into view. When it does, you'll see a halo of faint light centered on HD 221246, spangled with dimmer stars. Many of those apparent cluster members are in fact nearby field stars, less than 100 light-years away.

As for the "cluster," its reality is in doubt. There's definitely a gaggle of stars lurking out there beyond HD 221246, but it may just be a chance grouping. Still, NGC 7686 looks enough like a cluster to have caught the eyes of generations of professional astronomers, so we shouldn't feel bad for taking a look. At the very least, it gives us the opportunity to unpack some space in our heads while we behold something pretty, and that's a win in my book.

■ As much as he wants to understand the structure of the cosmos, Contributing Editor **MATT WEDEL** is still a sucker for a nice view.

PLANET VISIBILITY **Mercury:** hidden in the Sun's glow all month • **Venus:** visible at dawn all month • **Mars:** visible at dusk, sets near midnight • **Jupiter:** visible at dusk through November 7th • **Saturn:** visible at dusk, sets early evening

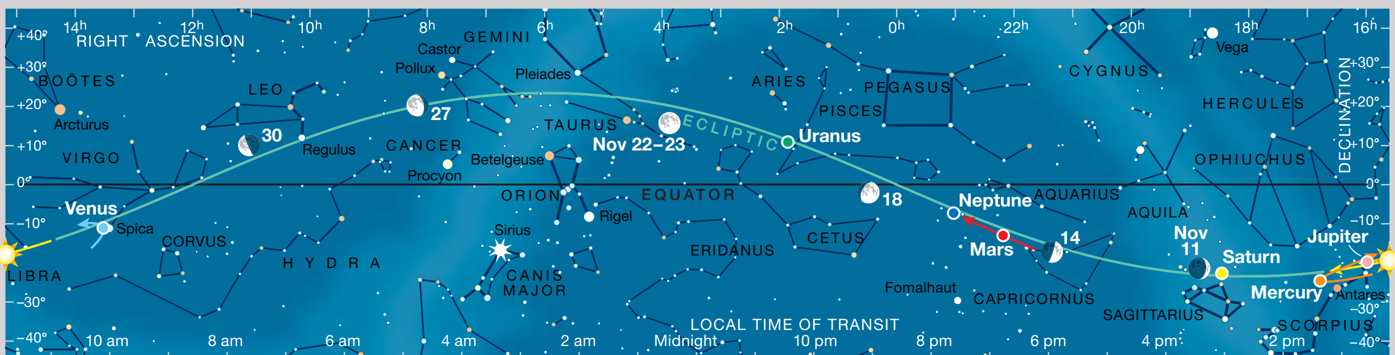


PLANET DISKS have south up, to match the view in many telescopes. Blue ticks indicate the pole currently tilted toward Earth.

November Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	$14^h\ 23.5^m$	–14° 15′	—	–26.8	32′ 14″	—	0.993
	30	$16^h\ 22.6^m$	–21° 33′	—	–26.8	32′ 26″	—	0.986
Mercury	1	$15^h\ 52.0^m$	–22° 51′	23° Ev	–0.2	6.0″	74%	1.121
	11	$16^h\ 35.4^m$	–24° 45′	23° Ev	–0.2	7.2″	52%	0.929
	21	$16^h\ 41.1^m$	–23° 22′	14° Ev	+1.5	9.2″	15%	0.729
	30	$15^h\ 58.5^m$	–18° 46′	6° Mo	+3.8	9.7″	3%	0.693
Venus	1	$13^h\ 42.8^m$	–16° 09′	10° Mo	–4.2	60.6″	1%	0.275
	11	$13^h\ 30.9^m$	–12° 22′	23° Mo	–4.6	55.3″	8%	0.301
	21	$13^h\ 33.6^m$	–10° 10′	33° Mo	–4.8	47.8″	17%	0.349
	30	$13^h\ 47.2^m$	–9° 45′	39° Mo	–4.9	41.4″	25%	0.403
Mars	1	$21^h\ 36.3^m$	–16° 42′	103° Ev	–0.6	11.9″	86%	0.788
	16	$22^h\ 09.9^m$	–13° 07′	96° Ev	–0.3	10.5″	86%	0.895
	30	$22^h\ 42.6^m$	–9° 27′	91° Ev	–0.1	9.3″	86%	1.001
Jupiter	1	$15^h\ 44.1^m$	–19° 04′	20° Ev	–1.7	31.3″	100%	6.290
	30	$16^h\ 10.7^m$	–20° 24′	3° Mo	–1.7	31.1″	100%	6.344
Saturn	1	$18^h\ 20.3^m$	–22° 47′	56° Ev	+0.6	15.7″	100%	10.577
	30	$18^h\ 32.4^m$	–22° 42′	30° Ev	+0.5	15.2″	100%	10.903
Uranus	16	$1^h\ 50.1^m$	+10° 44′	156° Ev	+5.7	3.7″	100%	18.959
Neptune	16	$23^h\ 00.6^m$	–7° 25′	110° Ev	+7.9	2.3″	100%	29.584

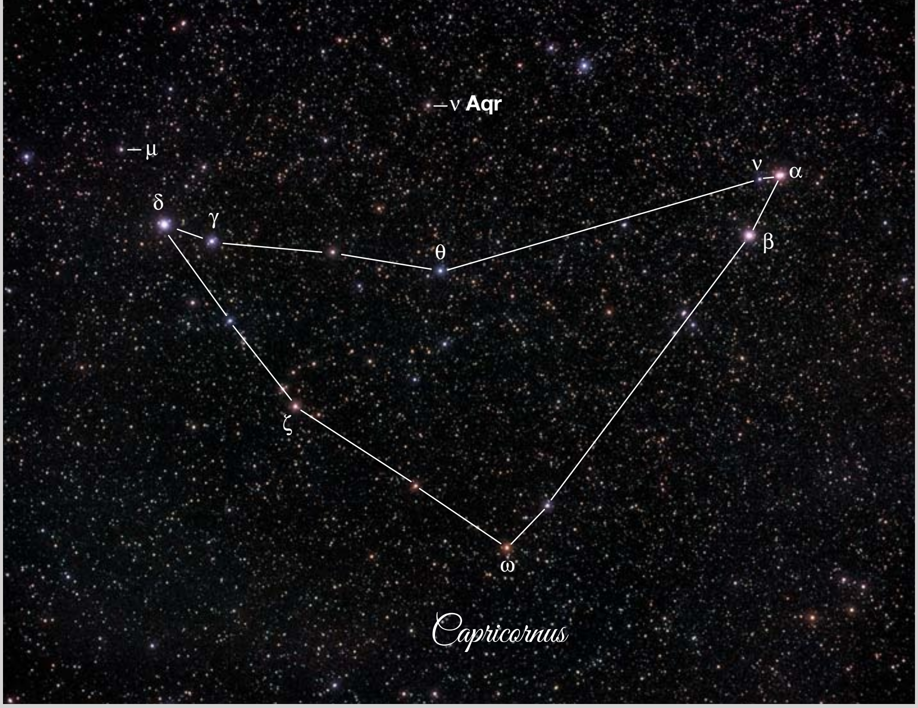
The table above gives each object's right ascension and declination (equinox 2000.0) at 0^h Universal Time on selected dates, and its elongation from the Sun in the morning (Mo) or evening (Ev) sky. Next are the visual magnitude and equatorial diameter. (Saturn's ring extent is 2.27 times its equatorial 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.com/almanac.



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

Doubles and More in Capricornus

We continue our exploration of the celestial Sea Goat — you might stumble upon some unexpected finds.



▲ **THE SEA GOAT** Look for the globular cluster M30 around 3¼° due east of Zeta (ζ) Capricorni and the planetary nebula NGC 7009 some 1¼° due west of Nu Aquarii.

Last month in this column we explored some surprising facts about the constellation Capricornus, the Sea Goat. There's much more to learn, so let's continue with our survey.

The paired (and paired paired) stars at the ends of Capricornus. The most fascinating sector of this constellation is the western end. It features Alpha (α) Capricorni — a naked-eye double star a few degrees from Beta (β) Capricorni, itself a yellow-orange and blue double for low-power binoculars. Alpha Capricorni consists of two yellow stars of magnitudes 4.3 and 3.6 that are about 6.3 arcminutes apart. The fainter star is Alpha^1 as the numbering here is based not on brightness but on right ascension; the more easterly (though brighter) star is designated Alpha^2. The same naming system is applied to Beta Capricorni; here again the dimmer star is designated Beta^1.

What's really marvelous about Alpha Capricorni is that it's an *optical double* — that is, two stars at greatly different distances that just happen to be along the same line of sight. The fainter star, Alpha^1, is 685 light-years from Earth whereas the brighter star, Alpha^2, is 108 light-years from us.

The components of Beta Capricorni appear about half as far apart as those of Alpha Capricorni. Shining at magnitudes 3.1 and 6.1, they require at least slight magnification to split and to see both components for observers with typical human vision. Beta Capricorni is known as Dabih. Both Alpha Capricorni, the pair, and Alpha^2 Capricorni, the star, are known as Algedi (or Giedi).

But there are further wonderful complications. As star expert Jim Kaler says so well: "Less than a degree east-southeast of Alpha (Algedi), actually pointed to by Algedi's two stars, lies fifth-magnitude (4.8) Nu (ν) Capricorni, the proximity with Algedi making it ridiculously easy to find." Nu Capricorni even has a proper name of its own, Al Shat.

Delving deeper for details with a good telescope, you might note that Alpha^2 has a 9th-magnitude companion 7 arcseconds away, and Alpha^1 has an 11th-magnitude companion 45 arcseconds from it.

What about the eastern end of Capricornus? Here we find, just a few degrees apart, Delta (δ) Capricorni (Deneb Algedi) and Gamma (γ) Capricorni (Nashira). Deneb Algedi shines at magnitude 2.9 and Nashira at 3.7. The two gain special attention this month as vastly brighter Mars passes less than 1° from Nashira during October 31–November 3 and again less than 1° from Deneb Algedi between November 3–5. Back on September 23, 1846, Neptune was discovered only about 4° northeast of Deneb Algedi, close to Mu (μ) Capricorni. Since then, Neptune has completed a little more than one orbit and is now in Aquarius — where Mars will catch up to it for a close conjunction next month.

Consolation for the dearth of deep-sky objects in Capricornus. If you need some help in locating Capricornus, just extend the line from Vega to Altair about one more of its own lengths onward — this brings you right to Capricornus. But there are also sights Capricornus itself can help you locate.

The constellation's only relatively famous deep-sky object other than its double stars is the globular star cluster M30, a respectably bright (7th magnitude) and interesting object. But the stars of Capricornus provide a consolation in guiding you to neighboring deep-sky objects. The marvelous Saturn Nebula (NGC 7009) is next to Nu (ν) Aquarii but is almost due east of Alpha Capricorni. About 11° from Deneb Algedi is that other famous planetary in Aquarius, the Helix Nebula (NGC 7293). Lesser objects just beyond the bounds of Capricornus include the globulars M75 and M72 (the latter near the asterism M73 and not far from the Saturn Nebula) and the elusive Barnard's Galaxy.

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

AKIRA FUJII

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

Brilliance at Dawn

Venus blazes as the "Morning Star" this month.

The evening sky is draining of bright planets. In October Venus left the evening, and now Jupiter is visible very low in the dusk only the first few days of November before it too is gone. Mercury becomes lost to those observing from northern latitudes. Saturn is moderately low in the southwest at nightfall. Only Mars is still well-placed, shining at its highest in the south just after the end of astronomical twilight, but it continues to fade and shrink in telescopes.

Fortunately the dawn sky now welcomes Venus, which leaps ever higher and brighter during November.

DUSK ONLY

Jupiter sets only about an hour after the Sun for viewers around latitude 40° north as November starts. By the end of the first week Jupiter is just a few degrees high 30 minutes after sunset — and then becomes lost from view on its way to conjunction with the Sun on November 26th.

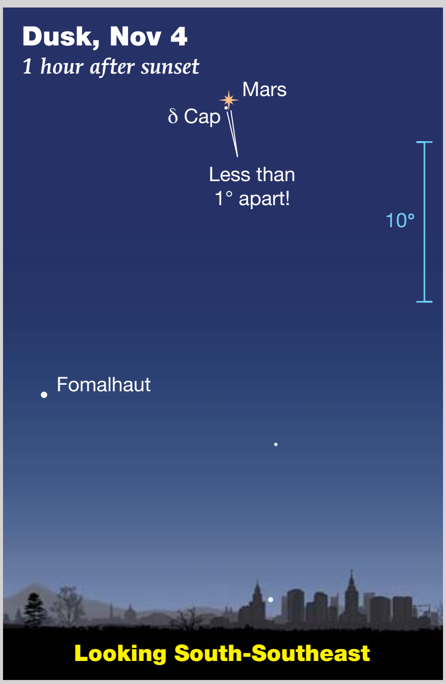
Mercury appears higher than Jupiter and more than 8° to the latter's left when it reaches greatest eastern elongation of 23° from the Sun on November 6th. But this is a low (shallowly angled) apparition of Mercury for viewers at mid-northern latitudes. On November 8th and 9th, zero-magnitude Mercury shines only about 2° from 1st-magnitude Antares — but the star and planet will be hard to see so low in the Sun's bright afterglow even with optical aid. In the following ten days or so, Mercury becomes much dimmer and lower and is lost from view. The swift planet goes through inferior conjunction with the Sun on November 27th. On that day Mercury is less than ½° from Jupiter, but the two are only about 1° from the Sun.

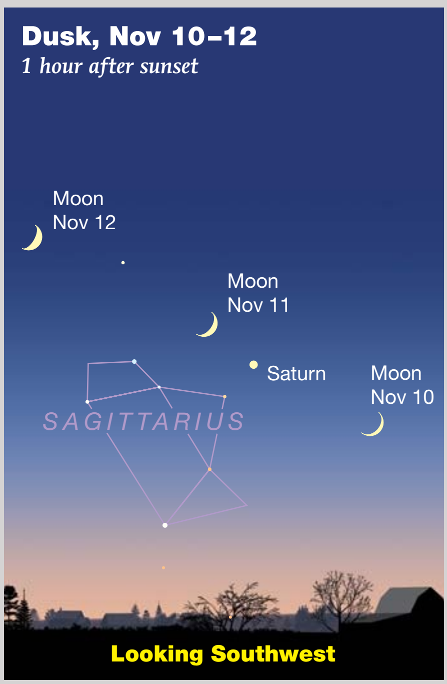
DUSK AND EARLY EVENING

Saturn begins November by setting more than 3 hours after the Sun but ends the month setting 2 hours after. The planet glows in the southwest, upper right of the setting Teapot pattern of Sagittarius. Its magnitude brightens a bit this month from +0.6 to +0.5.

DUSK TO MIDNIGHT

Mars transits the meridian around 8 p.m. daylight-saving time on November 1st and around 6 p.m. standard time on November 30th. Between these dates Mars dims from −0.6 to −0.1, and its apparent diameter decreases from 12″ to 9″. These are therefore the final





▼ 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.

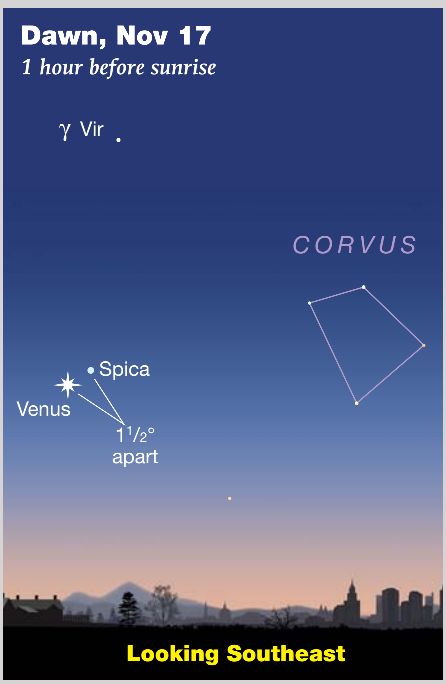
weeks that multiple surface features of Mars are likely to be visible on clear nights with good small- to medium-size telescopes. Can you detect that Mars looks slightly gibbous now that the planet is near eastern quadrature (90° east of the Sun)? Mars sets near midnight standard time all month.

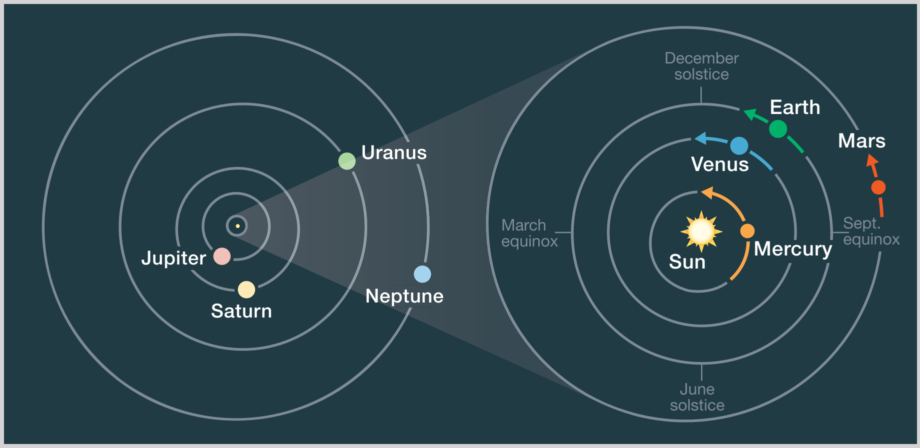
Campfire-colored Mars starts November in the vicinity of the two fairly bright stars at the eastern tip of Capricornus, Delta (δ) and Gamma (γ) Capricorni. It shines within 1° of the brighter star, 3rd-magnitude Delta, from November 3rd through 5th. Then Mars glides on to pass deep into Aquarius during the rest of November — and heads toward a close December 7th conjunction with Neptune.

This month, **Neptune** is highest about 2 hours after the end of astronomical highlight. Brighter **Uranus**, retrograding in Aries to the Pisces border, is highest in late evening. Finder charts for Neptune and Uranus appear in the September issue, pages 48–49.

ALL NIGHT

Asteroid 3 Juno reaches opposition at magnitude 7.4 on November 17th — a day after Juno's closest approach to Earth in the period 1980–2060. See p. 48 for details.





ORBITS OF THE PLANETS

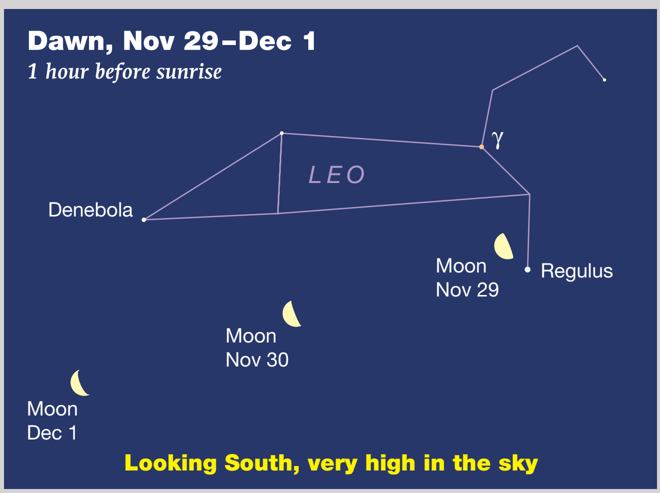
The curved arrows show each planet's movement during November. The outer planets don't change position enough in a month to notice at this scale.

DAWN AND PRE-DAWN

Venus was at inferior conjunction with the Sun on October 26th. The steep angle of the zodiac relative to the eastern horizon at autumn sunrises helps Venus rocket up into the dawn and even the pre-dawn sky during the course of November. For viewers around latitude 40° north, Venus precedes the Sun by only about 35 minutes on November 1st but by a whopping 3¼ hours on November 30th. The altitude of Venus at sunrise jumps from almost 6° to about 34° during November. In this period, the Morning Star brightens from magnitude –4.2 to its stunning peak brilliance of –4.9. How long after sunrise can you follow blazing Venus with your naked eye?

Venus is also fascinating in binoculars and telescopes this month. On November 1st, the globe of Venus is more than 60″ wide and less than 1% lit. By November 10th, the planet is less than 56″ across and more than 7% illuminated. On November 30th, Venus is down to 41″ wide and 25% lit.

Venus passed 1.2° from Spica on September 1st, but this month its retrograde motion brings it back to linger less than 1.5° from the star for the mornings of November 12–17.



MOON PASSAGES

The Moon is a thin waxing crescent in the west-southwest on November 10th at dusk, some 8° lower right of Saturn. The next evening, it's a little more than 3° upper left of the ringed planet. A waxing gibbous Moon is about 3° lower right of Mars at nightfall on November 15th. The just-past-full Moon is 2½° left of Aldebaran after dark on November 23rd, and the waning gibbous Moon is less than 2° upper left of Regulus on the night of November 28–29.

■ Contributing Editor **FRED SCHAAF** had the 10-mile-wide asteroid 7065 Fredschaaf named after him in November 2016.

Asteroid 3 Juno's irregular shape, as shown in this artist's concept, is probably the result of a collision.

An Asteroid Pays a Visit

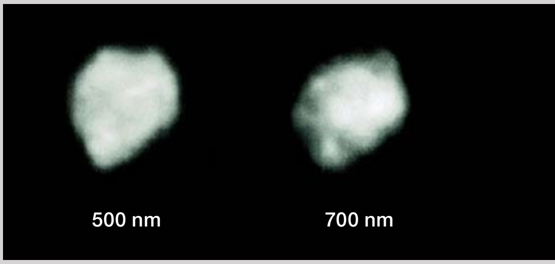
This month offers ideal viewing conditions for asteroid 3 Juno.

Asteroid 3 Juno makes its closest approach to Earth at 8:00 UT (3:00 a.m. EST) on Thursday, November 16th, and reaches opposition at 22:00 UT (5:00 p.m. EST) on the 17th. For mid-northern latitudes, the rocky body culminates around local midnight on the night of opposition, 45° above the southern horizon. If you're more of an early riser than a night owl, look for Juno about 25° above the southwest horizon before daybreak.

As the chart on the facing page shows, Juno is well placed for observing in Eridanus in November. About twelve days before opposition, the asteroid edges past the 5.3-magnitude star 35 Eridani. Juno's about 1° from 4.5-magnitude 32 Eri on the 16th and just a bit farther away from the same star on the 17th. After these encounters, the asteroid travels across a fairly sparse star field, but 21 and 22 Eri serve as good signposts in early December. Look for the dimming asteroid near 10 Tauri in mid-January.

Juno orbits the Sun every 4.4 years, and from our point of view, it offers its

▼ Images of Juno captured with the 100-inch Hooker telescope at Mount Wilson Observatory at four different wavelengths reveal the asteroid's rugged form. The possible 100-kilometer-wide crater — a region of low reflectivity — is visible in the lower left quadrant of the 833 nm and 934 nm images.

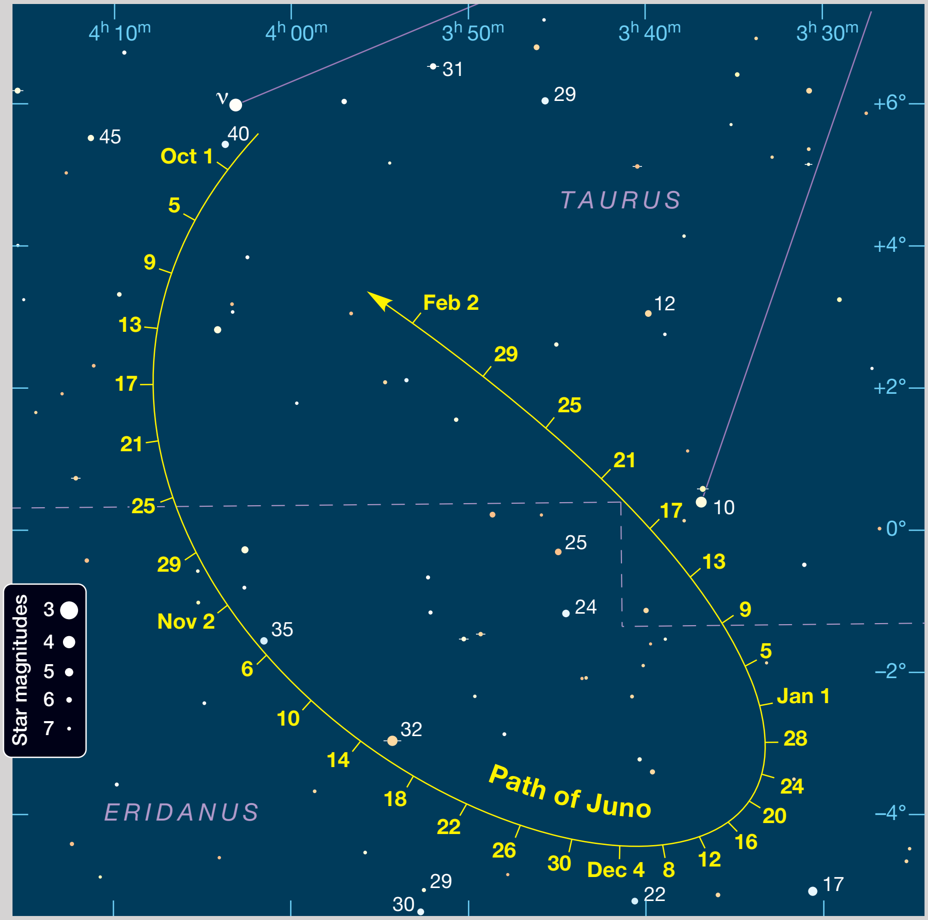


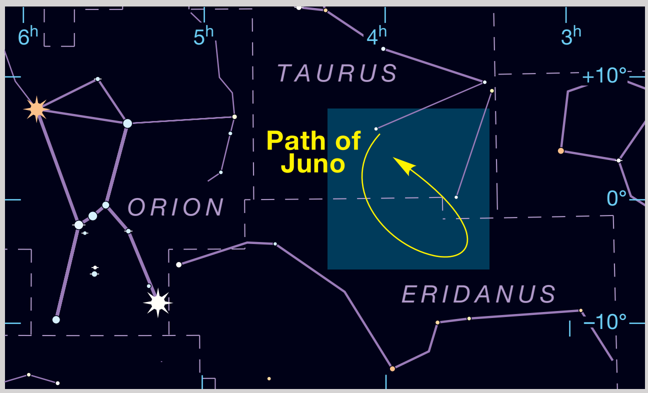
ARTIST'S CONCEPT: DAVID A. AGUILAR (HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS); JUNO IMAGES: SALLIE BALIUNAS (HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS) / MOUNT WILSON OBSERVATORY best oppositions every 13 years or so. Juno's distance from Earth at opposition depends on where it's at in its orbit, i.e., at aphelion or perihelion; we get better looks when it's nearer perihelion. During last year's closest approach, Juno was a relatively distant 2.090 astronomical units (313 million km) from us. On the 16th of this month, Juno will be 1.036 a.u. away, or only half as distant. And that's a tick closer than Juno came in 2005, when it slipped through the sky at a distance of 1.063 a.u. The next most favorable closest approach falls in 2031, when Juno will be just 1.044 a.u. from Earth.

Do these distances matter? Indeed they do. Juno has a high albedo — it's more reflective than we'd expect a stony asteroid to be — which bumps up its intrinsic magnitude. But proximity also affects visibility. Last year, Juno had an apparent magnitude of 9.8 during opposition. This year? A predicted 7.5.

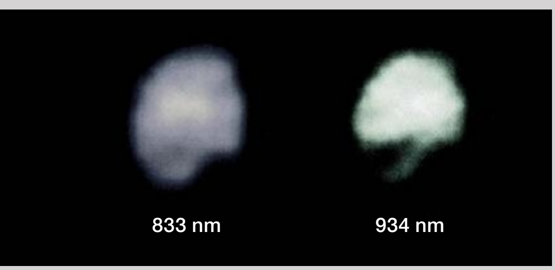
The asteroid's reflectivity and bright apparent magnitude during perihelic oppositions likely aided in its discovery. German astronomer Karl Harding picked it up on September 1, 1804, while observing from Johann Schröter's observatory near Bremen, Germany. On that evening, Juno was on its way to a September 27th closest approach of 1.17 a.u. and a visual magnitude of 7.6. This might explain why Juno, only the 11th-largest asteroid with a mean diameter of 233 km, was the third to be discovered.

Sallie Baliunas (Harvard-Smithsonian Center for Astrophysics) and colleagues took photos of Juno in 2003 at four different wavelengths using the 100-inch Hooker telescope at Mount Wilson Observatory. The resulting images led the science team to believe that the asteroid had a "bite" taken out of it by an impact (indeed, some of the silicate meteorites found on Earth may have originated from the collision). This damage shows up as a region of lower reflectivity in near-infrared wavelengths. Temperature contrasts revealed in images of Juno captured by the Atacama Large Millimeter/submillimeter Array (ALMA) in October 2014 don't exactly confirm the presence of an impact crater, but neither do they contradict it. The ten ALMA images were captured over a single 4.4-hour interval, but it takes more than 7 hours for the asteroid to rotate completely. Only 60% of the body's surface was revealed by the ALMA survey, which means we'll have to wait until a complete rotation of Juno is imaged to decide the matter more conclusively.





▲▶ The date ticks on Juno's path are plotted for 0^h Universal Time (on the evening of the previous date in the Americas). Interpolate to put a dot at the date and time you plan to observe, star-hopping there from Orion or Taurus. Juno dims from 7.5 to 8.2 by December 31st, and drops to 8.8 by the end of January.



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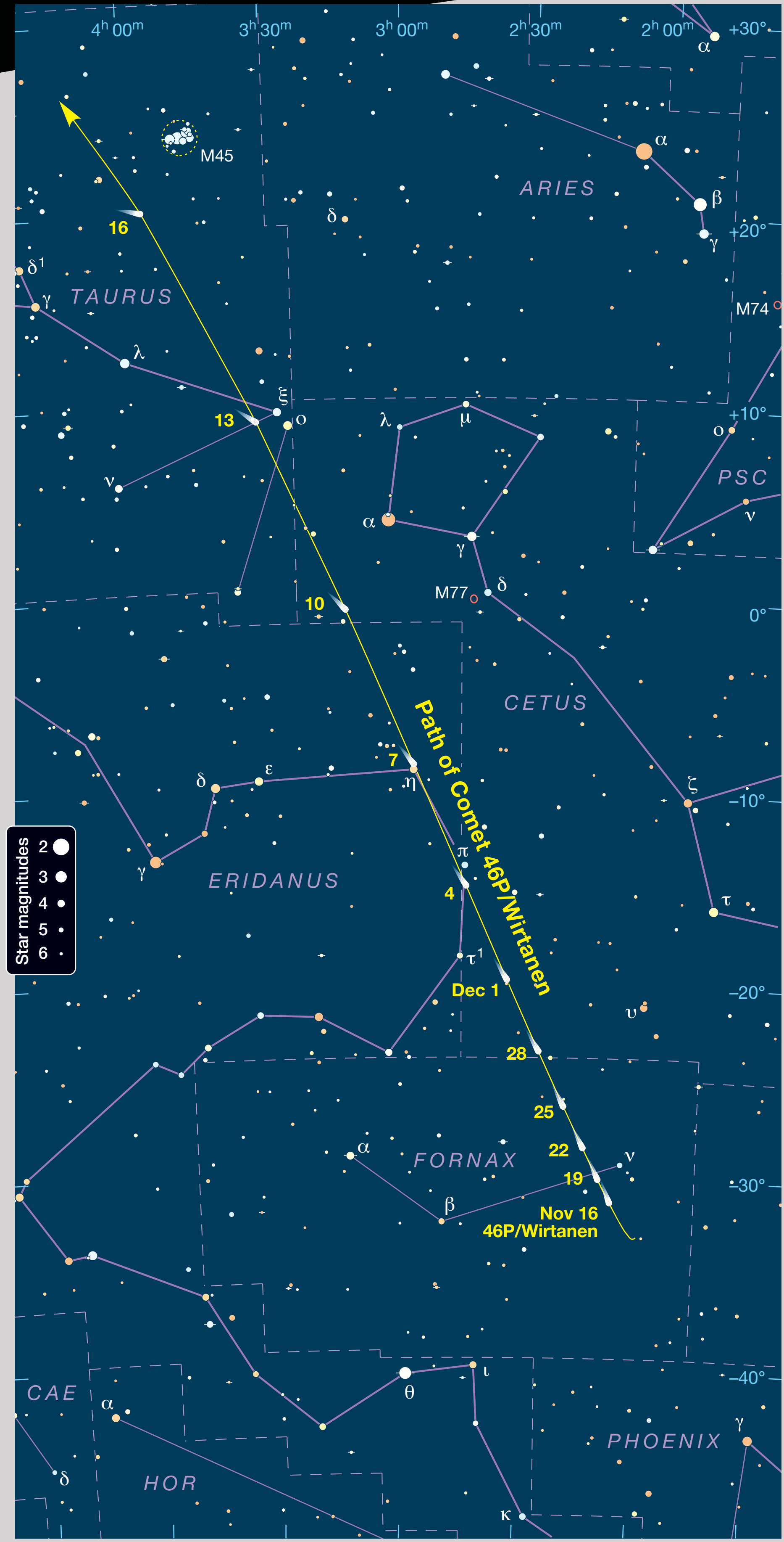
A Hyperactive Comet on a Chaotic Orbit

IF ALL GOES AS PREDICTED, Comet 46P/Wirtanen will come into visual range in the middle of November, climbing northward in Fornax before crossing into Cetus. Early December finds 46P slicing swiftly through Eridanus, on its way to a mad dash across Taurus. Observing conditions are optimal for this apparition. Because 46P is near opposition on the date of its closest approach to Earth, the comet's visible most of the night for both Northern and Southern Hemispheres. On December 16th, less than four days after the gassy ice ball reaches perihelion, 46P will be just 0.078 a.u. (11.5 million km) from us.

With an effective radius of 0.56 km, 46P's nucleus is modestly sized. However, it's also what astronomers consider *hyperactive*: The nucleus releases material at greater rates than similarly sized nuclei. This hyperactivity keeps 46P fairly bright for its size. Optimistic predictions have the comet's brightness reaching magnitude 7.5 or even blossoming into a naked-eye object. Some models project a brightening to magnitude 3, but magnitude 8.5 is a more realistic hope, even taking into account possible outbursts and heightened coma activity as the comet approaches perihelion.

With Comet 46P comes a chance for advanced amateur observers to contribute their data to a study led by



▶ The date ticks on the path of Comet 46P/Wirtanen are plotted for 0h Universal Time (on the evening of the previous date in the Americas). Look for it to be within binocular range near mid-November.

astronomers working at the Planetary Science Institute. The 4*P Morphology Campaign (**psi.edu/41P45P46P**), which kicked off in 2017 with the close approaches of Comet 41P/Tuttle-Giacobini-Kresak and Comet 45P/Honda-Mrkos-Pajdusakova, is also collecting images of the 2018 apparition of 46P. The science team invites observers to submit unenhanced, good signal-to-noise CCD images of the head of the comet (near-nucleus field) taken with professional and amateur scopes equipped with R, V, or specific narrowband filters, as well as images taken with a clear (or no) filter. An analysis of such images may lead to a better understanding of the coma's water and dust properties, the chemical composition of gasses in the coma, the rotational state of the nucleus, and more. It's possible some of this data will reveal the causes of 46P's hyperactivity in more detail. Visit the project website for instructions on contributing your images to the campaign.

Although the 4*P Morphology Campaign is focused on 46P's coma, equally intriguing is the comet's chaotic orbit. Like those of other Jupiter-family comets, 46P's orbit falls under the influence of Jupiter's gravity. Astronomers have observed every apparition of this particular comet since its discovery by American astronomer Carl Wirtanen in 1948 (except for the one in 1980, when it was too close to the Sun at perihelion), so its orbit and period are well known. However, both orbit and period change thanks to 46P's proximity to Jupiter at aphelion. In the past 70 years, 46P has experienced two particularly close planetary passes, the first in 1972, when it came within 0.28 a.u. of Jupiter, and the second in 1984, when it came within 0.47 a.u.

While 46P moved closer to Jupiter, the planet's gravity perturbed the comet's orbit, reducing both its perihelion distance and orbital period. The 1972 visit shortened 46P's period from 6.7 to 5.9 years, and the 1984 Jupiter-kick reduced it to an even more modest 5.5 years. Similarly, the perihelion distance dropped from 1.61 a.u. to 1.26 a.u. in 1972, then to 1.08 a.u. in 1984. Future encounters with Jupiter are predicted to increase the orbital period and perihelion distance, however. In 2042, 46P should come within 0.56 a.u. of Jupiter. Subsequently, the comet's orbital period will stretch to 5.78 years and its perihelion distance to 1.22 a.u.

With luck, 46P will be within binocular range when it starts moving northward past Gamma (γ) Fornaci in November. Even if it doesn't brighten to a naked-eye object, it will remain well placed for the Northern Hemisphere through the New Year and into March 2019. By then, however, it will have dropped back down to a 16th-magnitude target. The Southern Hemisphere can expect to lose sight of the comet as early as mid-to-late December.

Moon Hides Star

THE WANING GIBBOUS MOON, about 97% lit, occults Xi^1 (χ^1) Orionis on the evening and night of November 24th for North America. Western Europe will see it in the early morning hours of the 25th. Observers in the eastern half of the United States and Canada can try to spot the 4.4-magnitude star as it disappears behind the Moon's bright limb and reappears at the dark limb some 45–55 minutes later. Those on the western side of the North American continent will see only the reappearance of the star, and even then, the Moon will still be quite low.

Complete timetables for the event for cities and towns along the path are available from the International Occultation Timing Association (**lunar-occultations.com/iota/iotandx.htm**), but these will get you started:

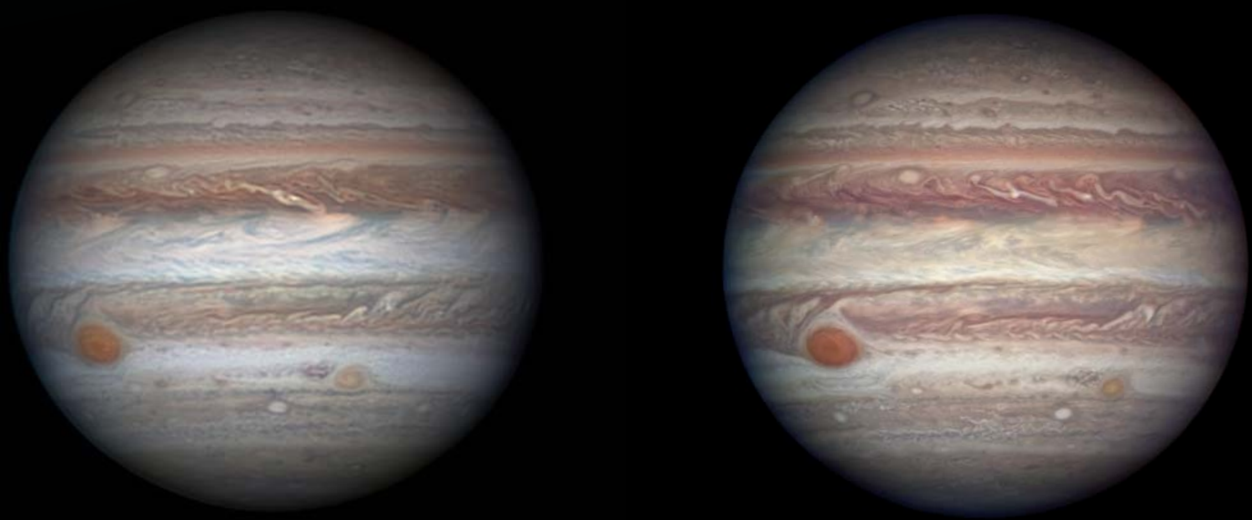
Anchorage, *reappearance* 7:20 p.m. AKST; **San Diego,** *r.* 7:52 p.m. PST; **Denver,** *r.* 9:05 p.m. MST; **Chicago,** *disappearance* 9:21 p.m., *r.* 10:17 p.m. CST; **Toronto,** *d.* 10:31 p.m., *r.* 11:27 p.m. EST; **Washington, D.C.,** *d.* 10:36 p.m., *r.* 11:13 p.m. EST; **Montreal,** *d.* 10:40 p.m., *r.* 11:37 p.m. EST; **Boston,** *d.* 10:44 p.m., *r.* 11:29 p.m. EST; **Halifax,** *d.* 11:57 p.m., *r.* 12:44 a.m. AST, November 25th.

▲ With autumn returning, Perseus is rising into the northeastern sky. 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 with respect to the comparison stars of magnitude 2.1 (Gamma Andromedae) and 3.4 (Alpha Trianguli).

Minima of Algol

Oct.	UT	Nov.	UT
1	0:58	1	13:54
3	21:47	4	10:43
6	18:35	7	7:32
9	15:24	10	4:21
12	12:13	13	1:10
15	9:02	15	21:59
18	5:50	18	18:48
21	2:39	21	15:37
23	23:28	24	12:26
26	20:17	27	9:15
29	17:05	30	6:04

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



How Much Does Size Matter?

The optimal aperture for viewing the Moon and planets is surprisingly modest.

Many years ago I attended a star party conducted on the grounds of a local university observatory. An imposing dome housed a massive 36-inch Cassegrain reflector that dwarfed the host of portable amateur instruments set up on the surrounding lawn. As twilight fell, the mammoth telescope was trained on Jupiter. When I took my turn at the eyepiece, I was greeted by the disappointing sight of a dazzlingly bright, shimmering blur devoid of any markings except for a pair of washed-out equatorial belts. Much to the chagrin of the observatory director, many of the smaller instruments nearby were providing very satisfying views of the planet.

Well over a century ago, lunar and planetary observers realized that a big telescope is no guarantee of better performance, even if its optical quality is beyond reproach. Large apertures are disproportionately handicapped by atmospheric turbulence. "The atmosphere," lamented the French astronomer André Couder, "is the worst part of the instrument." *Seeing* is caused by moving cells of air at altitudes ranging from roughly 100 meters to more than 16 kilometers. Because these cells differ in temperature, they also differ in index of refraction, so they act like lenses that change the focal position of the image in a telescope by bending incoming rays of light differently. Although these cells can vary enormously in size, atmospheric physicists have determined that at most locations most of the time they range in diameter from 4 to 8 inches.

When the aperture of a telescope is sufficiently large that it receives light that has passed through a multitude of air cells, the result is a blurred, tremulous image. When the aperture of the telescope is smaller than the diameter of the passing air cells, the image is relatively unblurred, although the focus changes subtly as individual cells drift across the light path. The larger the aperture, the less likely it is that the air mass over it will be optically homogeneous.

William Lassell (1799–1880), one of the leading observers and telescope makers of the 19th century, constructed impressive 24- and 48-inch reflectors that he transported to the island of Malta in search of an observing climate superior to that of his native England. He found that "large telescopes are proportionately less powerful than small ones . . . The visible errors of the atmosphere are, I believe, generally in proportion to the aperture of the telescope." With a 9-inch aperture, he noted that "seasons of tranquil sky may be found when its errors are scarcely appreciable," but with 24 inches of aperture "difficulties become truly formidable."

▲ Telescope aperture determines the smallest planetary features you can resolve, but only under the best conditions. Christopher Go's image of Jupiter (left), taken under near-perfect conditions with a 14-inch SCT on March 21, 2017, resolves many of the same features captured by the Hubble Space Telescope on April 3, 2017. Large land-based telescopes rarely outperform 12- to 16-inch aperture instruments due to the limits of our turbulent atmosphere.

LEFT: CHRISTOPHER GO;
RIGHT: NASA / ESA / A. SIMON (GSFC)

William Frederick Denning (1848–1931) was one of the most accomplished and influential amateur astronomers in Victorian England. Renowned for his observations of Jupiter, in 1885 he wrote that for showing markings on a bright planet "apertures of 6 to 8 inches seem able to compete with the most powerful instruments ever constructed." Noting that "separating power [resolution] is a function of aperture," he conceded that very minute planetary detail can only be discerned "by the high powers which may be used with large instruments." However, he argued that, "What the minor telescope lacks in point of light it gains in definition. When the seeing is good in a large aperture it is superlative in a small one. When unusually high powers may be employed in the former, far higher ones proportionately may be used with the latter."

Harvard College Observatory astronomer William Henry Pickering (1858–1938) founded an observatory in the hills of Jamaica where the modest diurnal temperature variation routinely made the humid atmosphere more tranquil than at sites at high elevations in the Andes Mountains. Despite the often superb conditions, Pickering alleged that 11- to 15-inch instruments showed finer detail than larger ones on nine nights out of ten. Even on the very best nights, "Nothing was to be gained by using more than 20 inches."

Many large telescopes are even more handicapped by their own thermal properties than they are by atmospheric turbulence. At most locations the temperature on a clear evening falls at a rate of 2°C to 3°C per hour. In still air a glass primary mirror 30 mm (1.2 inches) thick cools at a rate of about 3°C per hour, but a 76-mm (3-inch) thick mirror cools at a rate of less than 1°C per hour. Assuming that its thickness-to-diameter ratio is held constant, the mass of a mirror (corresponding to its heat capacity) increases with the cube of its diameter, but its surface area (corresponding to its ability to transfer heat to its surroundings) only increases by the square of its diameter.

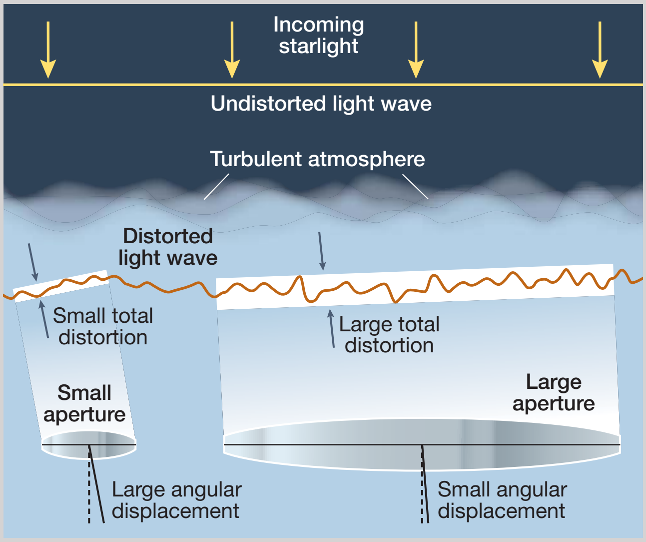
Large mirrors are very inefficient at shedding heat. Convection produces a thin, turbulent boundary layer of warmer air just above the surface of the optic that can blur the image every bit as much as turbulence thousands of meters overhead. Small wonder that Thomas Romney Robinson (1792–1882), who used the 72-inch "Leviathan of Parsontown" reflector for many years, reported in 1871 that "any differences of temperature between the speculum and the air in the tube is capable of injuring or even destroying definition, though the speculum be absolutely perfect. Hence there are few hours in the year when the 6-foot can display its full powers." One of Robinson's colleagues complained that during a two-year interval he enjoyed only three hours of excellent definition through the great reflector.

"... a 10- or 12-inch instrument of high quality is capable of revealing at least 75% of what can be seen on the Moon or brighter planets through even the largest Earth-based instruments."

The use of fans to provide a laminar current of air that sweeps away the warm boundary layer and accelerates cooling was pioneered in the 1920s by Pickering. He reported that "with poor seeing due mainly to currents in the upper air the resulting improvement is not marked, but with good seeing it is most striking."

Today fans are integral components of many commercial telescopes. But even with the aid of fans, it is difficult for a mirror of more than 50 mm (2 inches) thickness to closely "follow" falling evening temperatures. That thickness is typical of the thin mirrors of modern 16- to 24-inch reflectors that must be supported by elaborate flotation cells to keep their optical figure from distorting under their own weight.

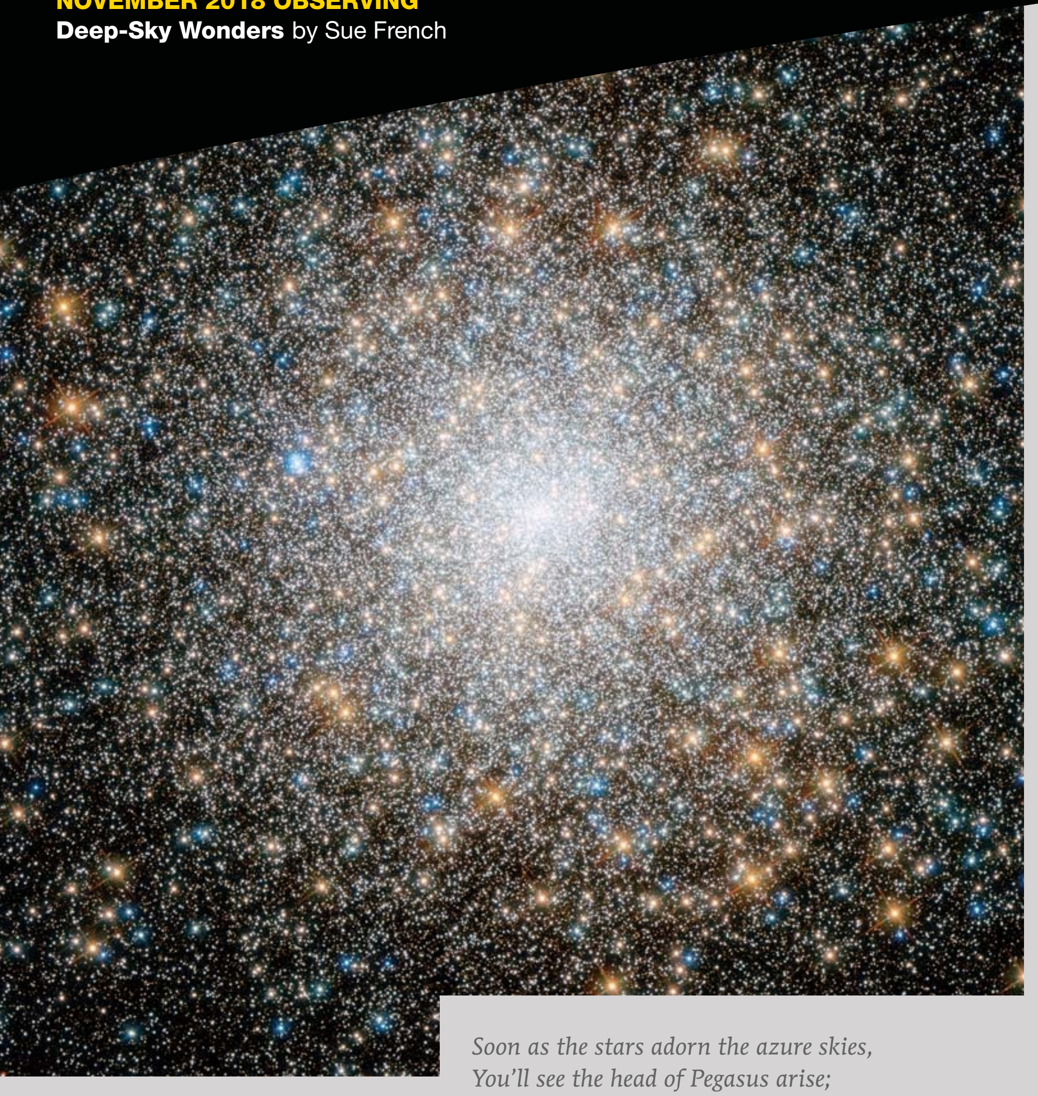
So, for lunar and planetary observers, how much does telescope size matter? Instruments with apertures smaller than 8 inches are certainly capable of providing very satisfying views, but they are less than optimal in terms of resolution and lack the image brightness required to reveal the muted pastel hues of many planetary markings. Based on five decades of observing through a vast array of telescopes, I'd venture to say that under excellent conditions, a 10- or 12-inch instrument of high quality is capable of revealing at least 75% of what can be seen on the Moon or brighter planets through even the largest Earth-based instruments. The larger apertures required to see the remaining 25% involve rapidly diminishing marginal returns. Many of the finest images of the Moon and planets have been captured using 12- to 16-inch instruments. It's no coincidence that this is the same size "sweet spot" determined by so many visual observers generations ago.



▲ The effects of atmospheric seeing on small and large telescopes are shown here. A light wave arriving from the target (a planet or star) is distorted by the turbulent atmosphere. When the distorted wavefront enters a telescope, its average "tilt" determines the target's position, while the total range of distortion influences the blurriness of the view. A small-aperture telescope sees a large displacement, but not much distortion, so the target appears relatively sharp but dances around, while a large telescope displays a blurry view while remaining relatively still.

LEAH TISCIONE / S&T

■ Contributing Editor **THOMAS A. DOBBINS** currently observes the planets using a 10-inch f/8 Newtonian reflector.



◀ At approximately 12 billion years of age, M15 is one of the oldest globular clusters known. The cluster contains more than 100,000 stars. Deep astroimages, such as this one based on data gathered by the Hubble Space Telescope's Wide Field Camera 3, reveal the cluster's hot blue and cooler yellow stars.

NASA / ESA

Pegasus Arise!

Look high to discover the glories of the Winged Horse.

Soon as the stars adorn the azure skies,
You'll see the head of Pegasus arise;
He sprung, they tell us, from Medusa slain,
The bloody spots appear upon his mane;
Above the clouds, he could the sky survey,
And with wing'd-feet cut his aethereal way;
But curb'd too much, low droop'd his falling wing,
When with his heel he made th' Aönian spring;
Now heav'n his further wand'ring flight confines,
Where splendid with his fifteen stars he shines.
—Ovid, *Fasti*, translated by William Massey, 1757

Ovid's verse tells of the grisly birth of Pegasus, his creation of the spring on Mount Helicon, and his ascent into the heavens. But at this time of the year, we don't need to wait for Pegasus to finish rising. Our winged horse is already present in all his glory at nightfall.

The globular cluster **Messier 15** is the unrivaled jewel of Pegasus, far outshining all the other deep-sky wonders in this constellation, with the exception of some notable stars. M15 is briefly described in my July 2018 column as seen through small- to medium-size scopes, and beautiful though it is, the view is even more spectacular in a large scope. Through my 15-inch scope at 216×, its countless wealth of stars spreads across 11′. The southern reaches of its bright interior are cracked by inky dark lanes. Dark patches also invade the regions east and west of the core, which flaunts a brilliant center.

In 1927, M15 became the first globular cluster found to host a planetary nebula, now known as **Pease 1**. American astronomer Francis Gladhelm Pease discovered the nebula on an image taken with Mount Wilson's 100-inch Hooker telescope, which celebrated its 100th birthday last year. Pease confirmed its nature with two spectrograms taken the following year.

Carefully following the star charts available at **https://is.gd/Pease1**, I hunted down tiny Pease 1 with the 15-inch scope. At 284× I spotted the little clump of stars that holds Pease 1 but couldn't tell which object was the pint-size planetary. However, adding an O III filter left only Pease 1 standing. Sharp-eyed observers report success with narrowband filters and scopes as small as eight inches in aperture.

Only 1.8° east-northeast of M15's heart, we find the ghostly planetary nebula **NGC 7094**. My 10-inch reflector at 187× reveals a very faint, round, 1½′ glow with a 13.6-magnitude central star. It marks the pointy end of an isosceles triangle formed with a 10th- and 11th-magnitude star 6½′ to the north. The nebula's western rim is somewhat brighter than the rest, and a narrowband filter makes it stand out a bit better. My sketch shows the view of NGC 7094 through the 15-inch scope at 216×. It appears unevenly brighter around its periphery with a narrowband or O III filter, and perhaps slightly flattened along its southeastern edge. The central star remains visible. Although a 16th-magnitude star dots the nebula northeast of its central star, I was unable to capture it. Can you?

Images of NGC 7094 and similar planetary nebulae exhibit intricate filamentary structure that earns them the fittingly descriptive name of Galactic

Soccer Balls or Galactic Footballs, the latter in areas of the world where soccer is more commonly referred to as football. Other Galactic Soccer Balls include Abell 43 in Ophiuchus and Kronberger 61 in Lyra.

Moving 1.1° south-southwest of M15 takes us to the nicely matched stars that form **Struve 2799** (STF 2799 or Σ2799). Through my 130-mm refractor at 102×, these 7.4-magnitude twins are close but attractively split. They are also similar in hue. My first impression was that the eastern star shone yellow, while the western one was closer to white, but then they seemed to switch colors as I concentrated on one star and then the other. I usually trust my first impressions, but look for yourself and see what you think. STF 2799 is a binary star whose current separation is a tight 1.9″, and it won't widen another tenth of an arcsecond until the year 2040.

You can see a much wider binary in **1 Pegasi**, whose components are generously separated in the 130-mm scope even at a mere 37×. This is fortunate because the companion glows five magnitudes dimmer than its primary and would be tough to spot if huddled as closely as STF 2799. Both stars emit a golden sheen, with the attendant perched northwest of its primary. Although the orbital period isn't well known, it appears to be well over 10,000 years, so the separation changes at a glacial pace.

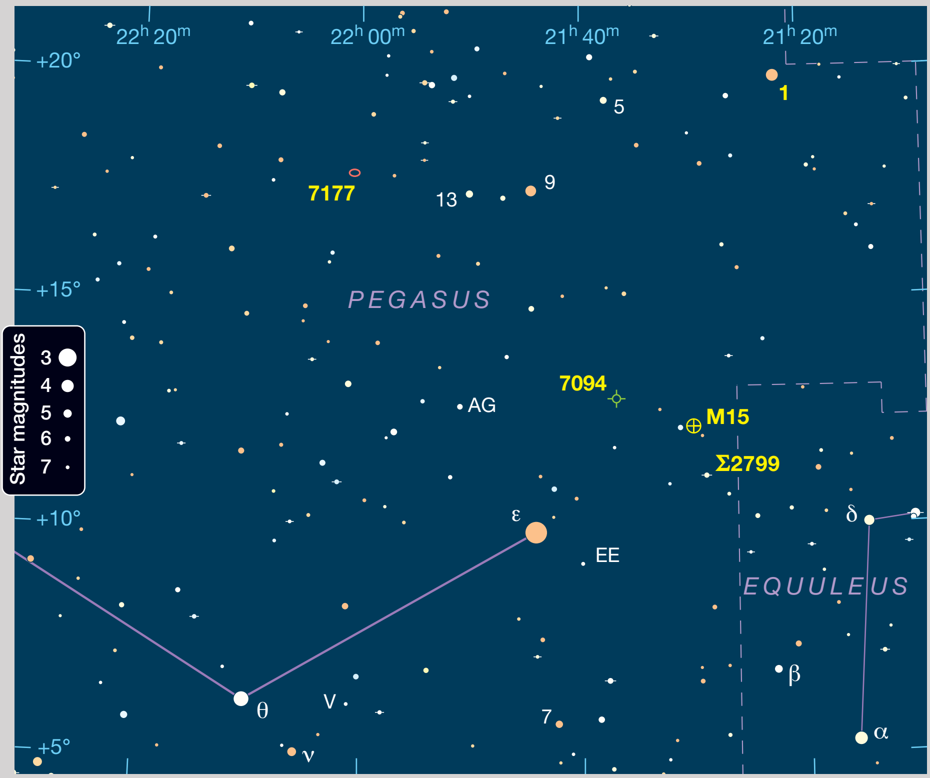
▶ The exceedingly faint NGC 7094 lies about 1.8° east-northeast of M15. While images reveal the nebula's filamentary structure, in the eyepiece it will look like a ghostly round glow. Use an O III filter to increase the contrast.

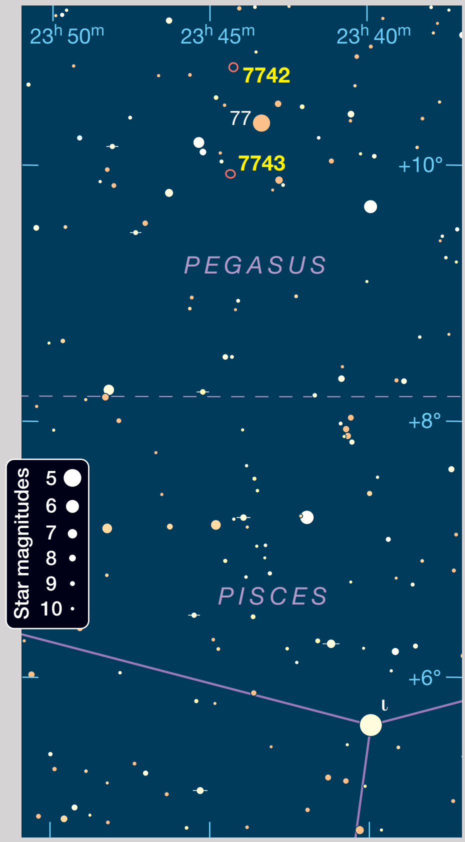
▶▶ The view through a 15-inch reflector at 216× reveals the dim 13.6-magnitude star at the center of the planetary nebula NGC 7094.

NGC 7094 IMAGE: STEFAN BINNEWIES / JOSEF PÖPSEL; SKETCH: SUE FRENCH

One of the brightest galaxies in Pegasus, **NGC 7177** resides 2.5° east and 27′ north of 13 Pegasi. Seen with my 130-mm scope at 37×, this spiral galaxy is a small oval glow at the east-northeastern end of a 4′-long arc of three faint field stars. At 102× a fourth star appears just south of the galaxy. The oval is about 2′ long and two-thirds as wide, aligned east-west. It's composed of a faint halo surrounding a large, fairly bright, oval interior. At 164× the core brightens toward the center, where rests a brighter nucleus. In my 10-inch scope at 207× the core looks tilted with respect to the galaxy's long axis.

Recent redshift-independent measurements place NGC 7177 about 80 million light-years away from us. Two supernovae have been found in NGC 7177, the first by Milton Humason dur-





▲ *Left:* The subtle spiral galaxy NGC 7177 lies east-northeast of 13 Pegasi. Look for an elongated haze with a brighter core at the east-northeastern end of an arc of three 12th- to 13th-magnitude stars. *Right:* Little more than an oval patch of light in the eyepiece, the faint fuzzy NGC 7743 looks its best in deep-sky images. Finely formed spiral arms wind tightly around the barred galaxy's bright central core.

NGC 7177: DOUG WHEELAND; NGC 7743: POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY

ing the 1960 Palomar Supernova Search at a photographic magnitude of 16.0. In 1976 Justus R. Dunlap (Northwestern University, Corralitos Observatory) reported the second feebly shining at visual magnitude 16.5.

Slightly dimmer than NGC 7177, the photogenic galaxy **NGC 7743** lies 28′ south-southeast of the red-giant star 77 Pegasi. Images show two spiral arms, each of which tightly wraps itself three-fourths of the way around the galaxy from its apparent wellspring at the core.

Through the 130-mm refractor at 48×, NGC 7743 is easily visible in a fall of faint stars tumbling southwest from a widely spaced, bright pair. North of NGC 7743, **NGC 7742** shares the field of view, the duo forming a squat isosceles triangle with 77 Pegasi. NGC 7742 is also easy to see, but smaller than its companion. At 102× NGC 7743 becomes a 1½′-long, east-west oval with a bright center and a very faint star crowding its south-southeastern edge. Less than 1′ across, NGC 7742 is round with a relatively large, bright interior and a faint star near its east-southeastern edge. This mist-filled crystal ball's nickname, the Fried Egg Galaxy, stems from the golden color of its core in a famous Hubble Heritage Team image.

In the 10-inch reflecting telescope at 213×, NGC 7743 shows itself as a fat oval, about 1.7′ long, exposing a core pinned by a brilliant, minuscule nucleus. NGC 7742 wears a faint fringe that stretches its diameter to 1′, and a starlike nucleus dwells in its heart. Turning the 15-inch reflector toward these galaxies, NGC 7743 grows to about 2′ × 1½′ and NGC 7742 to roughly 1¼′. NGC 7742 boasts markedly higher surface brightness than its neighbor.

A recent redshift-independent measurement places NGC 7743 at a distance of 66 million light-years. The latest such value for NGC 7742, 72 million light-years, is from R. Brent Tully's 1988 *Nearby Galaxies Catalog*.

On a star-filled night while Pegasus is yet arisen, be sure to sample some of his mixed bag of deep-sky treats.

■ Contributing Editor **SUE FRENCH** chases the Winged Horse and other celestial wonders from upstate New York.

Peak Pegasus

Object	Type	Mag(v)	Size/Sep	RA	Dec.
Messier 15	Globular cluster	6.2	18′	$21^h\,30.0^m$	+12° 10′
Pease 1	Planetary nebula	~14.1	2.5″	$21^h\,30.0^m$	+12° 10′
NGC 7094	Planetary nebula	13.4	94″	$21^h\,36.9^m$	+12° 47′
Σ2799	Double star	7.4, 7.4	1.9″	$21^h\,28.9^m$	+11° 05′
1 Pegasi	Double star	4.2, 9.3	36″	$21^h\,22.1^m$	+19° 48′
NGC 7177	Spiral galaxy	11.2	3.1′ × 2.0′	$22^h\,00.7^m$	+17° 44′
NGC 7743	Spiral galaxy	11.5	3.0′ × 2.6′	$23^h\,44.4^m$	+09° 56′
NGC 7742	Spiral galaxy	11.6	1.7′	$23^h\,44.3^m$	+10° 46′

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.

Depth Afield

Plunge into Pegasus and see how many faint galaxies you can spot with your scope.

▲ **MAGNIFICENT SPIRAL** NGC 7331, a galaxy in the northern reaches of the constellation Pegasus, is watched over by numerous smaller companions.

MASIL IMAGING TEAM

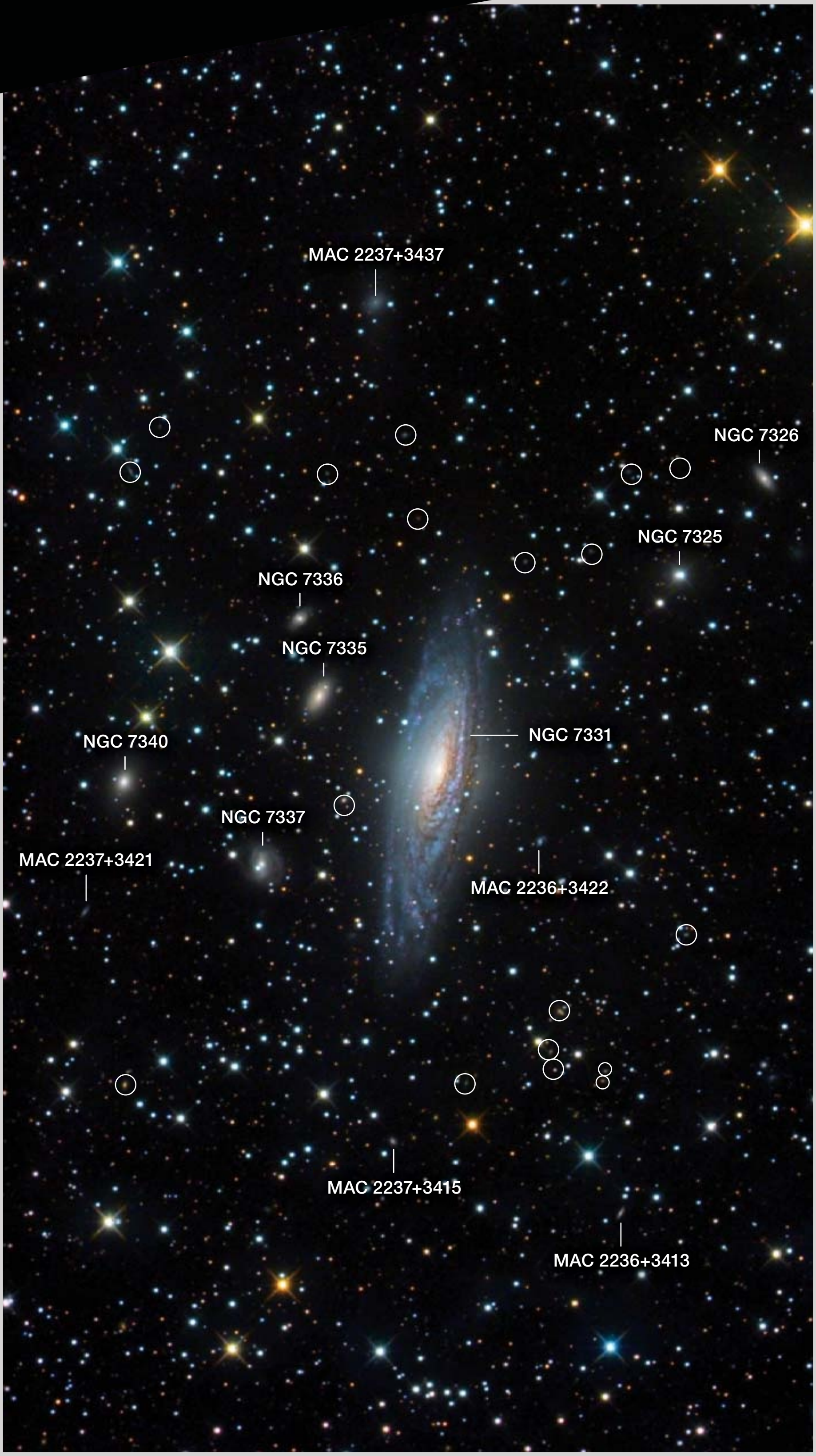
In the Greek myth of the white, winged horse Pegasus and his rider, Bellerophon, the duo fight the Chimera and perform other heroics. On their journey to Mount Olympus, Zeus dismounts the haughty equestrian but places ascending Pegasus in the heavens, where he rises in the clear autumn air as the thunderbolt-bearer of the gods. Crisp, dry October evenings offer a fine time to dig deep into the treasures of this relatively rich patch of sky. In the middle of the month, the constellation's northern region arcs nearly overhead at midnight. The hours on either side of late evening allow for a long and deep look into the area around its brightest galaxy.

NGC 7331 is a 9.5-magnitude spiral located 4.4° north of Eta (η) Pegasi. The galaxy, first observed by William Herschel in 1784, is 10.5′ × 3.5′ in size, around 45 million light-years away, and tilted 15° from edge-on. For many years it was considered a "twin" to the Milky Way Galaxy, but we now appreciate several differences between the two: The Pegasus galaxy has no apparent bar, the inner 5″ of the bulge counter-rotates with respect to the disk, and it's a *flocculent*, multi-armed spiral. Listed at number 30 in the *Caldwell Catalogue*, it can be spotted in binoculars. In progressively larger apertures detail can be appreciated in its outer arms. Images show a small, bright nucleus and a bulge that extends just beyond the edge of its minor axis, obscuring our view of the more distant, eastern spiral arms. At the 1996 Texas Star Party, my 25-inch reflector showed the galaxy to be 11′ × 3′ with a 5′ bulge, with granular detail in its outer arms.

But this magnificent spiral doesn't sit alone when observed in moderate- to large-aperture instruments. To its immediate east is a quartet of galaxies nicknamed the Fleas. In "The Winged Horse" (*S&T:* Nov. 2007, p. 74), the sharp-eyed Sue French spotted all the Fleas in her 4.1-inch refractor except for magnitude-16.8 NGC 7336. Most amateurs stop there, unaware of the treasures populating the depths beyond. Let's board a quest train to view the distant galaxies of Pegasus.

Within a few years after Russell Croman took up astrophotography, he was producing some of the finest images of deep-sky objects. A visit to his website (**www.rc-astro.com**) displays the marvelous detail he's captured in many targets. His image of NGC 7331 in Sue French's article caught my eye not only for the almost three-dimensional depiction of the large spiral, but also for the galaxies layered at progressive distances. Scattered across the image were dozens of galaxies ranging to beyond magnitude 20. To me, it appeared like a Hubble Deep Field for visual observers.

My friend and amateur astronomer Larry Mitchell has spent thousands of hours compiling the Mitchell Anonymous Catalog (MAC) of more than 125,000 objects, most of which are rather faint galaxies surrounding bright, well-known objects. In a hierarchy of ascending difficulty for visibility in deep-sky catalogs, MAC targets come after Messier objects and those listed in the *New General Catalogue* (sources prefixed with NGC) and other familiar catalogs, such as the *Uppsala General Catalogue of Galaxies* (UGC) and the *Catalogue of Principal Galaxies* (PGC). In the case of NGC 7331, Mitchell identified more than 50 MACs in a 1° field centered on the spiral. In addition to the MACs, there is a slew of formerly "anonymous" objects, presently being registered by



▲ **HOW DEEP CAN YOU GO?** The main observing targets are all marked, the brighter galaxies labeled with their names and the "anonymous" galaxies by the small, white circles. Starting with the galaxies with NGC in their names, move on to the MAC targets, and then the "anonymous" galaxies. How many can you spot in your scope?

MASIL IMAGING TEAM

their coordinates in the Sloan Digital Sky Survey and similar databases.

On October 7, 2007, I spent several hours using my 32-inch f/4 reflector to observe the 28′ × 21′ field of NGC 7331. After taking time to enjoy the beauty of the central galaxy, the first step in the image's distance ladder was the group of galaxies to the east, easily seen with direct vision. These are the 13th- and 14th-magnitude objects **NGC 7335**, **NGC 7337**, and **NGC 7340**, with the slightly fainter and more distant **NGC 7336** to their north. If the three brightest galaxies have been bestowed with several names, including the Fleas or the Deer Lick Group, then NGC 7336 might be called Ixodes, the Deer Tick. I easily saw these five galaxies in my 15-inch reflector from a dark site in central Minnesota, including the faintest, NGC 7336, at magnitude 14.5.

For comparison, take a look at Stephan's Quintet, 30′ south-southwest of NGC 7331. The four concordant-redshift galaxies in the Quintet lurk at eight times the distance to NGC 7331. The foreground galaxy of Stephan's five-member group is NGC 7320. Although it's at a similar redshift to NGC 7331, it's six times smaller and 4½ magnitudes fainter.

The magnitude-15.7 spiral **NGC 7326** that's 11.5′ northwest of the center of NGC 7331 is readily visible in the 32-inch scope as an elongated featureless object angled northeast-southwest. A string of stars connects NGC 7326 to the core of NGC 7331, and three-quarters of the way out along this string is another galaxy, **NGC 7325**, similar in brightness to NGC 7336 on the other side of the spiral.

I observed five galaxies from Mitchell's catalog. Observations of the MACs and other faint galaxies were done using my 32-inch f/4 reflector with a 5-mm Nagler Type 6 eyepiece at 650×, seeing of 7/10, and transparency 8/10. The first, **MAC 2237+3421**, is a 17.5-magnitude galaxy 3.6′ south-southeast of NGC 7340. **MAC 2237+3437** is the largest of the MACs at 0.8′ × 0.5′ and lies 13.1′ almost directly north of NGC 7331's center. In Croman's rendering it holds a pinpoint core, a halo tilted in a northwest-to-southeast direction, and curious 3′ extensions to the north and south. In the eyepiece it is a small, round glow less than 0.5′ in size.

Continuing clockwise around NGC 7731, 3.3′ southwest of the large spiral lies **MAC 2236+3422**, which could be held with direct vision. **MAC 2236+3413** is 12.5′ south-southwest of NGC 7331. Its elongated nature can be appreciated in the eyepiece, and it appears the same brightness as the previous MAC. The last of the MACs I observed was **MAC 2237+3415**, a 15.9-magnitude smudge 9.5′ south of NGC 7331. I missed MAC 2237+3427, which should have been visible but was overshadowed by NGC 7335 some 32″ to the east-southeast. Neither the Palomar Observatory Sky Survey nor Croman's image reveals MAC 2237+3427, and its nature remains unknown.

I also observed 18 "anonymous" galaxies (their coordinates and magnitudes are listed in the table below at right). Many correlate with objects in the U.S. Naval Observatory's USNO-B1.0 Catalog, and the faintest I was able to see that night was magnitude 20.3. The galaxies' magnitudes were either taken from the catalog, or I estimated them by interpolating between stars of known brightness. Only one galaxy in the list, of magnitude 17.1, is associated with an already-named source (in the 2 Micron All Sky Survey Catalog). All the anonymous sources listed below except for the five brightest were seen with averted vision, and all were less than 0.5′ in size and very faint.

For the intrepid observer, a paper by Johannes Ludwig and his team published in the November 15, 2012, *Astronomical Journal* announced the discovery of four dwarf galaxy candidates orbiting NGC 7331, along with a 2′ long tidal stream at its southeastern corner.

Amateurs have a rich variety of resources to help them explore the deep sky. The galaxies portrayed here take us from our own neighborhood to billions of light-years away, a significant fraction back toward the dawn of galaxy formation. The original Hubble Deep Field offered professional astronomers a glimpse into the earliest views of that process, and with diligence and effort we may travel in that direction. I have often dreamt of what the Hubble Space Telescope might reveal to a visual observer. Imaging and catalogs are improving so rapidly in accuracy and coverage that the days are likely not far off when all-sky, real-time imaging with drop-down menus of copious data will be at our fingertips. Automated, large, and fast reflectors will quickly slew to our targets with a voice command. But the challenge will still be, "How deep can we go?"

■ **DAVE TOSTESON** has been an amateur observer for more than 30 years. When he's not working as a family physician just north of St. Paul, Minnesota, he keeps busy by traveling to regional star parties and solar eclipses with his wife.

NGC 7331 and Companions

Object	Mag(v)	Size	RA	Dec.
NGC 7331	9.5	10.5′ × 3.5′	22^h 37.1^m	+34° 25′
NGC 7335	13.4	1.3′ × 0.6′	22^h 37.3^m	+34° 27′
NGC 7337	14.4	1.1′ × 0.7′	22^h 37.4^m	+34° 22′
NGC 7340	13.7	0.9′ × 0.6′	22^h 37.7^m	+34° 25′
NGC 7336	14.5	0.8′ × 0.4′	22^h 37.4^m	+34° 29′
NGC 7326	—	0.8′ × 0.4′	22^h 36.4^m	+34° 33′
NGC 7325	—	—	22^h 36.6^m	+34° 30′
MAC 2237+3421	17.3	—	22^h 37.8^m	+34° 21′
MAC 2237+3437	—	—	22^h 37.2^m	+34° 37′
MAC 2236+3422	15.5	—	22^h 36.9^m	+34° 23′
MAC 2236+3413	16.5	—	22^h 36.7^m	+34° 13′
MAC 2237+3415	15.9	—	22^h 37.2^m	+34° 15′

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.

"Anonymous" Sources

RA	Dec.	Mag(v)
22^h 37.7^m	+34° 17′	17.2
22^h 37.3^m	+34° 24′	16.9
22^h 37.7^m	+34° 33′	18.7
22^h 37.3^m	+34° 33′	19.7
22^h 37.7^m	+34° 34′	20.3
22^h 37.1^m	+34° 34′	18.3
22^h 37.1^m	+34° 32′	19.5
22^h 36.9^m	+34° 30′	19.1
22^h 36.7^m	+34° 31′	19.5
22^h 36.7^m	+34° 33′	19.1
22^h 36.6^m	+34° 33′	18.8
22^h 36.5^m	+34° 21′	18.4
22^h 36.8^m	+34° 19′	17.1
22^h 36.8^m	+34° 18′	19.1
22^h 36.7^m	+34° 17′	18.6
22^h 36.8^m	+34° 17′	19.8
22^h 36.7^m	+34° 17′	19.1
22^h 37.0^m	+34° 17′	19.6

The author takes a close look at the nearest and brightest Seyfert galaxy through a 48-inch telescope.

NASA / ESA / A. VAN DER HOEVEN

From mid-northern latitudes, **Messier 77** and Messier 74 must be the first two objects to observe during a Messier Marathon. They're visible only during a narrow window of opportunity as their precipitous plunge toward the onrushing western horizon competes with the slowly darkening twilight, which at best barely allows them to be glimpsed. The potential for frustration is high, because if neither galaxy can be seen there's no hope of observing all 110 Messier objects during the one-night marathon.

This race against the horizon and twilight makes the first phase of the marathon pretty hectic, so even just barely detecting these two galaxies is an exciting achievement that sets up the rest of the marathon for success. But there's no way to get a good look at either galaxy under these conditions, no matter how clear and transparent the sky may be. They're both beautiful spiral galaxies and deserve to be seen at their best when high in the autumn sky, so let's focus on what the remarkable M77 looks like through one of the largest amateur telescopes in the world.

My best chance to observe M77 came in October 2016 when I had four nights to observe it through Jimi Lowrey's 48-inch f/4 telescope. The first observation of the series is doubly remarkable because it was the next object after Arp 284 and the quasar 2333+019 (*S&T:* Oct. 2017, p. 62). Not only that, Jimi and fellow observer (and *S&T* Contributing Editor) Steve Gottlieb graciously stepped aside to give me 30 minutes of uninterrupted observing and sketching time on the 48-inch, and to repeat this privilege for three more nights. Thanks to them, I was like a kid in a candy shop!

That makes M77 the only object I've had more than a few minutes to sketch with the 48-inch. The detail I was able to see with a combined two hours of eyepiece time over four nights is a personal observing highlight. As always, the longer I looked, and the more I sketched, the more I saw. Sketching at the eyepiece is a powerful observing tool.

Even better, there are some remarkable similarities between M77 and 2333+019 that make both objects even more compelling.

otlight on a Seyfert

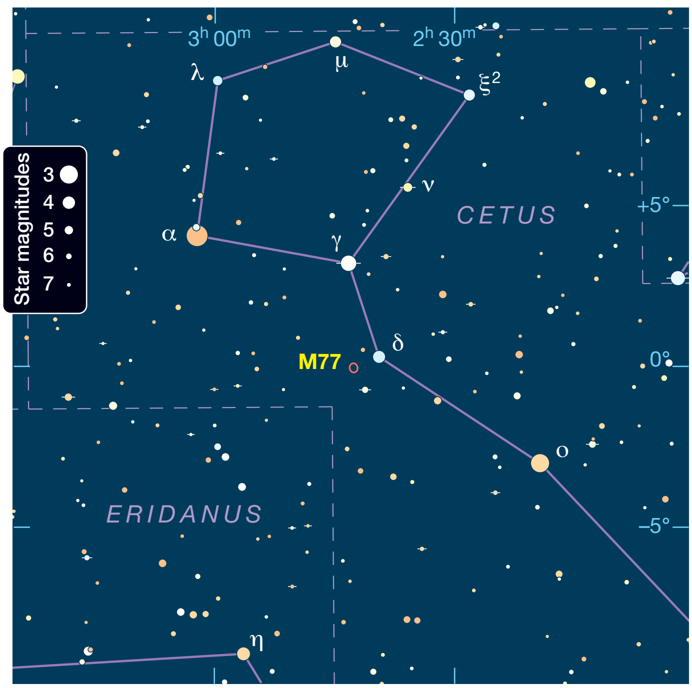
CLOSE AND BRIGHT Also known as Arp 37 and NGC 1068, M77 is the closest and brightest Seyfert galaxy, a type of galaxy with unusual emission lines first described by the astronomer Carl Seyfert in 1943. M77 has become one of the most studied galaxies in the sky because of its proximity and brightness. North is up in all images.

As always, the more I looked, and the more I sketched, the more I saw.

M77 Is Rather Special

From our frame of reference, the photons from quasar 2333+019 took approximately 10 billion years to reach our eyes and form a faint starlike dot. M77's relatively brand-spanking-new 47 million-year-old photons were arrayed in stunning spiral galaxy detail. I don't know of a single word that adequately describes how big the universe is that also includes the nonintuitive way expanding spacetime and relativistic distances interact, but it felt like I had seen a glimpse of that fun-house-mirror-immensity-time-insanity in 2333+019. That made the comparatively huge apparent size of nearby M77 feel like it was practically elbowing its way out of the eyepiece.

As different as they appear, these two objects have a lot in common: They're both galaxies that have an active supermassive black hole in their cores. Even if it's the closest and brightest Seyfert galaxy, we don't see M77's core as extraordinarily bright as a quasar's for two reasons, though: Its black hole isn't consuming enough matter, and its beamed outflow jet isn't pointed directly at us. But essentially, it's the same kind of object as 2333+019, just less powerful and viewed at a more oblique angle. Specifically, the compact *active galactic nucleus* (AGN) of a quasar is 100 times brighter at visible wavelengths than its host galaxy, while a Seyfert galaxy's AGN is typically about as bright as its surrounding galaxy. A substantial difference, but one seemingly of degree rather than of kind.



As a consequence, Seyfert galaxies are clearly visible along with their AGNs, while a quasar's host galaxy can be detected only with great difficulty because the direct brightness of its AGN jet overwhelms the surrounding galaxy. Curiously, quasars are all far away in spacetime while Seyfert galaxies are much closer, which suggests an as-yet-unproven AGN evolutionary process.

It's analogous to looking at a flashlight. The bulb looks progressively brighter the more directly it's aimed at your eyes. Try this — point a flashlight about 50° away from your eyes (M77's AGN is tilted 51° from our line of sight) and then gradually point it more directly at your face. The light gets brighter very quickly as the beam gets closer to your eyes.

M77's AGN — defined as the region around its supermassive black hole that produces emission lines from highly ionized elements — has been measured at approximately 1,000 light-years in diameter. M77's overall diameter is about 170,000 light-years, so this is a tiny area to produce as much visible light as the rest of the galaxy.

What's clear is that a supermassive black hole at the center of quasars and Seyfert galaxies powers their AGNs, and what we see, or don't see, is at least partially dependent on how active the supermassive black hole is and how closely aligned its jet is to our line of sight.

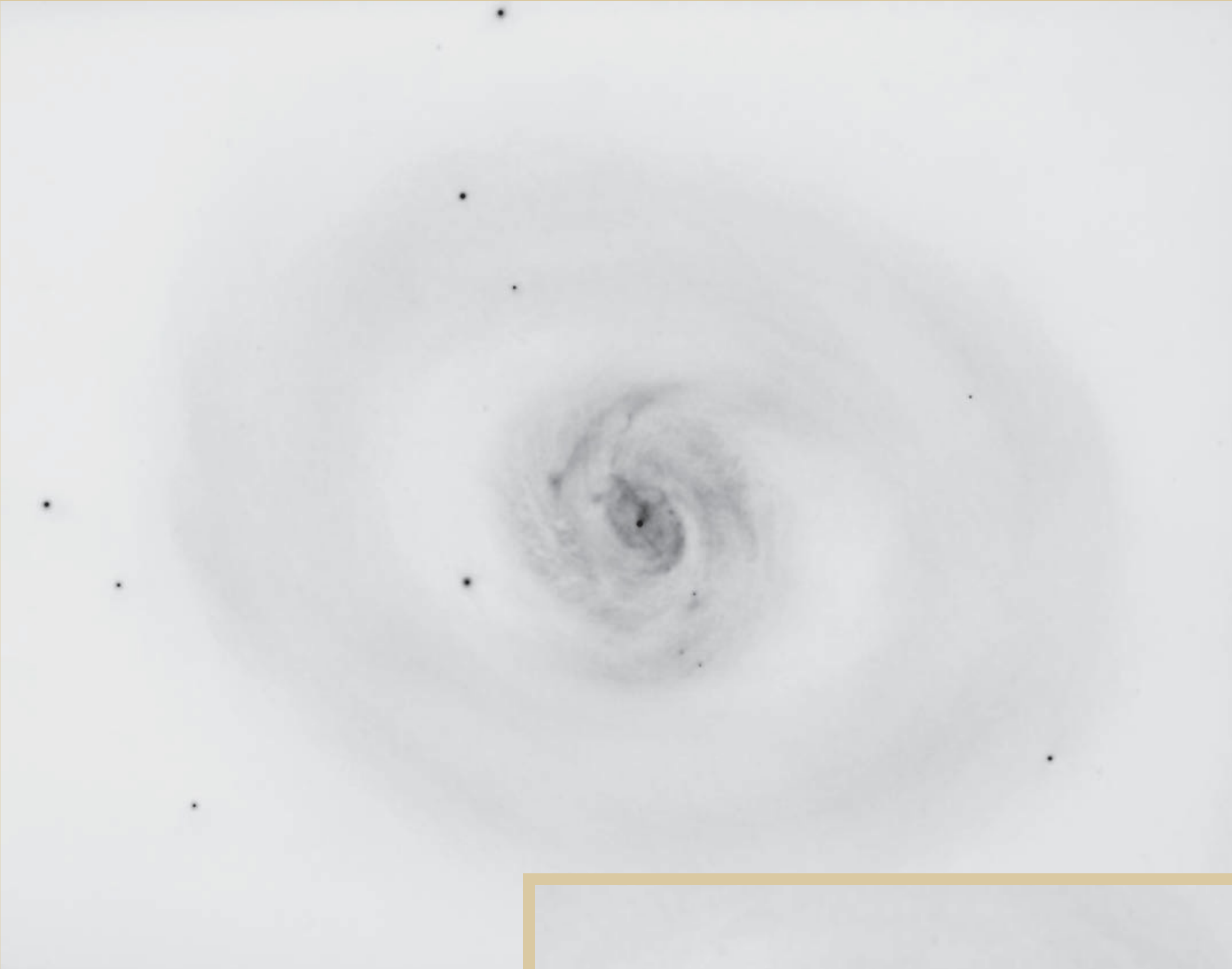
As the supermassive black hole actively consumes matter from its accretion disk, it drives the AGN to create two regions, one that produces broad emission lines, and another that produces narrow emission lines. The broad-line region is closer to the black hole, while the narrow-line region is farther out, along the jet. Type I Seyfert galaxies are oriented more face-on to our perspective, so we detect both narrow and broad emission lines from them. Broad lines can be used to measure the speed of rotation of the accretion disk because, as the diagram on page 64 shows, the broad-line region is located in the vicinity of the supermassive black hole and the accretion disk.

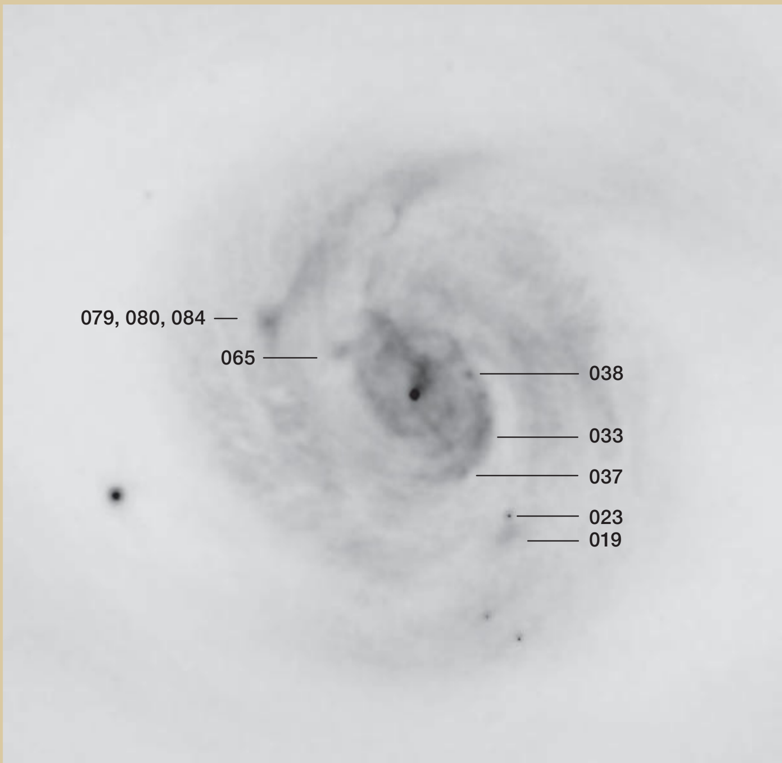
Type II Seyfert galaxies like M77 show only narrow line emissions because they're tilted farther from our line of sight, hiding the broad-line region. The orientation of their AGN seems to make all the difference.

M77 is classified as a Type II Seyfert because its 51° tilt initially allowed only narrow emission lines to be detected. Broad emission lines were later observed by looking at polarized light from the AGN region, so if M77 were oriented just a little more face on to us it might be categorized as a Type I Seyfert.

However, none of this was going through my mind while observing M77 with Jimi's 48-inch scope because I was too busy enjoying and sketching the incredible view.

So, what did I see?

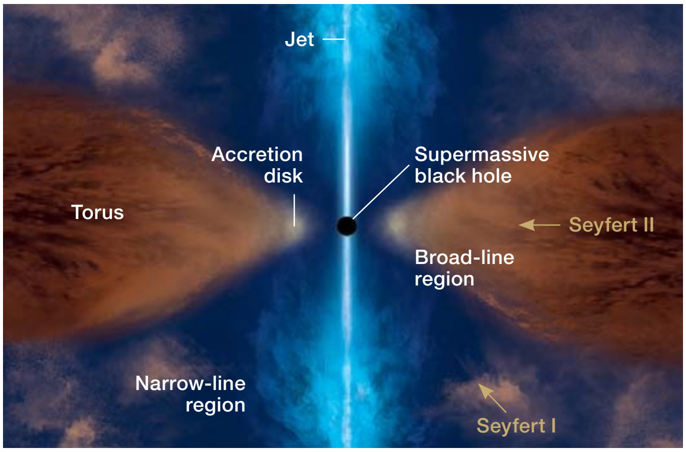




▲ **SKETCHING AT THE COLOSSUS** The author's finished pencil drawing shows M77 as seen through Jimi Lowrey's 48-inch telescope, combining a total of two hours over four nights of observing from Lowrey's West Texas observatory. Banich used magnifications from 286× to 812×. Sky Quality Meter readings ranged from 21.36 to 21.67 across the four nights.

▶ **H II REGIONS EMERGE** No filters were used in this sketch of the H II regions in the spiral arms of M77 as seen with Jimi Lowrey's 48-inch telescope. The numbers are from EKS 96 H II catalog (Evans et al. "An Atlas of H II Regions in Nearby Seyfert Galaxies." *ApJSS* July 1996). Note that EKS 079, 080, 084, and 065 are almost equally spaced and in a straight line with the AGN.

HOWARD BANICH (2)



▲ **DEEP INSIDE** The main components of a Seyfert galaxy are highlighted. The broad-line region is situated close to the black hole and accretion disk, while the narrow-line region is farther out along the cone of the jet. Orientation dictates whether we're seeing a Seyfert I or a Seyfert II.

M77 through the 48-inch

Four main structures make up the visual extent of M77, and they all fit nicely in the 286× field of view produced by a 17-mm Ethos eyepiece. The outer part of M77 is a broad, indistinct oval ring that's faintly connected to the much brighter central spiral arms. The central bar is surrounded by the spiral arms, and the AGN sits in the middle of it all. Let's work our way inward to it.

Outer Ring

This is an extensive, faint oval ring that surrounds the much more obvious parts of M77, and my views through the 48-inch are the only times I've seen this outer ring. I didn't detect it with my 28-inch scope under similar observing conditions, so it was quite a surprise to see this huge structure so well. It was a direct-vision object with the 48-inch, and after a couple of nights I was even able to detect slight brightness variations within the ring.

At first it looked like a wide, smoothly illuminated oval that is disconnected from the spiral arms within it. I didn't see the faint extensions of the two spiral arms connecting to the outer ring's inner circumference until the third night, when we had the best observing conditions. Even then, I only detected them with averted vision. They linked what otherwise looked like a faint bull's-eye to the much brighter inner regions of the galaxy.

Central Spiral Arms

There are two sets of arms here — the wide arms that envelop this bright region, and the even brighter inner arms closest to the central bar. They're separated by two fairly prominent dark lanes. The arms form a bright oval that's rotated about 40° to the outer ring. At first, I sketched the two ovals as having the same major axis, but after a couple of nights it became apparent that they were skewed quite a bit — 375× gave a good view of this.

The arms showed several small H II regions, and most remarkably what appears to be a collection of super star clusters and H II regions in the northeast portion of the arms (EKS 079, 080, and 084).

Spiral detail was almost like a texture as every magnification up to 812× brought out more detail. EKS 019 and 023 highlight the broad southwestern arm and also looked like a mixture of super star clusters and star-forming H II regions.

Off the southwestern end of the central bar there's a short and bright spiral arm that arcs north to south and is studded with three H II regions: EKS 033, 037, and 038. Interior to this spiral arm are two shorter arms oriented in the same direction. The one closest to the AGN curves around to the

◀ **PROBING DEEP** Composite images are useful for unveiling the different components in these sources. The spiral structure is revealed by the X-ray and optical data, while the radio data trace the jet powered by the supermassive black hole. Data from the Chandra X-ray Observatory are shown in red, optical data from the Hubble Space Telescope in green, and radio data from the Very Large Array in blue.

DIAGRAM: LEAH TISCIONE / S&T; COMPOSITE: NASA / CXC / MIT / C. CANIZARES / D. EVANS / NASA / STSCI / NSF / NRAO / VLA

GLORIOUS GALAXY This inverted version of the finished pencil sketch of M77 presents a more natural view of the galaxy. The outer ring has been slightly enhanced to make it more easily visible.

HOWARD BANICH

northeast portion of the bar. And oh my, what a sight it all was at 812× when the seeing would cooperate and momentarily settle down!

Central Bar

M77's central bar is crooked, asymmetrical, and not all that barlike. The southwestern portion, which is narrow and doesn't visually connect to the bright, well-detached inner spiral arm, seems to begin at the southern end of the AGN. The northeastern bar is broader, longer, and almost visually connected with the weak beginning of the northeastern arm. A magnification of 812× gave an outstanding view of this region on the best night.

The northeastern bar doesn't directly flow from the starlike AGN of the galaxy either — it was displaced north of the core and links to it with a bright spray of material. One of the two brightest H II regions is EKS 065, due east of the end of this bar and just barely in contact with the rest of the inner region. Great stuff.

AGN — 3C 71, Cetus A

The integrated visual magnitude of M77 is 9.6 while the AGN's magnitude is 8.9, so the galaxy and AGN are indeed roughly as bright as each other. At 812× the AGN is a starlike dot that's obviously the brightest part of the galaxy. It's located at the south end of a short spray of bright material pointing almost due north.

The AGN's 51° tilt to our line of sight effectively hides it from our direct view, though. Buried somewhere in there is the 10 million-solar-mass supermassive black hole that makes M77 a Type II Seyfert galaxy. It puts out enough radio energy to be listed as 3C 71, and enough X-rays to be cataloged as Cetus A. Makes me wonder how M77 would be classified if its AGN jet was pointed right at us.

The direction of the short spray of material that's connected to the starlike point is aligned with the stream of X-rays beaming from the AGN, as seen by the Chandra X-ray Observatory. Even though I didn't draw it at exactly the same angle — it's pointed a bit west of north in my drawing rather than a bit east of north as shown in the photos — I'm tempted to think I saw the visual manifestation of the AGN beam. It's certainly in the right place and pointed in nearly the right direction. The thought that I *might* have seen a bit of M77's AGN outflow gives me a delightful case of goosebumps.

And even if I never find out for sure, I can always savor the possibility. At the very least it's a far cry from barely seeing this extraordinary galaxy a few degrees above the western horizon during the frantic first moments of a Messier Marathon.

■ Occasionally observing with Jimi Lowrey and his colossal 48-inch telescope really aggravates Contributing Editor **HOWARD BANICH'S** semi-permanent case of aperture fever — but thank goodness he doesn't mind. You can reach him at **hbanich@gmail.com**.

iOptron's CEM120 Equatorial Mount

This heavyweight in iOptron's growing line of telescope mounts offers lots more than just a big payload capacity.

▲ iOptron's new CEM120 Center-balanced Equatorial Mount is the company's current heavyweight, with a rated load capacity of up to 115 pounds. It is well suited for portable use in the field or permanently installed in an observatory, where it's capable of fully remote operation.

ALL PHOTOS BY DENNIS DI CICCO

iOptron CEM120 Center-balanced Equatorial Mount

U.S. Price: $3,999 (tested with optional $899 Tri-Pier 360)
ioptron.com

What We Like

Excellent mechanical performance

Highly versatile cable-management system

Capable of fully remote operation

What We Don't Like

Limited astronomical information in hand-control databases

BIGGER IS BETTER. Right? At least that's what the advertising wizards on Madison Avenue have been drilling into us for as long as I can remember. From cars to TVs and just about everything in between, we've been led to view size as a mark of quality. Rationally we know this isn't true, but the concept lingers subconsciously and often affects our first impressions of a product. Such was the case with iOptron's CEM120 Center-balanced Equatorial Mount. My gut reaction to this new heavyweight was that it would be good. But was I reacting to its size or to the fact that I'd always been impressed with previous iOptron mounts I'd tested? Maybe it was both. But after dozens of nights testing the CEM120 last summer, I found it was indeed a superb performer packed with versatile features and even a few surprises.

The CEM120 is the third in iOptron's family of center-balanced mounts. The unusual positioning of the declination axis near the middle of the polar axis helps keep the mass of a setup (mount, telescope, and counterweights) roughly centered over the base of the mount, unlike a conventional German equatorial that is typically very off balance toward its celestial-pole end. As such, the CEM design is noteworthy for its rigidity despite its weight-to-load ratio. At 57 pounds (26 kg), the CEM120's equatorial head weighs only half of its recommended 115-pound load capacity.

The only drawback to the design is a limited ability to track past the meridian. The CEM120 can move a maximum of 14° (approximately one hour) past the meridian or start this much before the meridian with the telescope on the east side of the mount. But depending on the length of the telescope tube and the declination that it's pointed to, this angle can be even less. This limitation is not unique to the CEM design. Many commercial German equatorial mounts, especially ones in the CEM120's capacity class, have significant restrictions on straddling the meridian.

There's no need to waste space here giving a laundry list of the CEM120's specifications, since they are readily available from iOptron's website at **ioptron.com** and are also in the instruction manual that can be downloaded for free. It's worth adding that the instruction manual, quick-start guide, and various instructions for updating the mount and hand-control firmware are unusually detailed and very clearly written — kudos to their creators.

The CEM120 we borrowed for this

review is the basic model with stepper-motor drives on both axes. There's also the CEM120EC ($5,500) with a high-resolution encoder on the polar-axis drive that's spec'd to deliver a periodic error smaller than 0.15 arcsecond, and the CEM120EC2 ($6,998) with encoders on both axes. The mount I tested came with documentation showing that the polar drive had a measured periodic error of about ±2 arcseconds during a 4-minute rotation of the worm gear. Nevertheless, the tracking logs from my autoguider typically showed the periodic error to be even smaller and often only ±1 arcsecond.

Using the supplied Go2Nova 8407 V2 hand controller, the CEM120 is a stand-alone mount having all the features we've come to expect with any modern Go To telescope mount. I spent a number of nights operating the CEM120 for visual observing with only the hand controller. Despite allowing access to what at first might seem like a bewildering number of set-up and control functions, the hand controller is among the most intuitive I've tested. Most users will easily master the basic functions on their first night under the stars. The CEM120 comes with a GPS receiver, which never failed to quickly sync with the GPS satellites and automatically set the date, time, and my location in the hand controller's set-up menu.

While the hand controller's internal catalogs of celestial objects are extensive, there's only a limited amount of astronomical information about the objects. This isn't usually a handicap for me, since I create my observing lists from other sources and only used the hand controller to select my targets from the appropriate database and operate the mount's slewing and pointing.

Furthermore, today many observers connect their Go To telescopes to computers, tablets, or even smartphones running planetarium software. And the CEM120 has a robust set of options for doing this. You can connect the mount to an external device via serial (RS-232) or USB 2.0 cables, as well as through a standard Ethernet (LAN) connection to a computer network. And, if you want to go wireless, the mount offers built-in Wi-Fi. I tested them all successfully but typically used the USB option since I wanted to keep my laptop's Wi-Fi available for a link to my home network and access to the internet.

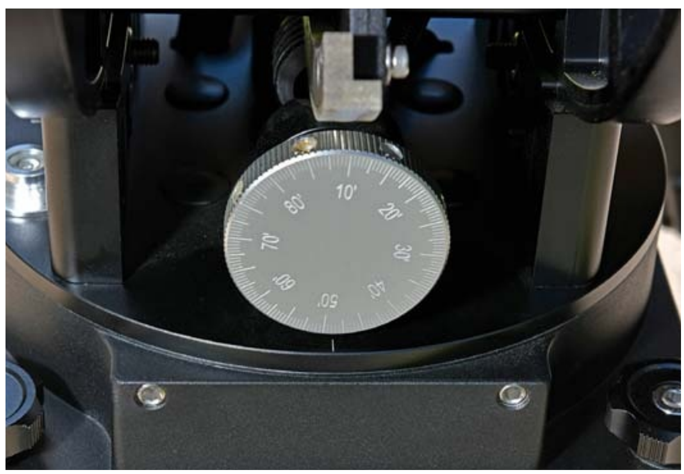
I briefly tried the CEM120 with its supplied Windows software *iOptron Commander.* But it only offers simple motion control of the mount and therefore isn't particularly useful as an observing tool. Fortunately, the mount is fully ASCOM compliant and thus easily connects with many planetarium programs that can control the mount. This worked well for me with *TheSkyX* from Software Bisque. But I first had to update all of the mount's firmware and also the ASCOM platform on my laptop

▲ As described in the text, the author tested the CEM120 for visual observing and CCD imaging with a Meade 14-inch Schmidt-Cassegrain optical tube assembly fitted with accessories that brought the total load weight to about 85 pounds.

to the latest versions before I could get the ASCOM connection to work.

Getting Outside

Mounts with the capacity of the CEM120 typically end up permanently installed in observatories. And it would be right at home in such a situation, though I put the mount through its paces from my



▲ Even with the CEM120 fully loaded with the telescope and 66 pounds of counterweights, the mount's calibrated azimuth (left) and altitude (right) controls worked very smoothly for polar aligning the mount.

suburban driveway using iOptron's new Tri-Pier 360 (an $899 option). And this provided one of the surprises I mentioned earlier: The mount was extremely easy to set up and use in the field. The heaviest piece is the equatorial head, but it comfortably balances on the top of the pier during assembly with no fear of it toppling off even if you're willing to heft it with the added weight of the 10½-pound counterweight bar attached.

But the real reason the CEM120 was such a joy to use in the field is its smooth polar alignment altitude and azimuth motions. Both adjustments are accomplished with calibrated hand knobs that are nice if you use an alignment routine that spits out the necessary corrections as angles. The CEM120 also has provision for a custom, built-in QHYCCD PoleMaster alignment camera, and there's an optional adapter available to use with a standard PoleMaster (reviewed by Alan Dyer in the July issue, p. 62). Neither the custom camera nor the adapter was available at the time of my testing, so I made my own adapter for a regular PoleMaster. As an aside, I agree with Dyer's conclusion that the PoleMaster is a great alignment tool, and most evenings I achieved accurate polar alignment in just a few minutes.

▼ In addition to various connections on the mount's base for powering and controlling the CEM120 via the hand control or with an external computer, there's a sophisticated internal cable-management system that connects power and communication ports on the mount's saddle plate with outputs on the non-moving end of the polar-axis housing. See the text for details.

The biggest challenge I faced testing the CEM120 as a portable mount was attaching a heavy telescope to it. To give the CEM120 a reasonable workout, a friend lent me a Meade 14-inch Schmidt-Cassegrain tube assembly fitted with a Losmandy-style dovetail bar. Even stripped of accessories, the scope weighed more than 65 pounds and was very awkward for one person to slide into the mating dovetail channel on the CEM120's saddle. Fully loaded with finderscope, electric focuser, and CCD camera, the scope weighed more than 85 pounds and required three 22-pound counterweights. Eventually I jury-rigged a furniture dolly and rolled the entire setup as a unit in and out of my garage rather than hassle with the nightly issues of getting the scope on and off the mount. Despite the full load of the tube assembly and counterweights, the altitude and azimuth adjustments worked beautifully during polar alignment. This is a real plus.

▲▲ The worm gears on both axes can be disengaged from their worm wheels with a simple lever "switch" (left), which is useful when balancing the mount. It's also a good idea to disengage the gears when transporting the mount. There are strong locking pins on both axes that engage at several fixed locations.

▲ The optional built-in QHYCCD PoleMaster polar-alignment camera wasn't available, so the author made an adapter for his PoleMaster — an alignment tool he highly recommends.

Cable Management

An incredibly versatile cable-management system built into the CEM120 is especially noteworthy. Virtually any electronic equipment attached to your telescope can be powered and controlled through internal wiring that runs from ports on the telescope saddle to connections on the lower, non-moving end of the polar-axis housing that iOptron calls the Input Panel. This means that just about any imaging setup can be configured without having wires dangling from the telescope that might snag when the mount is slewing and tracking.

You'll find detailed specifications for these ports in the instruction manual mentioned earlier, but here's an overview. There are four USB 2.0 ports on the saddle that feed out to a single port on the Input Panel. These will easily handle a CCD camera, filter wheel, electric focuser, and guide camera. But these USB ports are not powered, so they aren't useful for low-power devices that are normally powered through their USB connection (for example, some autoguiding cameras and small planetary imagers). For those there's a separate, powered USB 3.0 connection, which is backward compatible with USB 2.0 equipment.

The saddle has a pair of 12-volt DC ports and a single 5-volt DC port that are rated for a maximum current draw

▲ Not a single one of the thirty 10-minute exposures used to create this view of the small emission nebula Sh2-112 west of Deneb in Cygnus was rejected because of poor tracking with the CEM120 setup pictured on page 67.

of 1 ampere each, and all derive their power from the same 12-VDC source that powers the mount. There's another pair of ports rated for up to 5 amperes DC each that connect to a single port on the Input Panel. The voltage for these is simply determined by whatever you feed into the port on the Input Panel, and this is very useful if you have equipment that runs on special power sources such as 24 or 48 volts. Lastly, there's a single port with DIN-422 connectors on the saddle and Input Panel. This is the same connector used for the power source for Finger Lakes Instrumentation's CCD cameras.

While this cable-management system can likely handle any imaging setup that I can think of, it may require custom cables to make it a plug-and-play setup. For example, I needed short cables with male coaxial plugs on each end to feed power from the saddle ports to the inputs of my CCD camera and autoguider. And this will be true of most equipment that you'll want to power from these ports.

Performance

One word can summarize the performance I experienced with the CEM120 — flawless. Everything worked perfectly. The mount proved to be solid, quiet, and reliable for visual and imaging applications. The picture of Sh2-112 above is a good example of the CEM120's performance as an imaging platform. Captured with the 14-inch Meade operating at a focal length of 3,375 mm, it's a stack of thirty 10-minute exposures made on two consecutive nights. Not a single image had to be rejected because of poor tracking. Indeed, of the dozens of exposures I made of various objects during my testing, none was ever degraded by tracking errors.

As with most Go To mounts, the CEM120 can be parked and later resume observing without having to be re-initialized to the sky. But the mount can also be sent to a so-called Zero Position from a "cold" start (or after interruptions such as power failures or computer crashes). This position is accurate enough to allow resuming operations without a person having to be present at the mount. And that's key for any mount intended for remote operation. While my testing was always done with me sitting only a few feet from the mount, I could easily have been half a world away.

The CEM120 continues iOptron's track record of developing innovative telescope mounts that offer lots of performance relative to their cost — in other words, mounts that are a great value in today's marketplace.

■ **DENNIS DI CICCO** has been covering astronomical equipment in the pages of *Sky & Telescope* for 45 years.

▲ Robert Mass poses with Saturn on the Pere Marquette Rail Trail. The Sun is visible at the far end of the trail.

A Scale Model Solar System

This project is literally far out.

I LOVE BICYCLING TO PLUTO and back. My wife and I do it several times a month along the scale model solar system in our hometown of Eugene, Oregon. Now, thanks to Robert Mass, people can do the same in Midland County, Michigan.

Bob's scale model got its start nearly 38 years ago. He remembers: "I had taken my young children, Kathy, Phil, and Andy, to an open field north of town to see the great conjunction of the planets in 1980. As the last rays of the Sun disappeared, we and everybody around the world could see the five naked-eye planets form a very short arc in the west." More recently, he has been keeping track of Saturn and Jupiter's relative position in anticipation of their conjunction in 2020. That led his son Phil to mention the Eugene model laid out along 3.7 miles of river path, and together they calculated that they could do an even larger model along the Pere Marquette Rail Trail, an old railway right of way turned into a paved walking and bicycling path.

Eugene's Sun is 4.5 feet in diameter, for a 1:1 billion scale. Bob's is 7.5 feet in diameter, for 1:600 million scale. That puts his Pluto 5.6 miles (9 kilometers) away. There was a perfect stretch of path for that between the towns of Coleman and North Bradley. It's arrow-straight, so you can see the entire length of the solar system at once. With a small telescope, you can even see the Sun from Pluto. (And yes, since this is a scale model, seeing Pluto from the Earth is every bit as difficult as spotting the real thing.)

The section containing the Sun through Mars is in a grassy park within the city of Coleman. The straight section of trail ends there, allowing Bob to place the Sun off the trail but still directly in line with the extended centerline.

All of the planets were placed within their orbits' eccentric limits, but Bob did have to adjust their positions a bit. Mercury had to be placed close to perihelion to avoid putting it in the middle of a cross street. Pluto's position at the trail head in the Village of North Bradley 9 kilometers eastward places it well outside Neptune's orbit, but as Bob says, "It will be in perfect agreement with the real Pluto's position in a few decades."

Each planet sculpture is mounted on a three-feet-high by four-inch-square stainless steel pedestal so each sphere can be easily spotted. At each end of the system are information signs with a table of trail and solar system distances, a photo of the conjunction of 1980, Copernicus's heliocentric model of the solar system, and a map of the trail. Another volunteer, Henry Hellmann, co-authored the design of the signs and developed QR codes, which are affixed to the sculptures. These codes take smart phone users directly to a NASA site for detailed astronomical data.

The planets, rings, and stems were made of stainless steel so should be care-free for decades. The Sun was fabricated of steel and painted at the Gladwin Tank Factory (and Bob reports that "It just cleared the utility wires on its 26-mile trailer trip to Coleman.") The gas giant planets are hollow spheres purchased from Sharpe Products of New Berlin, WI, but the smaller planets were made in Bob's own machine shop, using a custom sphere-turning lathe attachment that he also made himself.

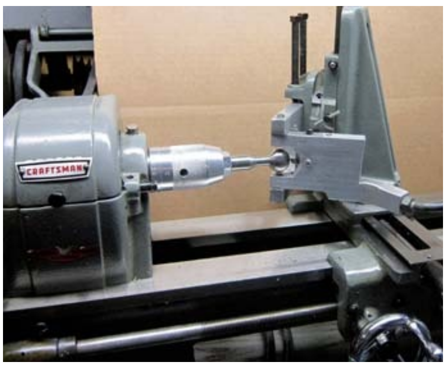
◀ All the planets were gathered for a group photo next to the Sun before their final installation.

ROBERT MASS: CHARLES BONHAM, BONHAM PHOTOGRAPHY; SUN AND PLANETS: BEN TIERNEY

Bob reports that "Many winter days were spent sanding, polishing, drilling anchoring holes, and drilling and tapping the holes for the planets' labels."

Most of the $21,000 financing for the materials and contracted fabrication came from the Midland Area Community Foundation. The Rail Trail is part of the Midland County Parks and Recreation Department, whose members were a major part of the design, construction, and now maintenance of the scale model. They celebrated the project's grand opening in May of 2017.

The Rail Trail public park is always open and free to visit. Hiking or biking is the best method of touring the solar system, but parallel roads and crossroads provide easy access and viewing. The trail area is mostly wooded, with occasional homes and farms with blocks of fields. It's hard to imagine a more pleasant way to get your exercise and contemplate your place the universe



▲ Bob made a sphere-cutting tool for his lathe so he could make the inner planets himself.

ROBERT MASS

at the same time. As Bob says, "Many of us parents and grandparents have had a joyous time explaining to the next generations the vast differences in sizes and distances to our neighboring planets."

To locate a solar system model near you, visit **https://is.gd/ss_model**.

For more information about this project, contact Robert Mass at **massro@gmail.com**.

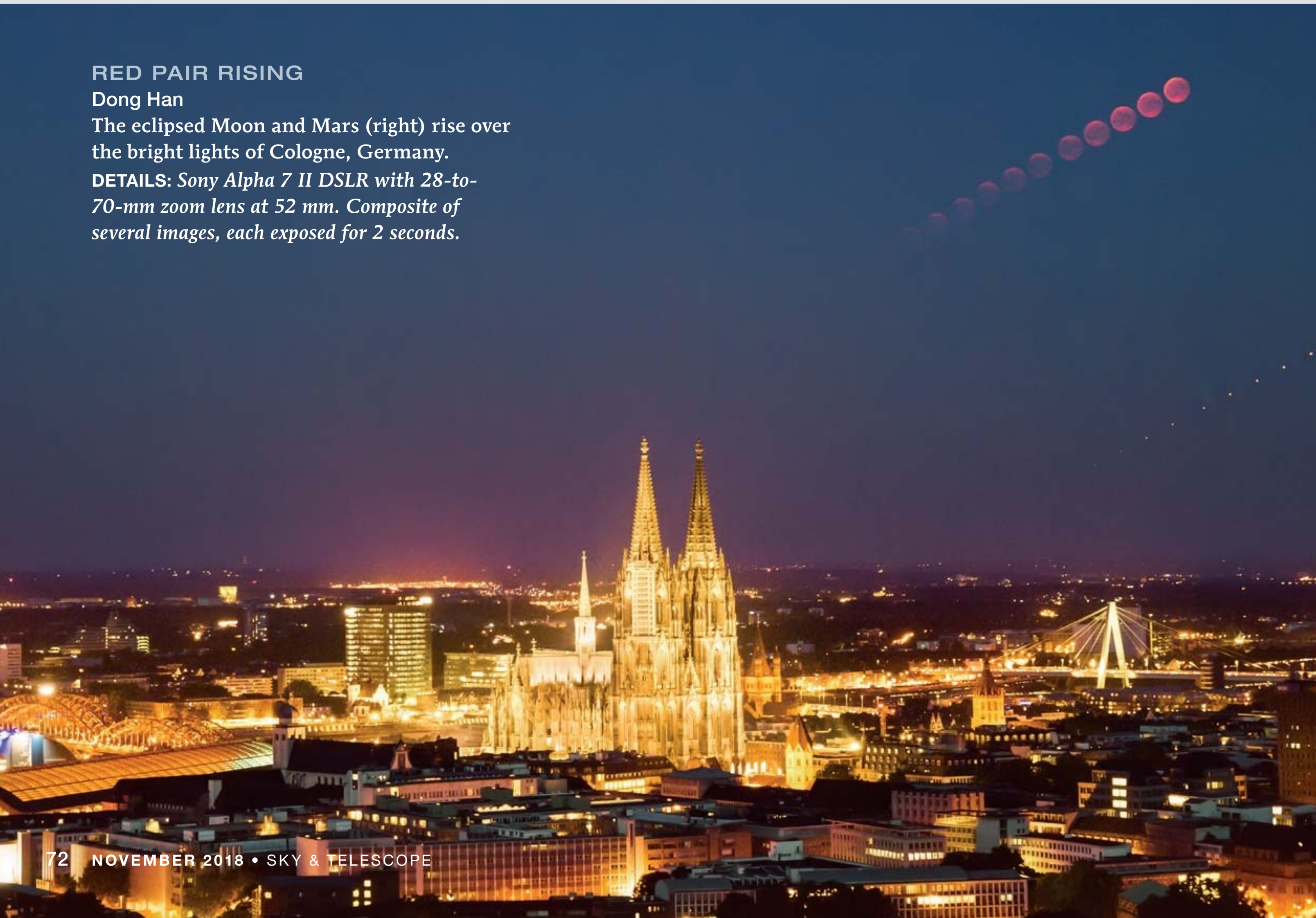
■ Contributing Editor **JERRY OLTION** hopes to bicycle Bob's scale model someday, too. If you'd like Jerry to consider your project for this column, send him your ideas at **j.oltion@gmail.com**.

▷ OVER-UNDER ECLIPSE

Renato Langersek

The Moon is seen on the evening of July 27 shortly after entering the longest lunar eclipse of the 21st century. South is up, as the Moon normally appears when seen from the Southern Hemisphere, in this case Brisbane, Australia.

DETAILS: *Canon EOS 5D Mark II DSLR camera with 1,000-mm lens at f/10. Total exposure was 0.5 second at ISO 1600.*



RED PAIR RISING

Dong Han

The eclipsed Moon and Mars (right) rise over the bright lights of Cologne, Germany.

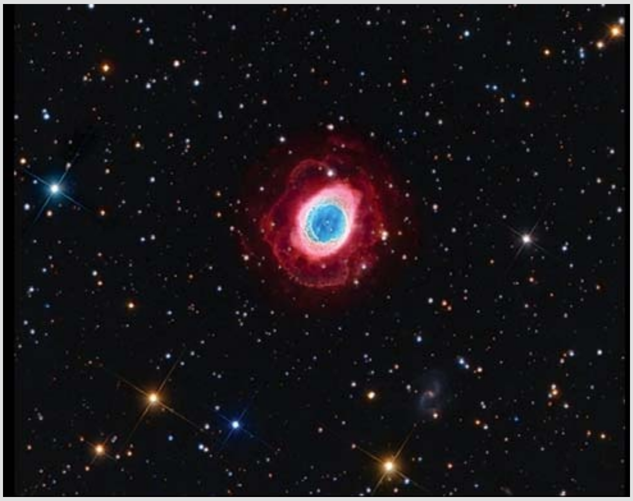
DETAILS: *Sony Alpha 7 II DSLR with 28-to-70-mm zoom lens at 52 mm. Composite of several images, each exposed for 2 seconds.*

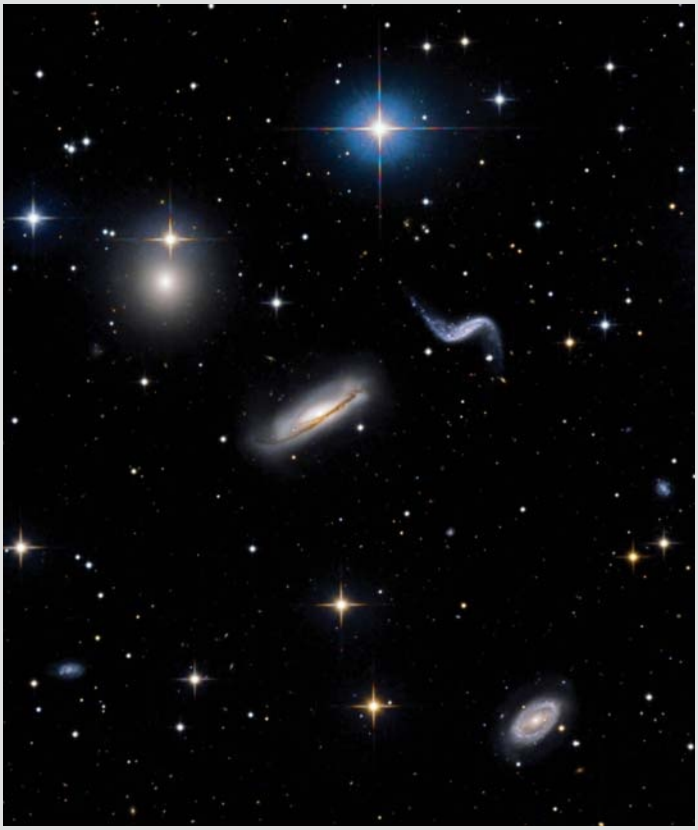
▷ COMPACT GALAXY GROUP

Richard S. Wright, Jr.

Hickson 44 in the sickle of Leo contains several interesting galaxies, including NGC 3193 (left), NGC 3190 (center), NGC 3187 (right), and NGC 3185 (bottom right).

DETAILS: *Sky-Watcher Quattro 300P Imaging Newtonian with Starlight Xpress Trius-SX694 CCD camera. Total exposure: 6.8 hours through Baader LRGB filters.*





△ RING FLOWER

Luigi Morrone

This deep image of M57 in Lyra displays the dying star's faintest outer shells, resembling the petals of a rose.

DETAILS: *10-inch Newtonian reflector with Atik 383L CCD camera. Total exposure: 7½ hours through color filters.*

▷ ONE-ARMED SPIRAL

Keith Quattrocchi

NGC 4725 in Coma Berenices is a large spiral galaxy about 40 million light-years distant that has a single spiral arm riddled with pinkish star-forming regions.

DETAILS: *16-inch RCOS Ritchey-Chrétien telescope with SBIG STL-6303 CCD camera. Total exposure: 10⅔ hours through Astrodon LRGB filters.*

THE BUTTERFLY

Stacey Fox

Just east of the bright star Sadr (right) lies the large emission nebula IC 1318, which is bisected by the thick dust of LDN 889.

DETAILS: *Stellarvue SV70T refractor with ZWO ASI1600MM Pro CMOS camera. Total exposure: 5 hours through narrowband filters.*

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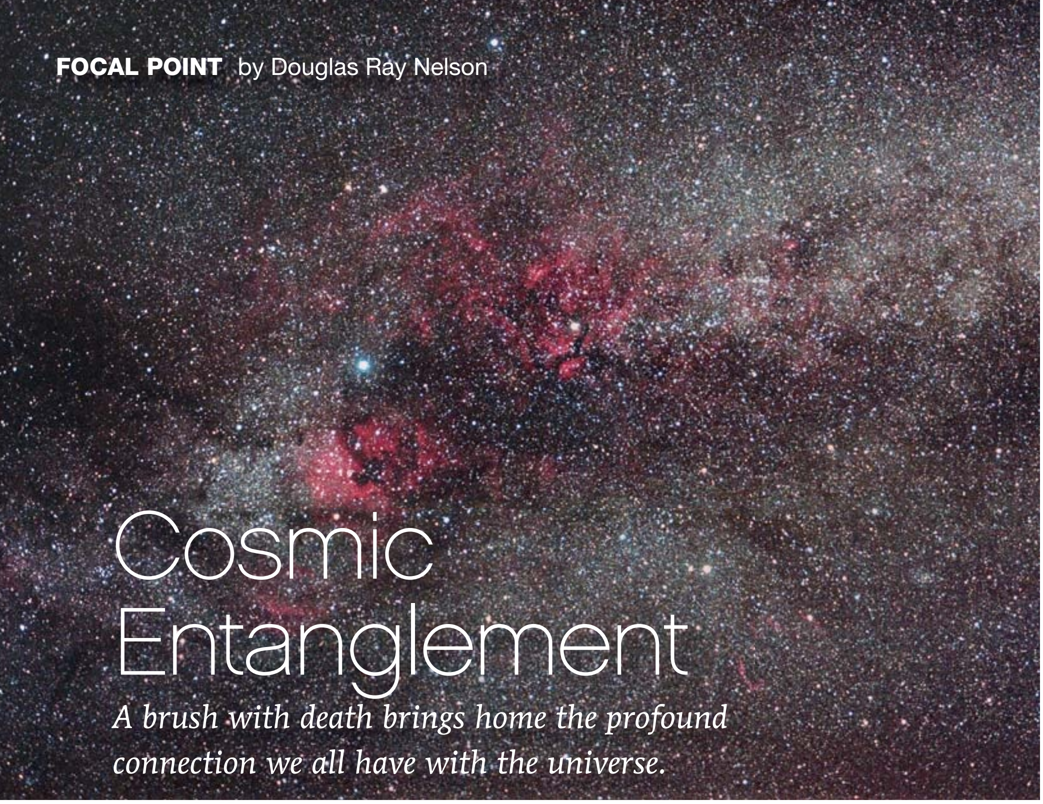


Cosmic Entanglement

A brush with death brings home the profound connection we all have with the universe.

I COULD NOT HAVE BEEN more than eight years old. “Look into the eyepiece,” the astronomer said. “You’ll see Saturn.” I knew Saturn from pictures — the planet with rings — but I’d never observed it with my own eyes. I peered into the eyepiece and perceived a small dot encircled by white rings. “Some of those nearby stars that you see are actually Saturnian moons.” I was hooked.

In my teens, I knew the names of the brighter stars. During that time, on a bitterly cold night in 1986, I stood on a dark street in a small town and made out a smudge low in the sky. It was Halley’s Comet. Very faint, but there. It would make a better showing in 2061. I’d be 90. “See you later,” I whispered to the comet.

In my twenties, I sat atop a ladder and gazed into an enormous tube with a mirror on the bottom. Comet Shoemaker-Levy 9 had fragmented and smashed into Jupiter. Dark plumes the size of Earth marked the impacts. Night after night, I tracked Jupiter until it sank below the horizon, knowing that I would likely never view such a rare event again.

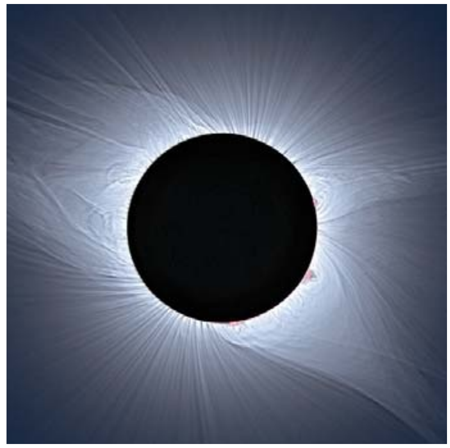
In my thirties, I worked as a planetarium curator and star party host. “Welcome to the stars,” I said to the crowds. Over years of school shows, I told thousands of children, “There is no reason to be afraid of the dark. In fact, the nighttime sky has so much to be excited about. Let’s take a look!”

In my forties, I climbed to the top of the world. Well, maybe not the top. But from a steep hill surrounded by Wyoming grassland, I watched my first total solar eclipse. The Moon ate the Sun and both became a single hole in the sky darker than pitch and crowned with a blazing halo.

The climb that day took every bit of strength I had. I barely made it. The same was not true of my companion. He didn’t think the climb was a big deal. I felt like it had nearly killed me. Indeed, it had.

A couple of months later, during an annual checkup, my doctor discovered a heart murmur. A cardiologist found heart disease, and I soon had open-heart surgery. It saved my life, and I’m still in recovery.

Facing death, I reevaluated life. Had I lived well? What would I change? Which were my favorite memories? Time and again, my mind drifted to nights under the stars. Each had been time well spent.



▲ Beloved objects in the author’s life, clockwise from above: Saturn taken by Voyager 2 in 1981; Halley’s Comet shot by the Kuiper Airborne Observatory in 1986; a starscape featuring Cygnus; and the 2017 total solar eclipse.

How many stargazing nights do I have left? I don’t know, but the number is finite. Each session is a gift from the universe, an opportunity to observe where I came from and where I am going. You see, we are entangled, the cosmos and I. It is part of me, and I am part of it. This is the way it has been and, even after I’m gone, the way it forever will be.

■ Las Vegas–based **DOUG NELSON** blogs at **confessionsofastargazer.com**. He’s not afraid of the dark, but sometimes he does wonder if a monster is hiding under his bed.

SATURN: NASA / JPL; HALLEY’S COMET: NASA; CYGNUS AND ECLIPSE: SEAN WALKER / *S&T*

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