Galileo as artist at the dawn of the telescope age p. 24

NOVEMBER 2020

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Vol. 48 • Issue 11


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CONTENTS

NOVEMBER 2020
VOL. 48, NO. 11

ON THE COVER
The Tarantula Nebula (NGC 2070) is one of the largest star-forming regions known, and lies within the Large Magellanic Cloud.

FEATURES

COLUMNS

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ON THE COVER: TARANTULA NEBULA: ESO/IDA/DANISH 1.5 M/R. GENDLER, C. C. THÖNE, C. FÉRON, AND J.-E. OVALDSEN. JUPITER: NASA, ESA, A. SIMON (GODDARD SPACE FLIGHT CENTER) AND M.H. WONG (UNIVERSITY OF CALIFORNIA, BERKELEY)

Our little neighbor galaxies

The Large Magellanic Cloud is the most significant satellite galaxy of the Milky Way. It contains the Tarantula Nebula (pink, upper right), one of the largest star-forming regions known. ESO

Travelers to the Southern Hemisphere know that the sky there is loaded with amazing sights, in some ways much richer than the sky we northerners are usually stuck with. The jewel of the southern sky, the Large Magellanic Cloud (LMC) is a tiny barred spiral galaxy that orbits our Milky Way, lying at a distance of 163,000 light-years. Found mostly in the constellation Dorado, it shines at 1st magnitude and is so bright that it appears to naked-eye viewers as a detached portion of the Milky Way.

Lying relatively nearby in the sky is another little galaxy, the Small Magellanic Cloud (SMC), centered in the southern constellation Tucana. It is another barred spiral, some 200,000 light-years away, that also appears as a detached portion of Milky Way nebulosity. Both these galaxies were "discovered" by sailors during Ferdinand Magellan's circumnavigation of the globe in 1519–1522, thus their names. (But, of course, being naked-eye objects, they have been visible over the entirety of human history.)

In his story, "A Tale of Two Galaxies" (page 16), Knut Olsen of the National Optical Astronomy Observatory describes his personal encounters with the Magellanic Clouds. He has studied them using data from the Hubble Space Telescope, gazed at them during his observing time in Chile, and quite deeply pondered what they mean to us.

Olsen's tale of discovery leads us to the significance of what the Magellanic Clouds tell us. As satellites of the Milky Way, their composition and orbits hold secrets to both past and future. For example: In 1987, a telescope operator at Las Campanas Observatory in Chile spotted an unfamiliar star in the LMC. This turned out to be Supernova 1987A, the closest and brightest supernova observed on Earth in nearly 400 years.

For years, astronomers have recognized that the LMC and SMC are an interacting pair of galaxies, and that a tidal stream of material exists between them. They've found that the LMC has made off with stars from its smaller neighbor, and that the future of the Clouds is written in trouble. The two galaxies occasionally will slam into each other, as they have in the past, but ultimately they will likely be consumed by the Milky Way, absorbed into our larger system of stars.

Yours truly,

David J. Eicher
Editor

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ASTRO LETTERS

Perseverance blasted off from Earth on July 30, and is planned to reach Mars in February 2021. NASA/JPL-CALTECH

Getting ready for Mars

I just want to let you know that I find Jake Parks' articles in *Astronomy* to be some of the best written — the piece on the NASA's Perseverance probe is absolutely fantastic! It's clearly written, captures so many interesting asides, is beautifully illustrated, and was an absolute pleasure to read. **—Mike Schimpf,** Pacific Grove, CA

Combining art and science

As an artist, writer, and science aficionado, I loved the way Bob Berman wound scientific notions with poetry in his article, "A Tribute to Carbon." Not only was I introduced to new information, it was done in such a beautiful, visual way. Good job! **—Lynn Eckerle,** Jackson, MI

Hats off to Kaler

The July special issue, "All About Stars," was the best issue of *Astronomy* ever! I always look forward to a learning experience when I read *Astronomy*, but this issue was a learning experience from cover to cover. I particularly enjoyed Jim Kaler's comprehensive article on the life of stars, but every single article was excellent. Thanks for vastly increasing my understanding of the stellar universe we live in. **—Larry Crary,** Stuart, FL

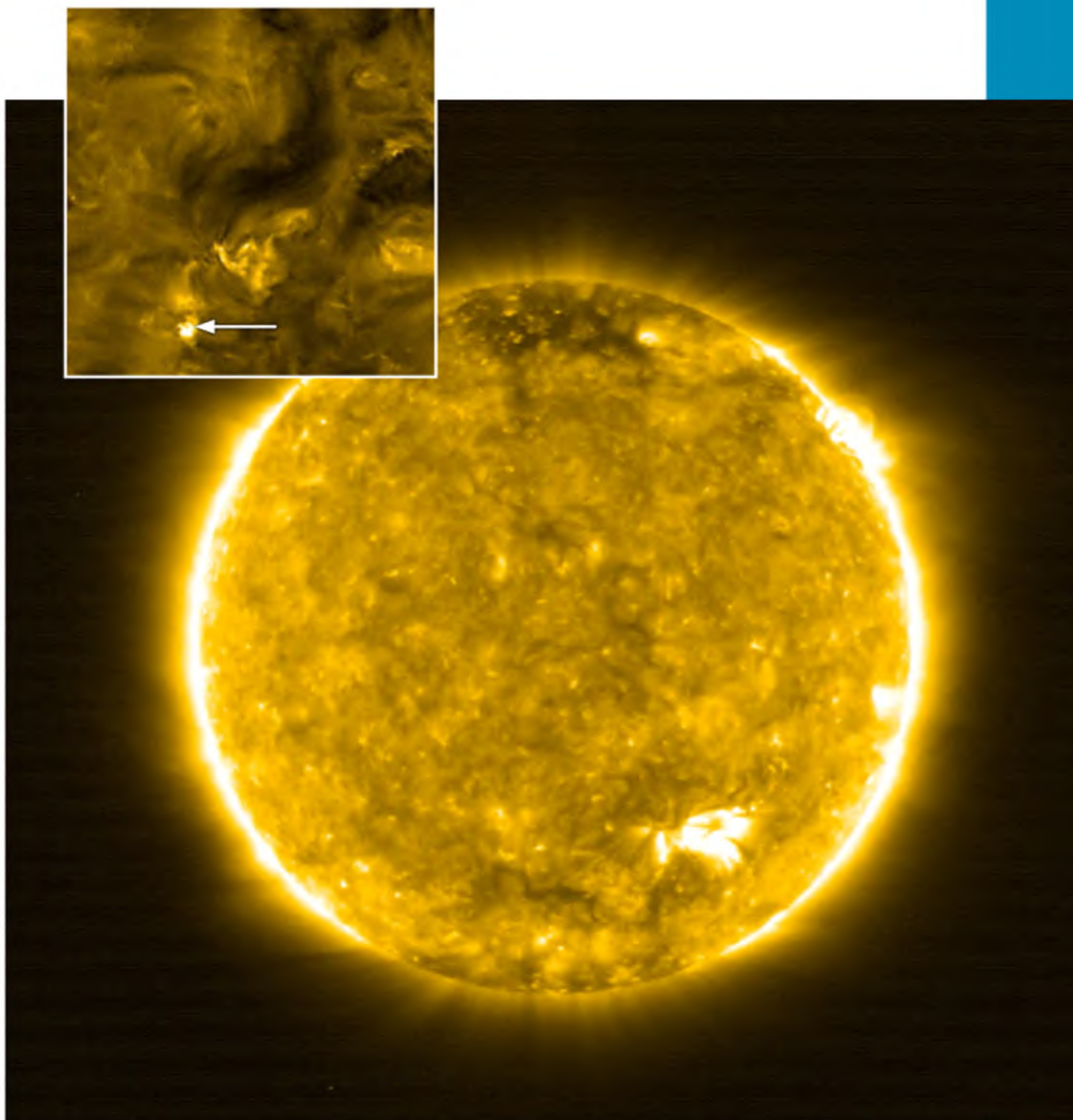
At long last, a clear, concise, and complete description of how stars are born and die. The wonderful, fluid writing of Professor Emeritus Jim Kaler gives us a picture rarely seen outside of textbooks and lengthy treatises. While a lesser writer would be tempted to stop and digress many times, Jim's fluid writing caries us through to completeness. I encourage all new students of astronomy to clip this article and save it for future reference. **—Donald Craig Jr.,** Indianapolis, IN

We welcome your comments at Astronomy Letters, P.O. Box 1612, Waukesha, WI 53187; or email to **letters@astronomy.com**. *Please include your name, city, state, and country. Letters may be edited for space and clarity.*

SNAPSHOT

CAMPFIRES ON THE SUN

Solar Orbiter captures the closest photos of our star.



On June 15, NASA and the European Space Agency's Solar Orbiter made its first close pass of the Sun, coming within 48 million miles (77 million kilometers) of our star. During the pass, the spacecraft's suite of 10 instruments went to work, snapping the closest images of the Sun ever taken. The shots were meant simply to confirm the instruments are working properly. But they also revealed a new discovery: an army of small bright spots, each about one-millionth to one-billionth the size of a regular solar flare, all over the Sun. Scientists are now calling them campfires.

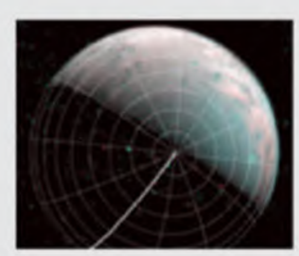
It's possible campfires are miniature versions of the flares we spot from Earth. But they also may be related to nanoflares — small, brief, ubiquitous bursts of energy across the Sun thought to heat the corona (the Sun's outer atmosphere). The Solar Orbiter team now plans to measure the campfires' temperatures, which should reveal whether they're just mini solar flares or an important heating mechanism for the corona. —ALISON KLESMAN

SOLAR ORBITER/EUI TEAM/ESA & NASA/CSL, IAS, MPS, PMOD/WRC, ROB, UCL/MSSL. BOTTOM FROM LEFT: NASA/BILL INGALLS; NAOJ; NASA/JPL-CALTECH/SwRI/ASI/INAF/JIRAM

HOT BYTES

DRAGON SPLASHDOWN
The SpaceX Crew Dragon *Endeavour* spacecraft safely returned to Earth August 2 with NASA astronauts Bob Behnken and Doug Hurley aboard.

NOT SO SUPERMASSIVE
The galaxy IC 750 has a lighter-than-expected supermassive black hole — less than 140,000 times the mass of the Sun, according to new data from the Very Long Baseline Array.



VIEW FROM ABOVE
NASA's Juno probe made the first infrared map of the north pole of Jupiter's moon Ganymede in 2019. The ice there has no crystalline structure, thanks to constant plasma bombardment.

PERSEVERANCE BEGINS JOURNEY TO THE RED PLANET

The rover will search for signs of ancient martian life, pluck oxygen from Mars' thin air, and gather samples for a future return mission.

BLAST OFF. Perseverance lifts off aboard a United Launch Alliance Atlas V rocket the morning of July 30, officially kicking off the Mars 2020 mission. The rover will arrive at Mars on February 18, 2021. UNITED LAUNCH ALLIANCE

After years of anticipation, NASA's latest robotic explorer, the Perseverance rover, blasted off for Mars July 30 at 7:50 A.M. EDT. Departing atop an Atlas V-541 rocket from the historic Space Launch Complex 41 at Cape Canaveral Air Force Station in Florida, the ambitious rover is the latest in the space agency's long lineage of Red Planet explorers. Perseverance is expected to land in Mars' Jezero Crater on February 18, 2021.

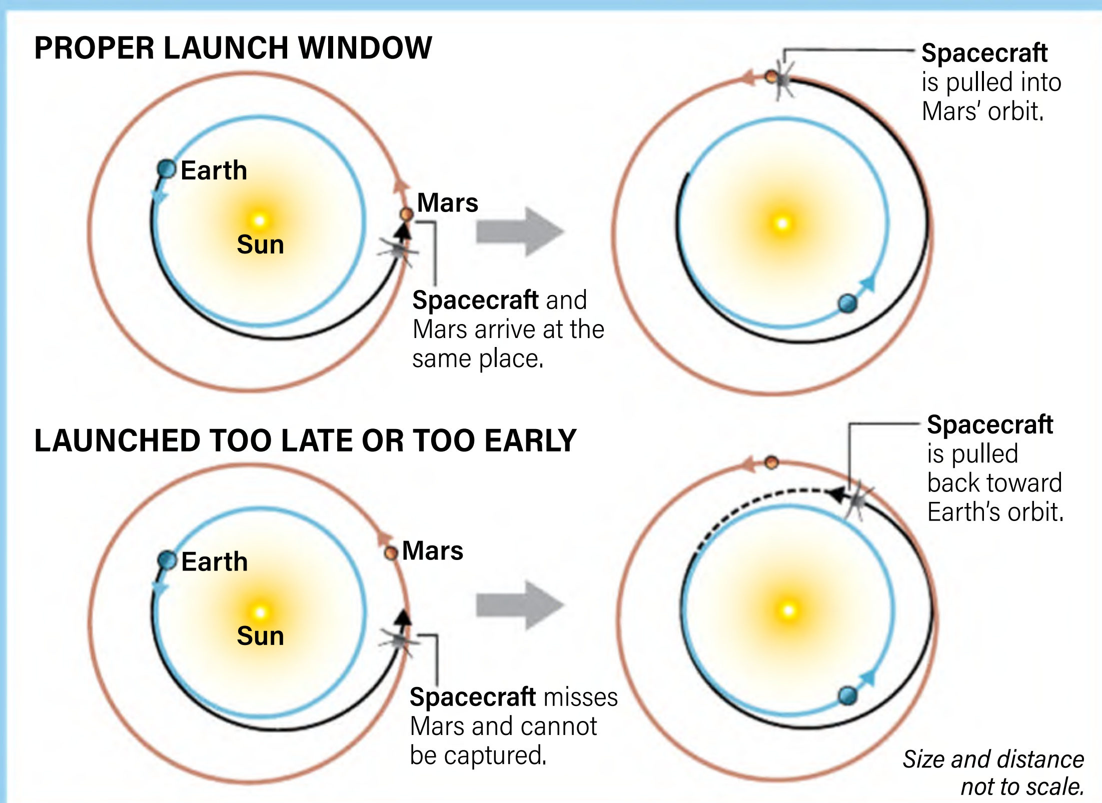
The $2.7-billion mission will seek out sites that were potentially habitable in the past, looking for signs of ancient microbes within rocks and collecting promising samples for a future return mission. But it also was designed with the intention of paving the way for human exploration.

"With the launch of Perseverance, we begin another historic mission of exploration," NASA Administrator Jim Bridenstine said in a statement. "This amazing explorer's journey has already required the very best from all of us to get it to launch through these challenging times."

PERSEVERANCE'S TOOLKIT

The new rover carries a sophisticated suite of instruments capable of collecting and preparing samples that will one day be returned to Earth. Perseverance will drill into intriguing rocks, seal samples in titanium tubes, and deposit them on the martian surface for a future (and so far, unplanned) mission to pick up and deliver back to Earth. Once here, researchers will scrutinize them in laboratories with more powerful equipment than can be sent to Mars.

LAUNCHING A MISSION TO MARS



ASTRONOMY: ROEN KELLY

THE RIGHT TIMING. When sending a spacecraft to the Red Planet, efficiency is key. Since space travel isn't cheap, any craft leaving Earth needs the perfect window of opportunity. The course between two circular orbits that uses the least energy is known as the Hohmann transfer orbit. In the case of travel between Earth and Mars, a rocket flings the object away from Earth and into an elliptical orbit around the Sun. The craft coasts around to meet Mars on the other side, arriving within seven to nine months. Mars and Earth don't have perfectly circular orbits, so launch windows are also timed for when the planets are closest to each other. But this window only opens every 26 months, meaning delays can force missions to wait until the planets align again. – CAITLYN BUONGIORNO

FAST FACT

In 2003, Mars came within 35 million miles (56 million kilometers) of Earth, marking the planets' closest approach in 60,000 years.

Perseverance is also ferrying a small helicopter drone named Ingenuity, just under 2 feet (0.6 meter) tall and weighing less than 4 pounds (1.8 kilograms). Intended as a technology demonstration, Ingenuity can take off, hover a few dozen feet above the surface, and land on flat ground.

Another mission objective is to pave the way for humans to explore Mars. The rover is carrying the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE), which will use electricity to extract oxygen from carbon dioxide in the atmosphere. Also a proof-of-concept experiment, the technology could one day support astronauts or even produce locally sourced rocket fuel.

If astronauts eventually gain access to water on Mars — a reliable source of hydrogen — scientists can tweak MOXIE's basic technology to make more complicated products, Michael Hecht, MOXIE's principal investigator, tells *Astronomy*. "Once you have water and you have electrochemistry," Hecht says, "you can start making anything from paraffin to beer." – JAKE PARKS

QUICK TAKES

JAMES WEBB DELAYED

Due to technical challenges and the ongoing COVID-19 pandemic, the target launch date for NASA's James Webb Space Telescope has been pushed back from March 2021 to October 31, 2021.

SENDING MARS HOPE

In July, the United Arab Emirates became the first Arab nation to launch an interplanetary probe. The spacecraft, named al-Amal (Hope), will arrive at Mars in February 2021 for a two-year mission to study the Red Planet's dynamic atmosphere.

FILLING THE VOID

New data from the Sloan Digital Sky Survey has allowed astronomers to create the largest-yet 3D map of the universe, filling in gaps about how it expanded over the past 11 billion years.

ULTIMATE TELESCOPE

A 100-meter-wide telescope on the Moon would be powerful enough to detect the cosmos' first generation of stars, says a team at the University of Texas. They've dubbed the fanciful facility the Ultimately Large Telescope.

WHAT A VIEW

The spot on Earth with the steadiest skies for astronomy is atop Dome A, an Antarctic ice dome, according to a new study. The previous record-holder for the site with the least atmospheric turbulence (which distorts images) was Dome C, also in Antarctica.

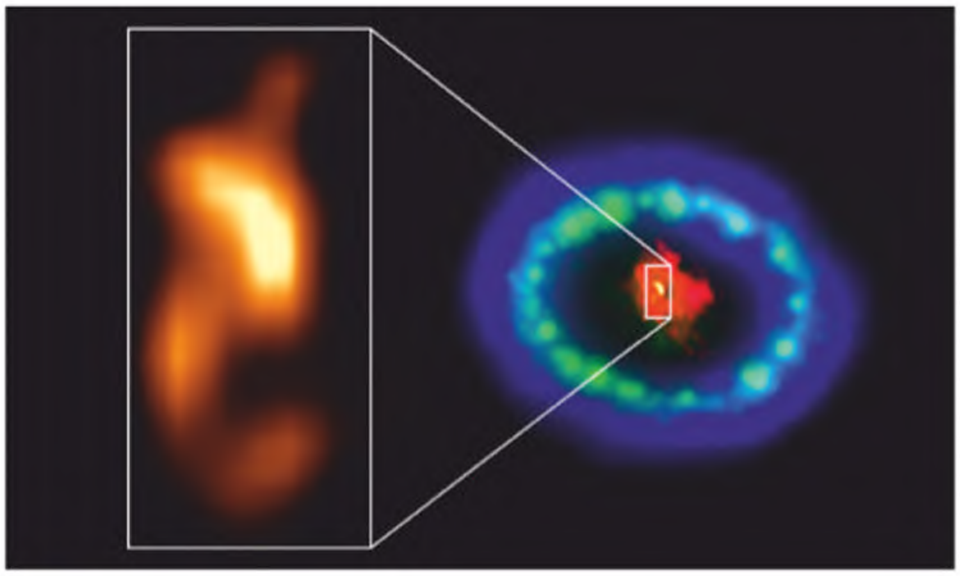
VENUSIAN VOLCANISM

Scientists have discovered 37 volcanoes on Venus that are still active. The new work, which suggests the interior of the planet is still churning, may help researchers choose geologically active locations for future missions to target.

DANCING PLANETS

For the first time, researchers have used a ground-based telescope to detect two exoplanets orbiting in a resonance that allows them to gravitationally interact, tugging on each other and disrupting the timing of their passes. – MARK ZASTROW, C.B., J.P.

A neutron star lurking in Supernova 1987A



THE BLOB. ALMA captured high-resolution images that revealed a hot, slightly off-center "blob" (inset) within the core of Supernova 1987A. The material seen by ALMA in radio wavelengths is colored red and yellow. Hubble's visible view is displayed in green and Chandra's X-ray view is shown in blue. ALMA (ESO/NAOJ/NRAO), P. CIGAN AND R. INDEBETOUW; NRAO/AUI/NSF, B. SAXTON; NASA/ESA

» On February 24, 1987, an unexpected cosmic explosion rocked the astronomical community. Dubbed Supernova 1987A (SN 1987A), the fiery event — triggered by the implosion of a massive star — was the closest observed supernova since the invention of the telescope. It occurred just 170,000 light-years away in the Large Magellanic Cloud, a satellite galaxy of the Milky Way. SN 1987A was so bright that naked-eye observers could spot it for several weeks.

The event wasn't just a visual feast. It also gave astronomers an unprecedented opportunity to investigate the processes that trigger supernovae, as well as how these powerful blasts ripple through their surroundings. Despite their destructive power, supernovae leave remnants, typically in the form of a black hole or neutron star, depending on the mass of the exploding star. In the case of SN 1987A, one mystery has endured: What did the blast leave behind?

In a new paper published July 30 in *The Astrophysical Journal*, astronomers report they've found compelling evidence that SN 1987A is still harboring a neutron star, which, at just 33 years old, would make it the youngest such stellar corpse yet found. Using the Atacama Large Millimeter/submillimeter Array (ALMA) radio telescope in Chile, they were able to pierce through the dust and gas left behind by the supernova to see what lies within.

ALMA's high-resolution images revealed a hot "blob" lurking in the core of SN 1987A, located right where astronomers think its suspected neutron star should be. The blob itself is not the neutron star — because neutron stars compress about 1.4 times the mass of the Sun into a sphere just 15 miles (25 kilometers) across, they are impossible to see directly.

Instead, the blob is a giant gas cloud dramatically outshining its surroundings. It spans about 4,000 astronomical units — 1 astronomical unit, or AU, is the average Earth-Sun distance — and it's estimated to have a temperature of some 9 million degrees Fahrenheit (5 million degrees Celsius).

"There has to be something in the cloud that has heated up the dust and which makes it shine," co-author Mikako Matsuura of Cardiff University said in a press release. She argues the most likely culprit is a neutron star, dubbed NS 1987A.

Now that astronomers have found the likely location of the neutron star, the real quest for understanding can begin. One question is whether NS 1987A is a run-of-the-mill neutron star or a pulsar — a more exotic type of neutron star that emits powerful beams of radiation as it spins. To find out, astronomers must continue to monitor the blob for periodic variations in its brightness that might give away the consistent rhythm of a pulsar within. —YVETTE CENDES

JAMES JOSEPHIDES (SWINBURNE ASTRONOMY PRODUCTIONS) AND THE S5 COLLABORATION

RISING FROM THE ASHES

The Milky Way is home to around 150 globular clusters — compact collections of stars orbiting largely in the far reaches of the galactic halo. Stars in these ancient clusters are old enough to have watched the Milky Way grow up over billions of years. But sometimes, gravitational forces wrench star clusters apart. Recently, scientists discovered one such unlucky cluster: The Phoenix Stream was torn apart by our galaxy more than 2 billion years ago. It is likely that the Phoenix Stream will one day be absorbed into the Milky Way, ultimately following a path similar to other ancient clusters that have long since disappeared. —C.B.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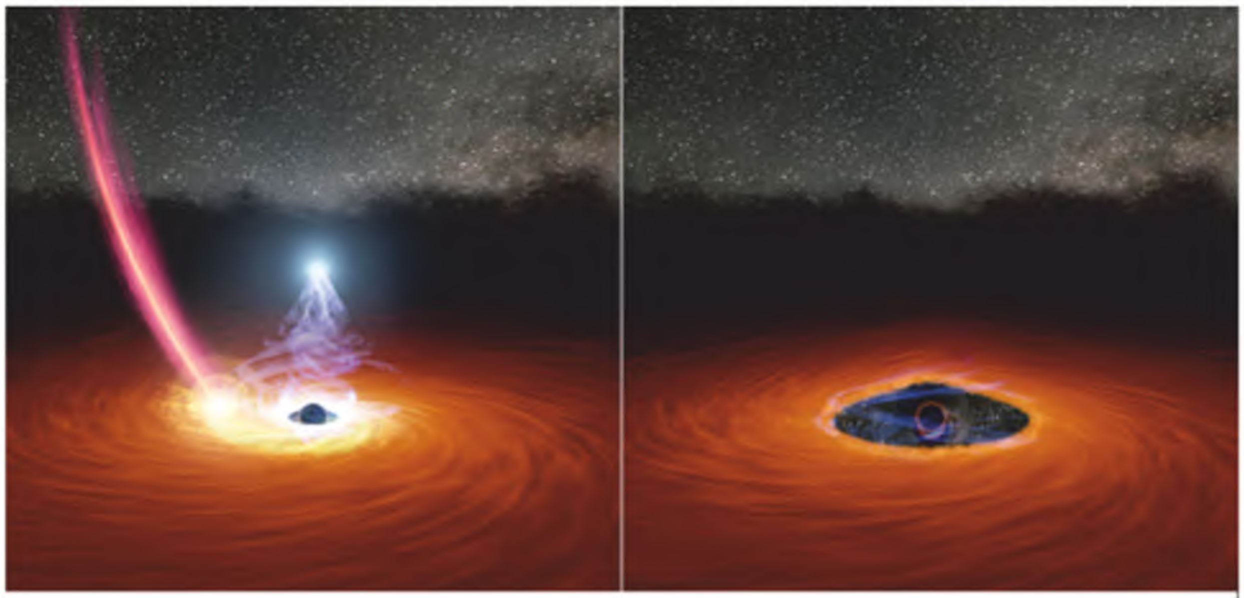


DECROWNED. The left panel of this artist's rendering shows a black hole consuming a star (the red trail). This process disrupts gas within the accretion disk surrounding the black hole (yellow-orange), potentially cutting off the black hole's corona — a cloud of ultra-hot electrons that shines brightly in X-rays (white) — from its source of power. NASA/JPL-CALTECH

Black hole loses its crown — then gets it back

» Ravenous supermassive black holes at the centers of galaxies are often accompanied by a glowing corona of superhot gas, which hovers around the black hole and emits powerful X-rays. These X-rays can vary significantly in brightness over time, flickering under the influence of the processes that power them.

In March 2018, astronomers around the world aimed their telescopes at a galaxy roughly 270 million light-years away named 1ES 1927+654, whose central black hole was spotted undergoing a particularly dramatic transformation, flaring up to 40 times its original brightness in optical and ultraviolet light. But then, X-ray telescopes including NASA's Neutron star Interior Composition Explorer mounted to the International Space Station, plus three other NASA and European Space Agency space telescopes, watched the black hole's X-ray corona abruptly disappear. The observations were published in *The Astrophysical Journal Letters* July 15.

Over the course of 40 days, the corona faded to a mere 1/10,000 its original brightness. "It became undetectable, which we have never seen before," said study co-author Erin Kara of MIT in a press release. Even more curious: Over the next 100 days, the corona reappeared, gathering strength until it was ultimately 20 times brighter than it originally had been.

The team speculate that the dramatic death and rebirth of the X-ray corona may have occurred as the supermassive black hole gobbled up a star, ripping it apart in the process. Simulations published last year show that during such an event, called a tidal disruption, the stream of debris would collide with the accretion disk of gas that circles a black hole's event horizon. This would cause the inner disk to quickly fall in and disappear. Without the disk's magnetic field to feed on, the corona would be cut off from its energy source and vanish — only to gradually rebuild itself as material originally farther out in the accretion disk flowed inward to replenish the inner disk.

But how exactly a black hole's corona is powered remains unclear. Astronomers hope more observations of events like this one can help them better pin down the source of the corona's energy. —M.Z.

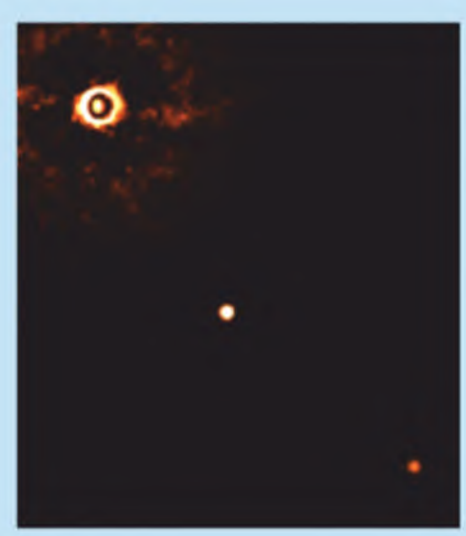
19

The number of asteroids in our outer solar system recently determined by researchers at São Paulo State University to have origins in other star systems.

Two exoplanets seen circling a Sun-like star

Astronomers using the European Southern Observatory's Very Large Telescope (VLT) have captured the first-ever image of multiple worlds circling a star that resembles a younger version of our Sun. The system, called TYC 8998-760-1, is roughly 300 light-years away in the southern constellation Musca.

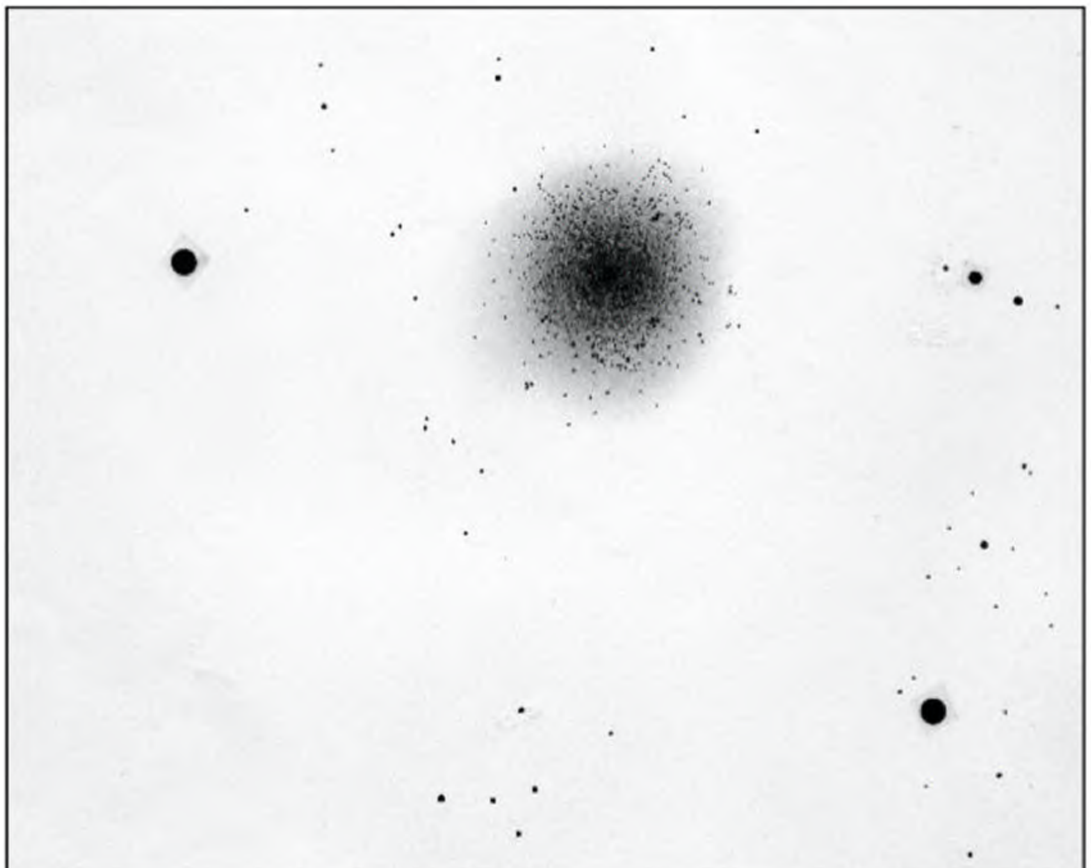
The inner planet lies about 160 astronomical units from its host star (1 astronomical unit, or AU, is the average Earth–Sun distance) and is roughly 14 times the mass of Jupiter. The more distant planet is located about 320 AU from its star and weighs about 6 Jupiter masses. To make such a challenging detection, the VLT used its state-of-the-art adaptive optics to correct for image distortion caused by Earth's turbulent atmosphere, and a coronagraph to help block excess light from the target star. —M.Z.



ESO/BOHN ET AL.

Anatomy of the observer

Amateur astronomers are, by nature, mindful watchers.



Astronomy Editor Dave Eicher made this sketch of M13 in Hercules years ago, using a 17.5-inch f/4.5 reflector at 50x.
DAVID J. EICHER

Astronomy Editor David J. Eicher recently shared a drawing he'd made long ago at the eyepiece of his 17.5-inch reflector. Myriad dots depict a globular cluster, M13. But what the sketch really reveals is patience — and that introduces today's topic: the makeup of an *observer.*

Being an observer is a quality you and I have in common. In the 21st century, it's an attribute unusual enough to merit examination. That's because modern humans tend to be busy and non-observational. This busyness means we are often scattered and unfocused.

In seeking examples of common activities in which one might naturally be an observer, motorcycling comes to mind. On my big old 800-pound (363 kilograms) touring bike, the word *touring* suggests I get to watch the changing scenery in a relaxed manner. But no such luck. A biker's attention is typically split in multiple directions. You're obsessively watching the road for ruts and gravel, while also focusing on the edge of the woods to spot any deer ready to spring out.

It's not usually very relaxing. And neither is using a telescope, if we're honest. If you have a restless mind — and most of us do, at least some of the time — your sky session brims with distractive choices. Should I change to a binoviewer? Phone a friend to join me? Insert a filter? Take some pictures? Boost the magnification? View something else?

Observing — extensively watching an object — is a quiet activity with focused attention, a form of meditation.

In some states, teachers now give instruction in mindfulness. Children take to it readily and it converts restless, knee-shaking energy into a quiet, enjoyable focus on whatever is in front of them. For adults, meditation does the same thing. Calmly placing full attention on a single object, whether one's breath or a candle's flame, helps the mind perceive whatever's happening with a pleasurable clarity that's absent when attention darts between myriad things or mental chatter.

Observing — extensively watching an object — is a quiet activity with focused attention, a form of meditation. It is like nothing else. We observers are mindful without trying. By losing ourselves in the countless details of whatever's in the eyepiece, we "grok" the celestial object with a satisfying completeness.

It's said that backyard astronomers perform useful science and, while that's sometimes true, it's more often the case that the activity is as wonderfully purposeless as playing jazz. Or, if one must cite a goal, it's simply to be amazed, or to have revelations.

For example, there's a break in the lunar Apennine mountain chain, a gap equaling the distance between Washington, D.C., and Baltimore. It looks like a place where lava flowed. But which way? A careful look-see reveals wrinkle patterns that make it clear the magma went from Mare Serenitatis into Mare Imbrium, not the other way around. Good luck getting anyone else excited about this — but, for observers, seeing exactly what happened 3.8 billion years ago confers an oddly profound satisfaction.

Sometimes it's not details that hold our focus. Sometimes the pleasure comes from observing something intensely alien. Who among us hasn't deliberately looked at the 8th-magnitude star HDE 226868 in Cygnus solely because, once a week, this massive star is hurled around like a wrestler flung disrespectfully by its companion X-1, the sky's surest black hole? There's nothing visually special here. And yet we cannot resist.

And who hasn't taken the trouble to observe the violent version of *West Side Story* unfolding in Virgo? This is the strange, blue, near-lightspeed jet being hurled off the west side of the monster galaxy M87. Its color largely comes from Cherenkov radiation, emitted when electrons break the lightspeed barrier. How can we not stare?

And how can I not feel a kinship with you, my fellow observers, at star parties and meets? Our bodies may be just as carbon-based as the other 8 billion members of *Homo bewilderus*. But we are not like them.

BY BOB BERMAN
Bob's newest book, Earth-Shattering *(Little, Brown and Company, 2019), explores the greatest cataclysms that have shaken the universe.*

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A tale of TWO

One large and one small, the Magellanic Clouds are familiar sights in the southern sky — and they can teach us a great deal about the Milky Way.

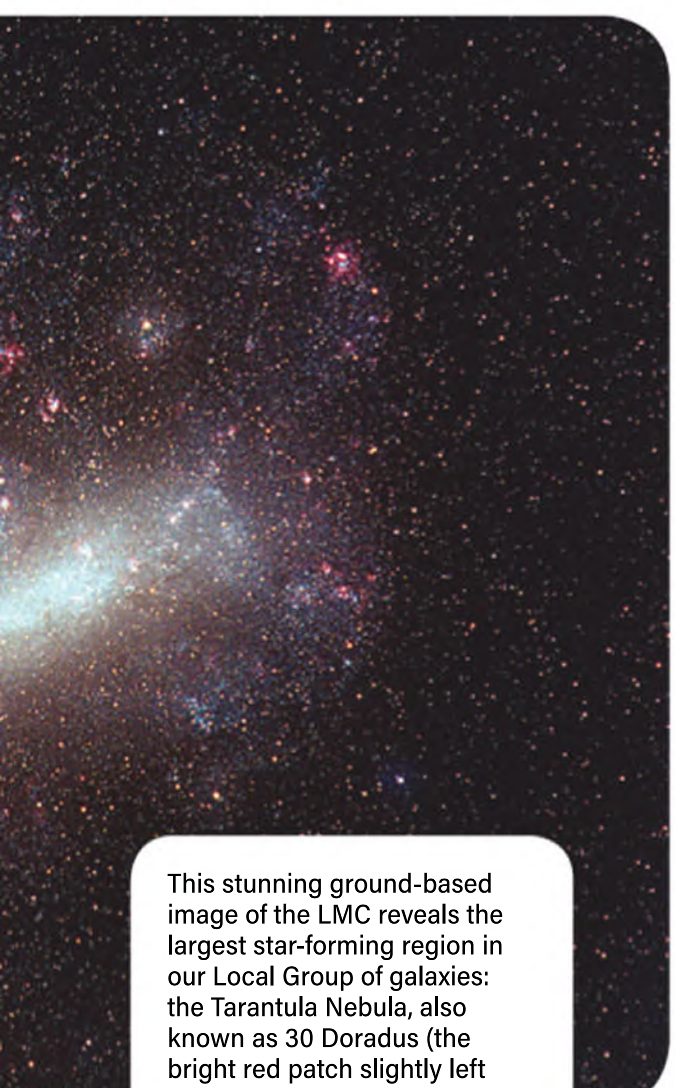
BY KNUT OLSEN

I FIRST SAW THE MAGELLANIC Clouds with my own eyes when I arrived at the Cerro Tololo Inter-American Observatory (CTIO) as a postdoctoral researcher in 1998. The Large and Small Magellanic Clouds (LMC and SMC) — a pair of dwarf galaxy companions to the Milky Way — had, of course, been observed by countless people before. But it still felt surreal to marvel at them while standing in a dark Chilean desert.

The clouds are part of the culture and lore of many groups of Indigenous peoples in South America, Australia, and southern Africa, where they were named to represent things like the feathers of rheas, a South American relative of the ostrich; the tracks of celestial animals (Setlhako); a pair of cranes (Prolggi); and an old couple sitting by a campfire (Jukara). Polynesian and European sailors also used the Magellanic Clouds as celestial guides, and Europeans later named them to recognize Ferdinand Magellan's 16th-century circumnavigation of the globe.

The Milky Way stretches above Cerro Tololo Inter-American Observatory, where the author worked for eight years studying the Large Magellanic Cloud (lower left) and the Small Magellanic Cloud (upper left). ANJA VON DER LINDEN

GALAXIES



This stunning ground-based image of the LMC reveals the largest star-forming region in our Local Group of galaxies: the Tarantula Nebula, also known as 30 Doradus (the bright red patch slightly left of center). ECKHARD SLAWIK

The SMC is chock-full of obscuring clouds of interstellar dust that block visible light. But the European Southern Observatory's Visible and Infrared Survey Telescope for Astronomy, equipped with infrared capabilities, allows astronomers to peer through the dust, revealing myriad stars. ESO/VISTA VMC

The Tarantula Nebula (30 Doradus), located in the LMC, is the most luminous known starburst region in the Local Group of galaxies. DAMIAN PEACH

The Milky Way's Orion Nebula, seen in this composite image captured by the Hubble Space Telescope, is the closest massive star-forming region to Earth.

ORION NEBULA: NASA, ESA, M. ROBBERTO (SPACE TELESCOPE SCIENCE INSTITUTE/ESA) AND THE HUBBLE SPACE TELESCOPE ORION TREASURY PROJECT TEAM

But what made seeing the LMC and SMC special to me was that I had spent the previous three years working with data on the clouds, collected by the Hubble Space Telescope. This served as the basis of my Ph.D. thesis, which focused on the star formation history and the oldest star clusters in the LMC. Yet I had never seen the clouds in person.

My Ph.D. adviser at the University of Washington, astronomer Paul Hodge, who sadly passed away late last year, had taken a boat to South Africa and spent weeks at Boyden Observatory to collect his own thesis data on the clouds. But my data had arrived on digital tapes in the mail. Moving to Chile was going to be the start of my own scientific adventure. And my personal encounter with the Magellanic Clouds surely was an unforgettable experience.

The Magellanic Clouds

Besides being spectacular nighttime objects, the Magellanic Clouds are popular targets for professional astronomers. In fact, they've been featured in more than 15,000 research papers, a total to which my thesis added two. There are many reasons for their popularity, including their proximity. They are as nearby as galaxies get, roughly 160,000 light-years for the LMC and some 200,000 light-years for the SMC. This means they are close enough to be studied in detail, yet far enough away that their stars can be approximated as being at uniform distances — unlike those of the Milky Way, where it can be difficult to see the forest for the trees.

The clouds also have a number of notable features, such as the LMC's Tarantula Nebula, usually referred to as 30 Doradus, which is the largest star-forming region in our Local Group of galaxies. Northern Hemisphere astronomers are generally more familiar with the Orion Nebula (M42), a nursery for massive stars in our own galaxy. But, if placed at the distance of the Orion Nebula, 30 Doradus would span across one-fifth the sky, even casting shadows at night! At the center of 30 Doradus is a dense, massive cluster of stars called R136, which, with an age less than about 2 million years, houses stars so young that even the most massive members have yet to finish their short lives.

The stars just outside R136 but still within 30 Doradus formed a few million years earlier, giving them more time to evolve. The light from one of these stars, caught in the act of ending its brief career by exploding as a supernova, famously first reached Earth in 1987. (At that point, I was in high school and more interested in electric guitars than astronomy.) Oscar Duhalde, a telescope operator at Las Campanas Observatory, discovered the unfamiliar "new" LMC star when he stepped outside to gaze at the skies. The event, named SN 1987A, kicked off a frenzy of observations and renewed focus on the study of supernova explosions, particularly how they can be used to measure distances. This culminated in the 1998 discovery of dark energy by two supernova survey teams.

My journey to the clouds

Because massive stars evolve quickly and with high complexity, they challenge our ability to model and understand the physical processes that occur within them. Phil Massey is one of the prominent astronomers who have spent their careers studying them. In 2001, he was scheduled to observe the LMC's red supergiants, which evolved from stars with masses between about 10 and 25 times the mass of the Sun, but his travel plans were interrupted by the tragedy of September 11.

I was both the local instrument scientist for the spectrograph Massey was scheduled to use and had overlapping scientific interests, so he invited me to join the project if I would collect the data. The Blanco 4-meter telescope's Hydra-CTIO spectrograph was a finicky instrument, but it had great capabilities. It could collect light from more than 100 objects at a time using optical fibers mounted to small magnetic buttons that were precisely placed on a metal plate by a high-speed robotic arm.

When it worked smoothly, watching it go was pure joy. The spectra, which chart an object's light across a range of energies, rolled in by the dozens. But when it misbehaved, it was misery, forcing trips to the Cassegrain cage where it was mounted to the telescope to disentangle a rat's nest of crossed fibers, leading to hours of lost time. Luckily, Massey's run was scheduled right after two nights of work aimed at fixing Hydra's technical problems. The observing run was nearly flawless, yielding hundreds of spectra of LMC red supergiants.

From those and other spectra, Massey, along with astronomer Emily Levesque of the University of Washington, developed techniques to measure the temperatures of red supergiants, resulting in a revised temperature scale that resolved a previous disagreement with theoretical stellar models. They also identified several stars with radii of about 1,500 times that of the Sun, making them some of the largest stars known.

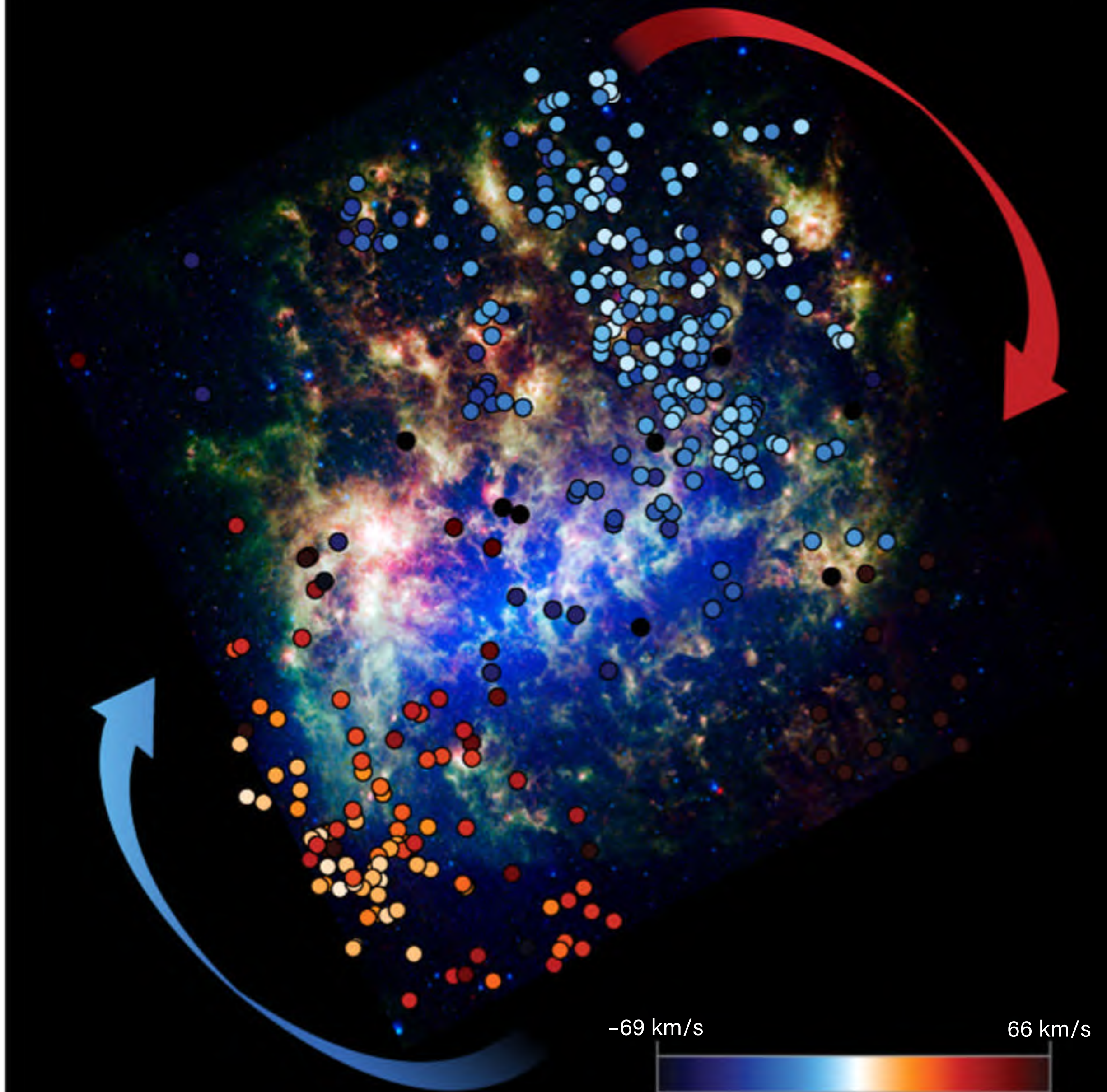
The pair also recently applied these techniques to observations of the red supergiant Betelgeuse, demonstrating that the star's temperature had changed little even while it famously dimmed by more than a magnitude. They concluded that the dimming was caused by an episodic release of dust grains from the star's atmosphere.

My own interest in red supergiants lay in using them as probes of the LMC's gravitational structure. The spectra of the stars allowed us to measure their velocities along the line of sight. The faster the supergiants were moving, the more Doppler shifted their spectra would be. To determine their speeds, I would digitally slide each star's spectrum over a reference spectrum for which I knew the corresponding velocity. I'd then simply measure the shift between the lines.

In the 1970s, Vera Rubin and other astronomers used similar techniques to measure the velocities of the stars orbiting in galaxies such as Andromeda and M33. They found that as they looked farther from the galactic centers, the orbital velocities were too high to be explained by just the gravitational pull from the luminous matter within the galaxies. This discovery of dark matter has since stood the test of time; it is now central to our consensus understanding that galaxies formed through the settling of ordinary matter onto concentrated dark matter halos.

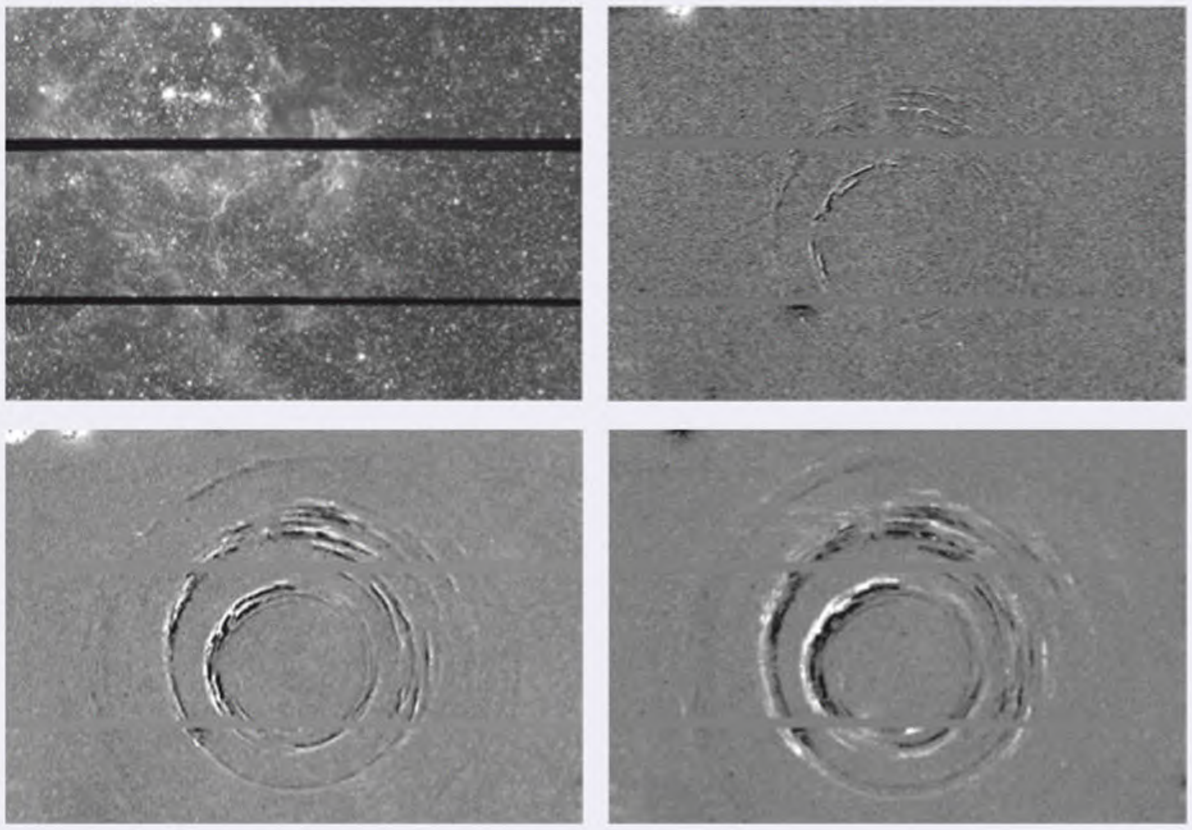
The presence of dark matter means that the stars located in the outskirts of disk-shaped galaxies typically maintain constant high orbital speeds, despite the fact they are far from their galactic cores. In other words, the galaxies' rotation curves are "flat." And because the red supergiants located in the outskirts of the LMC fall on a flat rotation curve, they indicate the Milky Way's largest satellite galaxy also has a significant amount of dark matter.

ODDLY ORBITING STARS



The LMC is tilted with respect to our line of sight. As its disk spins clockwise, the stars at the top right appear to recede, stretching (or redshifting) their light to redder wavelengths. In the same way, the stars at the bottom left appear to approach us, blueshifting their light to shorter wavelengths. About 95 percent of the LMC's stars follow this pattern, but the other 5 percent — shown here as red and blue circles, indicating whether their light is redshifted or blueshifted, respectively — have the opposite pattern. The deviation suggests these stars did not originate in the LMC, but instead have been captured by the LMC from the SMC. SPITZER IMAGE: MARGARET MEIXNER AND KARL GORDON (SPACE TELESCOPE SCIENCE INSTITUTE/AURA/NASA); COMPILATION BY K. OLSEN (NOIRLAB/AURA/NSF)

ECHOES OF SUPERNOVA 1987A



TOP LEFT: The LMC's ethereal nebulosity and rich star field are apparent in this October 2001 image. TOP RIGHT: Subtracting the first shot from a second image taken in December 2001 highlights changes in brightness, revealing a nested set of circles. White pixels were brighter in the December image, black pixels were fainter, and gray pixels did not change. BOTTOM ROW: Subtracting the original shot from others taken in 2002 (left) and 2004 (right) shows that the circles are rippling outward from the center — the site of SN 1987A — at the speed of light. These echoes are reflected light from the original supernova, observed almost 20 years after the initial blast. ARMIN REST (HARVARD)/SUPERMACHO/EHS COLLABORATION

Dark matter leads to light echoes

Fifty years after its discovery, we still don't know what dark matter is made of — but not for lack of trying. In the 1990s, a leading candidate for the composition of dark matter was massive compact halo objects (MACHOs): unseen black holes, neutron stars, or dim brown dwarfs.

Several groups looked for signs of such objects by observing stars in the LMC and hoping to catch the sudden brightening that would occur if a MACHO passed directly in front of it. The foreground MACHO would act as a gravitational lens, with its invisible mass bending the light rays from the background star and amplifying the light we see. (This is technically an example of a microlens, because the distorted shape of the background star would be measured in micro-arcseconds.) The result would be a predictable increase in brightness of the background star as the MACHO approached, followed by a dimming as it moved away; the whole event might last for hours, days, or weeks. Astronomers have found a few microlensing events in the LMC, and thus a potential source of dark matter, but more events are needed before definitive conclusions can be made.

Around 2005, I participated in a project led by physicist Christopher Stubbs of Harvard University and astronomer Armin Rest of the Space Telescope Science Institute, in which we observed fields in the LMC every other night. The goal was to detect brightness changes in stars that would be indicative of microlensing events. Rest developed software that subtracted every microlensed image from a previous template image, carefully tracking the offsets, distortions, and resolution of the pair. He would then identify objects that varied between the two images and trace how their brightnesses evolved over time. The team would visually scour these light curves, as well as postage stamp-sized versions of the difference images, separating true astronomical objects from image artifacts and other junk.

In late 2003, Gajus Miknaitis, then a graduate student at the University of Washington working on the project, found strange objects that he called "moving nebular ghosts." I calculated that if these were in the LMC, they would have to be moving at the speed of light. He soon looked at the full-size difference images, rather than the postage stamp versions, and noticed that the ghosts formed concentric circles on the sky. At the center of those circles was SN 1987A.

We were seeing light echoes — the original light from the supernova reflected off surrounding dust clouds in the LMC, like sound waves bouncing through the Alps. The echoed light's pinball path meant it took extra time to make it to Earth, arriving about 15 years after the light that came straight from the supernova. These light echoes form rings tracing the surfaces of surrounding dust clouds that are located the same distances from the supernova. Individual rings with different radii represent reflections from sheets of dust at different distances from the explosion. It turned out that these light echoes had been discovered before by another project, so we had simply rediscovered them.

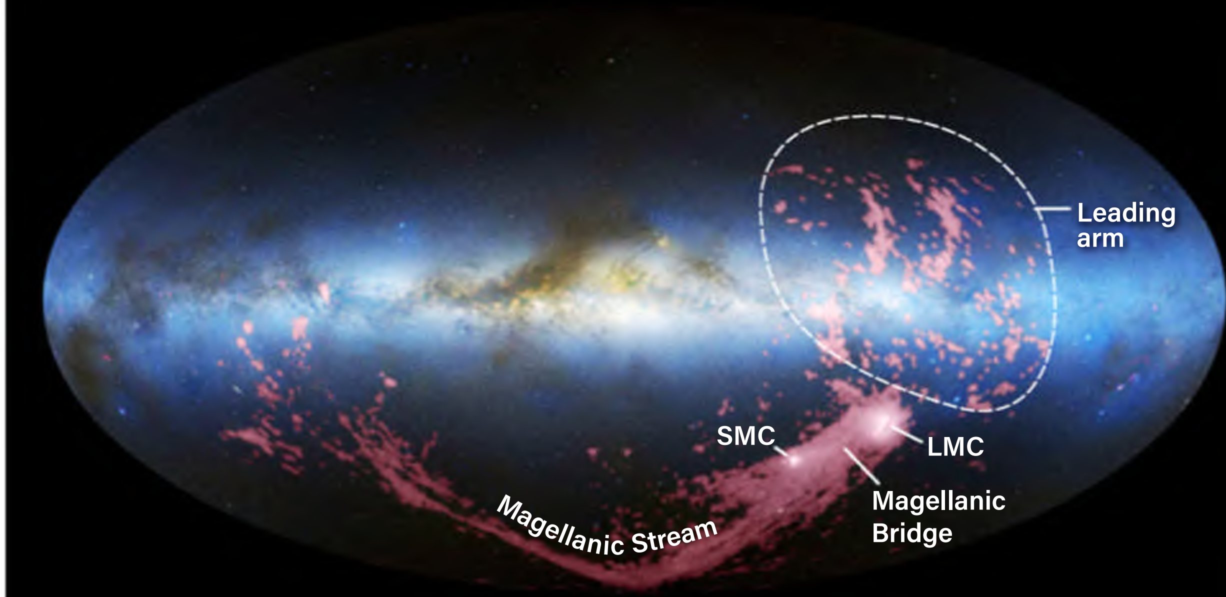
But as Rest continued to scrutinize the observations, he started finding additional light echoes with arcs that corresponded to locations other than that of SN 1987A. These new echoes were from supernovae that had exploded in the LMC centuries ago, yet we were still seeing the original explosions in delayed form. These light echoes revealed a unique way to study supernovae long after their initial blasts. And while our project ultimately did not find compelling evidence for MACHOs as an important source of dark matter, we still found something totally unexpected — and potentially quite powerful.

Following my work analyzing red supergiants in the LMC, my colleagues and I used the Hydra-CTIO spectrograph to measure velocities of other stars in the LMC. We concentrated on stars much older than the young red supergiants to see how the passage of billions of years would affect their dynamics, and eventually gathered thousands of spectra.

After dissecting the data, we found that most of these older stars had velocities that traced the same flat rotation curve as the red supergiants; however, they also exhibited a bit more random noise, which is expected given they've experienced billions of years of orbital evolution. But roughly 5 to 10 percent of the total had velocities that suggest they are orbiting in the opposite direction as the rest — very strange! It would be just as weird if one of the planets in our own solar system orbited the Sun in the wrong direction.

Because we could only measure the velocity of the stars along the line of sight (motion toward or away from us), another possibility was that the stars are orbiting in the same direction as the rest but are highly inclined, traveling well above and below the disk of the LMC. We concluded this was a more likely situation, and recently confirmed it by obtaining full 3D velocities of the stars using data from the Gaia satellite. But that still didn't explain how this small subset of oddly orbiting stars got on their current track.

A COSMIC CONNECTION



The Magellanic Stream stretches almost halfway around the Milky Way, as revealed by 21-centimeter (radio) emissions from neutral hydrogen atoms (pink). This long stream of gas leads and trails behind the LMC and SMC, as well as connects the two clouds via a bridge of neutral hydrogen.

Tracing stars back through time

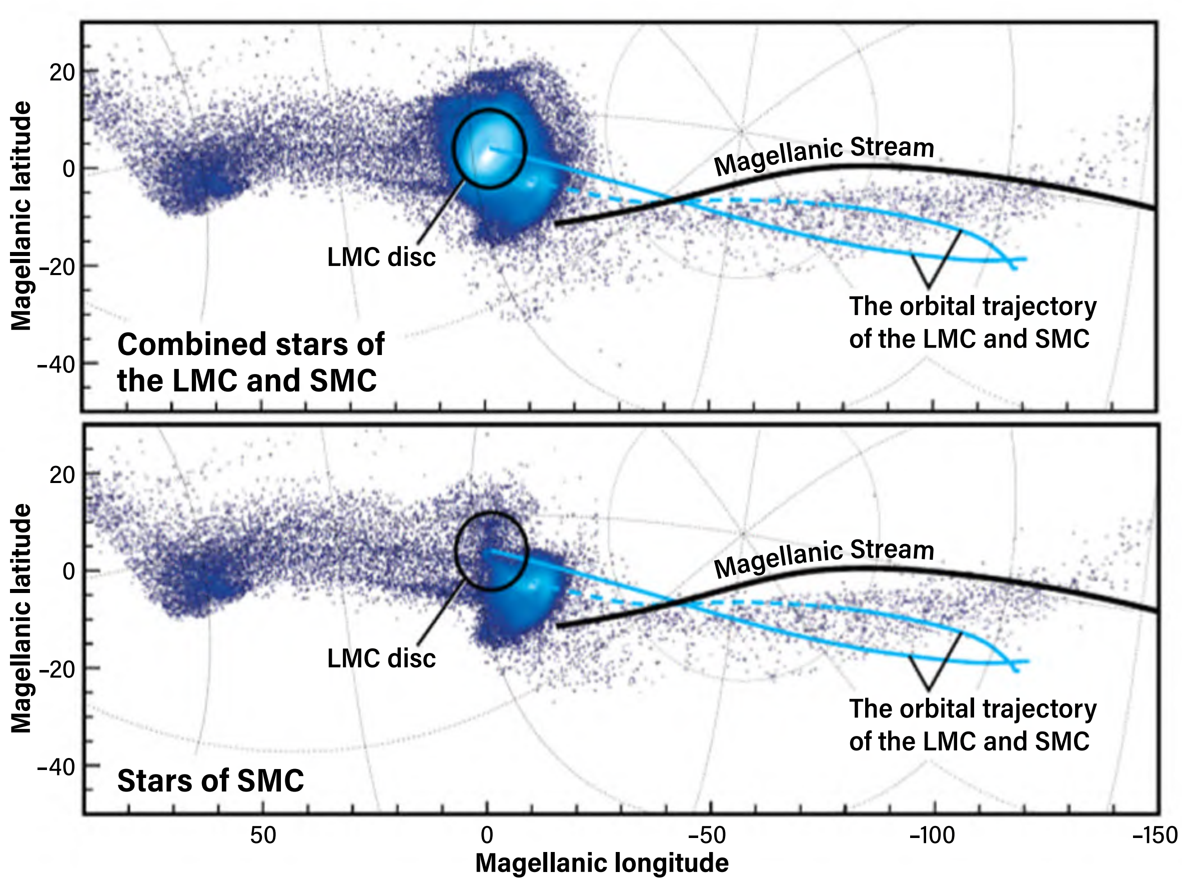
We have known for a long time that the LMC and SMC are a pair of gravitationally interacting galaxies. The most obvious result of this interaction is the Magellanic Stream and its leading arm, which form of a twisted ribbon of neutral hydrogen gas that astronomer David Nidever of Montana State University found extends over more than half the sky.

This ribbon includes streamers that connect to both the LMC and SMC, with two of these filaments converging on 30 Doradus. Viewed from the LMC, the streamers have the same velocities as those of the strangely moving stars we had previously found. Moreover, we measured the abundance of iron in some of our weird stars, finding they had surprisingly little iron compared to other stars in the LMC. However, they were a good match for SMC stars.

Based on the streamers and seemingly migrant stars, we concluded that the LMC had stolen stars from its smaller sibling, the SMC. These displaced stars are now orbiting in front of and behind the LMC's disk. Plus, the arms connecting the LMC and SMC were apparently ripped out along with these stars and are now falling onto the LMC's disk, right at the location of 30 Doradus. This scenario would explain why 30 Doradus is forming stars so aggressively. The infalling material provides external pressure on 30 Doradus and keeps the stellar winds and supernovae within from completely blowing away the nearby gas, which would halt further star formation. These ripped-out, massive stars might also be the source of the microlensing events that were seen in the 1990s, which would further rule out MACHOs as a significant source of dark matter scattered throughout the Milky Way.

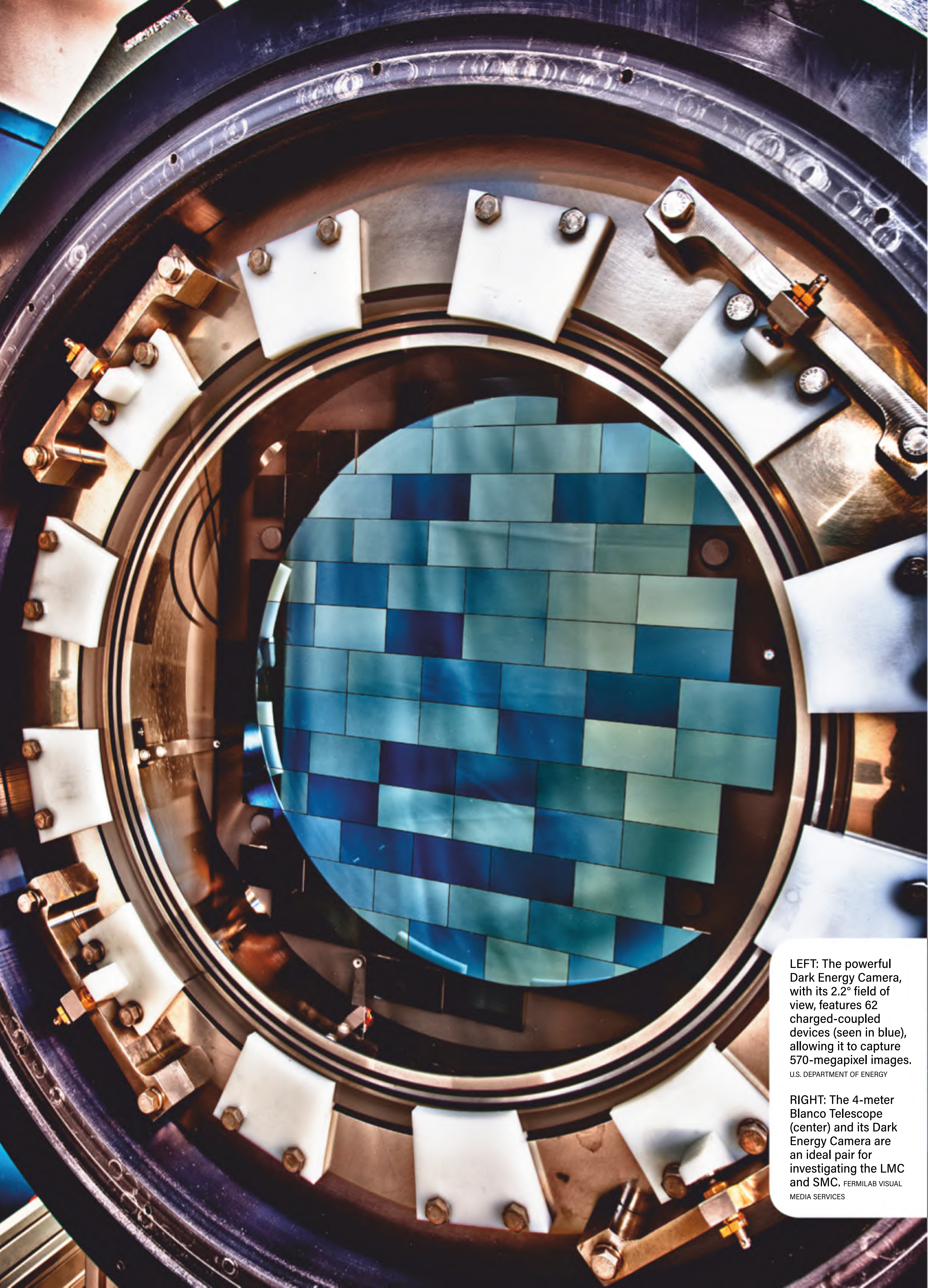
With better data and more sophisticated theoretical models, exactly how the Magellanic Clouds have been interacting with each other over the eons is becoming clearer by the year. Astronomer Nitya

MIXING THE MAGELLANIC CLOUDS



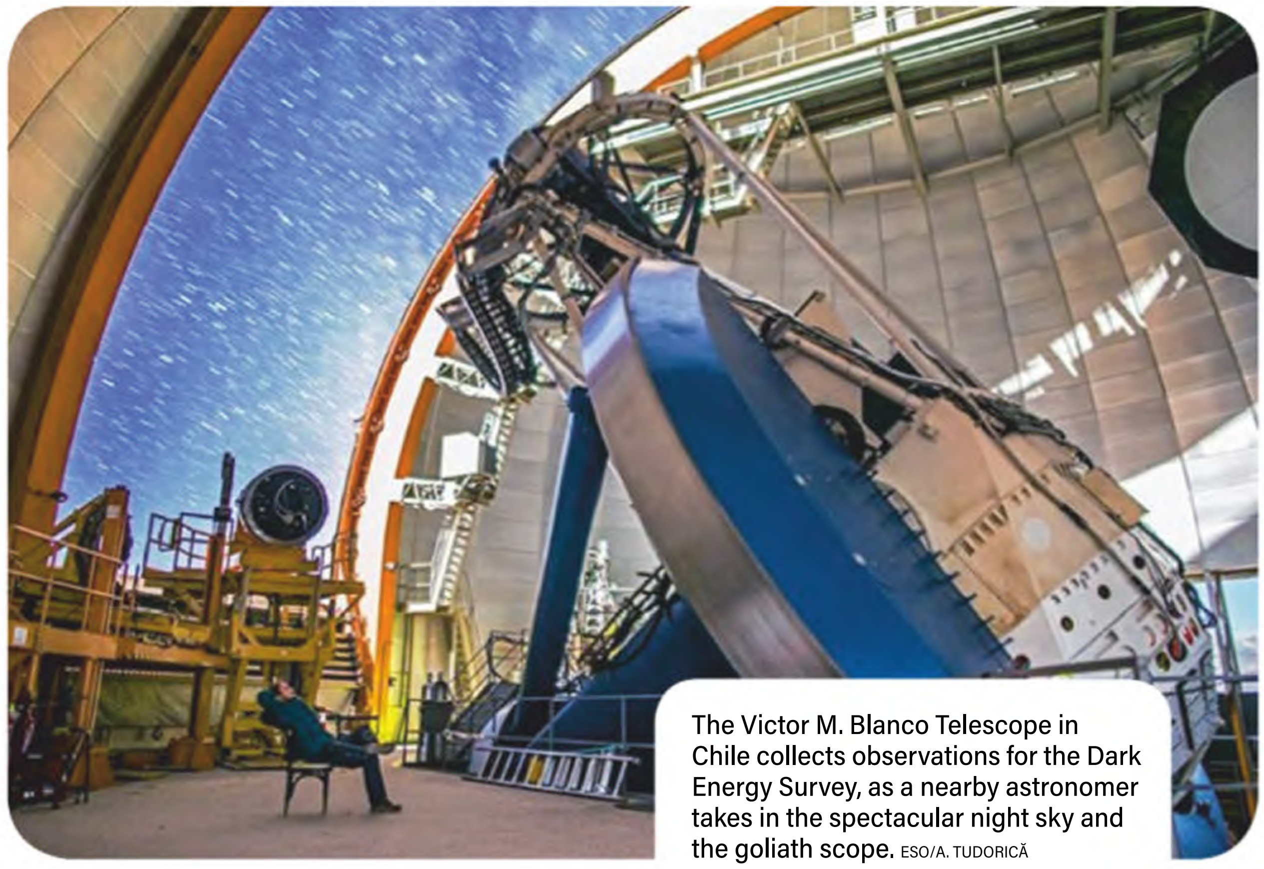
A simulated collision of the LMC and SMC reproduces many of the observed features of the Magellanic system, including the leading arm and trailing stream of material, as well as the presence of SMC stars in the LMC's disk. The top panel shows the combined stars of the LMC and SMC in the simulation, while the bottom panel shows only the SMC stars, demonstrating that most of the stellar debris polluting the system likely originates from the SMC. GURTINA BESLA; REPRODUCED FROM BESLA ET AL.2013, *MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY*, 428, 2342

MAGELLANIC STREAM MAP: L. NIDEVER, ET AL., NRAO/AUI/NSF AND MELLINGER, LEIDEN/ARGENTINE/BONN SURVEY, PARKES OBSERVATORY, WESTERBORK OBSERVATORY, AND ARECIBO OBSERVATORY



LEFT: The powerful Dark Energy Camera, with its 2.2° field of view, features 62 charged-coupled devices (seen in blue), allowing it to capture 570-megapixel images. U.S. DEPARTMENT OF ENERGY

RIGHT: The 4-meter Blanco Telescope (center) and its Dark Energy Camera are an ideal pair for investigating the LMC and SMC. FERMILAB VISUAL MEDIA SERVICES



The Victor M. Blanco Telescope in Chile collects observations for the Dark Energy Survey, as a nearby astronomer takes in the spectacular night sky and the goliath scope. ESO/A. TUDORICĂ

Kallivayalil of the University of Virginia and others have been hard at work measuring the 3D motions of nearby galaxies, including the Magellanic Clouds. They have determined that the clouds are only loosely bound, if at all, to the Milky Way. Astronomer Gurtina Besla of Steward Observatory has led work to model the motions of the clouds, finding that the LMC and SMC have made several close passes over the past few billion years — and that they likely collided with each other about 300 million years ago.

Such a collision would naturally explain how the LMC stripped stars and gas from the SMC, as well as how the Magellanic Stream formed. Furthermore, it predicts that stars from the clouds should have been flung far from their parent galaxies, meaning they'd now be spread out over large areas of the Southern Hemisphere's night sky. This is why my current interest, and that of many others, is to map the sky in search of these stars.

Charting the nearby southern sky

One of the best instruments for mapping large areas of southern sky is the Dark Energy Camera, or DECam, which is also mounted on the Blanco telescope at CTIO. This instrument has a field of view 4.5 times wider than the Full Moon and was built to conduct the Dark Energy Survey (DES), which aims to measure the properties of dark energy, as well as chart the halo of the Milky Way and explore the outskirts of the Magellanic Clouds.

In 2015, two groups — one led by astrophysicist Keith Bechtol of the University of Wisconsin-Madison and the other by Sergey Koposov of Carnegie Mellon University — used the DES data to discover eight new extremely faint, low-mass dwarf galaxies. Some of these galactic specters have locations, distances, and velocities that make them likely satellites of the Magellanic Clouds — in other words, satellites of satellites.

The Survey of the MAgellanic Stellar History, or SMASH, collaboration, led by Nidever, and the DES Collaboration have also found stars from the Magellanic Clouds as far as 20° from the LMC and SMC, showing that they extend much farther than previously thought. Finally, astronomers Vasily Belokurov of the University of Cambridge and Denis Erkal of the University of Surrey have used data from the Gaia satellite to map the clouds' stars with stunning detail. Their 2018 paper, "Clouds in arms," shows that the SMC and LMC span roughly 15° and 30°, respectively, and they both have arms that extend far beyond that.

It has been 22 years since I first saw the Magellanic Clouds with my own eyes. Since then, I've learned just how closely connected they are to so many astronomical discoveries. But, even more importantly, I've realized they still hide many surprises.

When I gaze at them now, I imagine what they might have looked like over their lifetimes: a pair of galaxies, condensed from gas settling onto lumps of dark matter, dancing around each other while simultaneously accelerating toward the Milky Way. As they race to meet our galaxy, they occasionally slam into each other, tossing out great plumes of stars and gas both ahead of and behind them. During their tango, the pair occasionally flares up as colliding gas kicks off bursts of intense star formation. And all the while, a small audience of faint dwarf satellites sits on the periphery.

Some of this picture might be exaggerated by my imagination, but it is also almost certainly missing some fascinating details that I couldn't yet dream of. I've learned that scientific research is like jumping into a canoe on an uncharted river — even with a goal in mind, you often have little idea of what lies ahead, other than almost certain adventure.

Acknowledgements

I dedicate this article to Paul Hodge, my trusty guide to graduate school, the Magellanic Clouds, astronomy, and the Cascades. He was exceptional in his kindness, humility, intelligence, and curiosity, and I miss him deeply. I thank all of my collaborators and colleagues, who have made this astronomical adventure fun and exhilarating.

Knut Olsen *is an astronomer at the Optical-Infrared Astronomy Research Laboratory. He now lives in Tucson, Arizona, but will always remember his time under the southern sky.*

HOW GALILEO blended science and art

Always drawing, sketching, or painting, Galileo Galilei saw the cosmos through an artist's eye.

BY DAN FALK

GALILEO GALILEI (1564–1642) is often recognized as the founder of modern physics, perhaps even the father of modern science itself. But this popular image neglects one important facet of his Renaissance personality: Galileo the artist.

Art and science have always been intertwined, and Galileo exemplified how they can inspire and inform one another. In addition to being a skilled observer and a keen thinker, he was a talented artist, trained in cutting-edge perspective techniques pioneered by his fellow Italian artists. His artistic sensibility played a key role in his scientific insights, leading some 400 years ago to a new picture of the universe.

A MAN OF SCIENCE

Galileo is remembered first and foremost as a scientist. His father was a skilled musician, teacher, and music theorist who produced several surviving compositions. Galileo's mother was an educated woman from a well-to-do family who could claim a cardinal among her relatives. In 1581, the young Galileo set off to Pisa to study medicine — more to satisfy his father's desires than his own. It soon became clear that his real interest was in mathematics; he had also been interested in astronomy

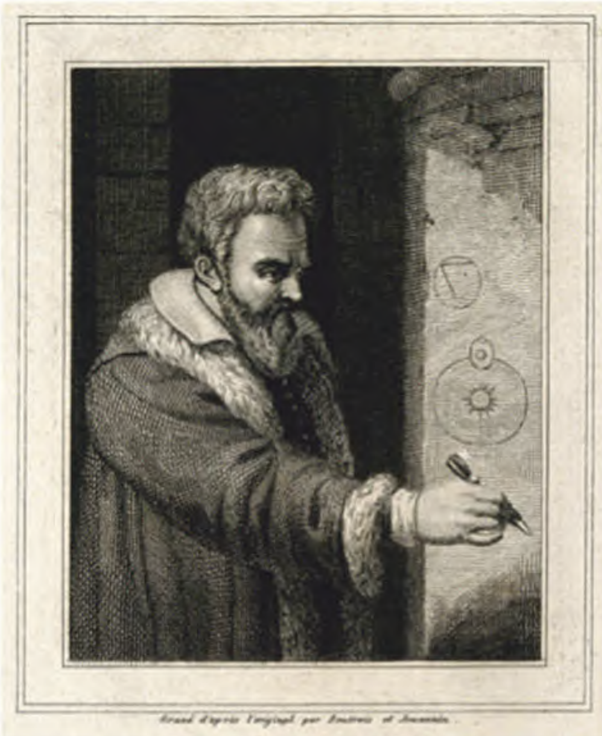
Earthshine occurs when sunlight reflecting off Earth illuminates the portion of the Moon still in shadow. Galileo ultimately — correctly — concluded this was the source of what he called the Moon's "secondary light." This image, taken from New South Wales, Australia, shows the daylight side of the Moon illuminated directly by the Sun at right, with earthshine illuminating the nighttime portion of the Moon at left. DYLAN O'DONNELL

from an early age. By the 1590s, he was already drawn to the Copernican model of the heavens, in which the Sun, rather than Earth, is recognized as the center of our system of planets. When a new star appeared in the sky in 1604 — the supernova now known as Kepler's Star — Galileo delivered a series of lectures on the remarkable object, speculating on its significance.

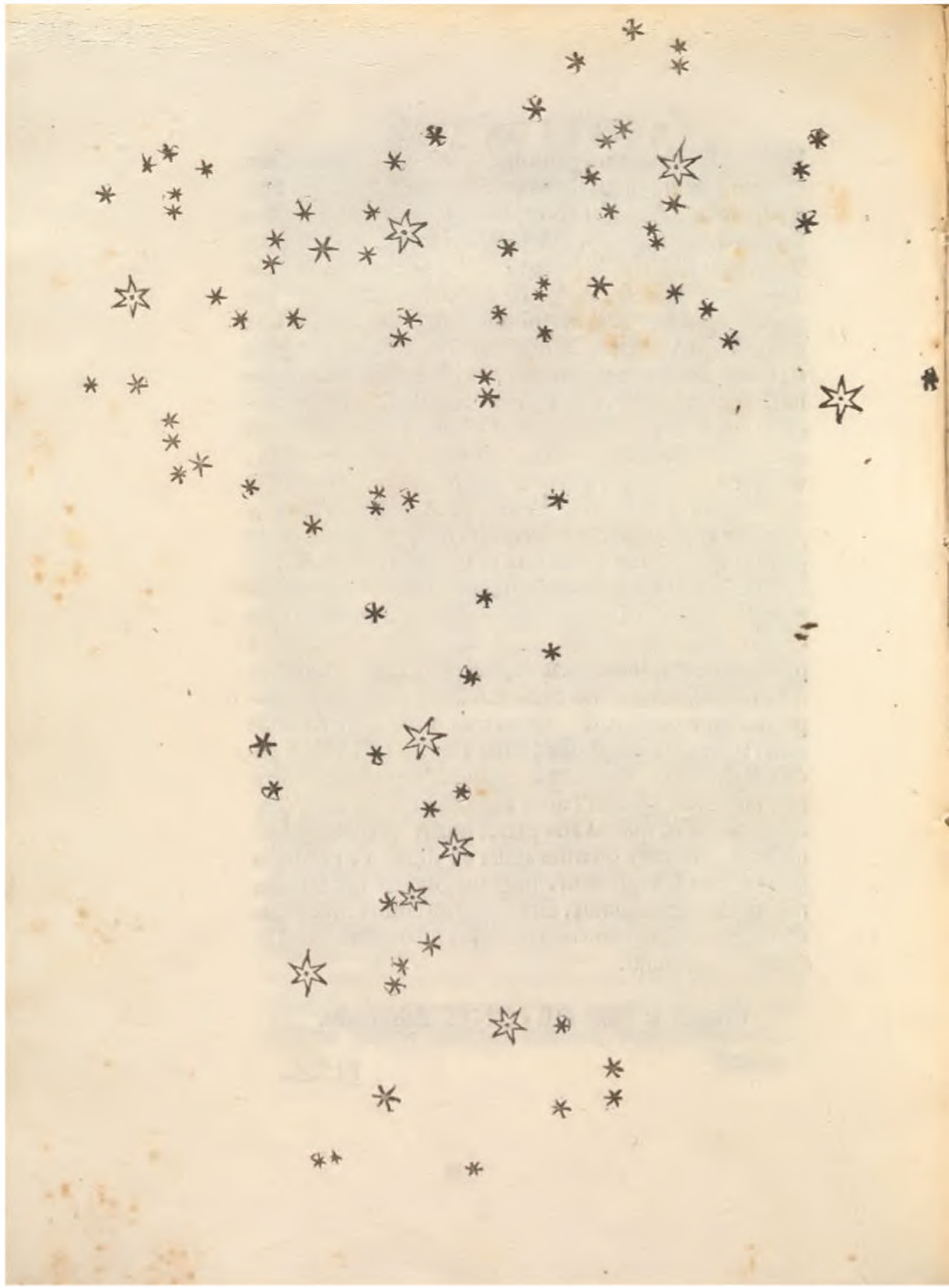
Galileo was teaching mathematics at the University of Padua in 1609 when he learned of a curious optical device from Holland that was said to make distant objects appear as if they were much closer. Improving on the original Dutch invention, Galileo made a device that could magnify 20 or even 30 times. In the fall of 1609 and the winter of 1610, he aimed this instrument at the night sky and made a series of jaw-dropping discoveries. With his telescope, he observed that the Moon has an irregular surface peppered with mountains, craters, and flat plains; that the Milky Way is made up of thousands of stars too faint to see with the unaided eye; and that Jupiter is accompanied by four "stars" seemingly in orbit around the great planet. All of these are recounted in *Sidereus Nuncius* (*Starry Messenger*), which Galileo published in March 1610. He would later analyze sunspots and discover that Venus, like the Moon, displays distinct phases.

Physics also commanded Galileo's attention. Throughout his life, he studied motion — especially accelerated motion — by experimenting with falling bodies and by rolling objects down inclined planes. He also studied what

Galileo Galilei was not only a man of science, but also an accomplished artist with a keen eye. Historians speculate his talent for art ultimately helped him decipher the physical reality of the objects he observed. GALILEO GALILEI (1564-1642). OIL PAINTING AFTER JUSTUS SUSTERMANS, 1635. COURTESY OF THE WELLCOME COLLECTION, ATTRIBUTION 4.0 INTERNATIONAL (CC BY 4.0)



ABOVE: This line engraving of Galileo depicts the astronomer alongside a drawing that shows Earth's orbit around the Sun, as well as the Moon's orbit around Earth. GALILEO GALILEI. LINE ENGRAVING BY BOUTROIS & JOUANNIN AFTER J. A. LAURENT, 1822. COURTESY OF THE WELLCOME COLLECTION, ATTRIBUTION 4.0 INTERNATIONAL (CC BY 4.0)



RIGHT: Galileo turned his telescope on familiar constellations, including Orion (left). With the aid of greater magnification, he identified numerous "new" stars (drawn as small star shapes) amidst the previously known naked-eye stars (depicted with larger star-shaped outlines) of the Hunter's belt and sword. Similarly, he identified many new stars among the familiar luminaries of the Pleiades (right). GALILEI, GALILEO. *SIDEREUS NUNCIUS.* APUD THOMAM BAGLIONUM, 1610. COURTESY OF THE SMITHSONIAN LIBRARIES (HTTPS://DOI.ORG/10.5479/SIL.95438.39088015628597)

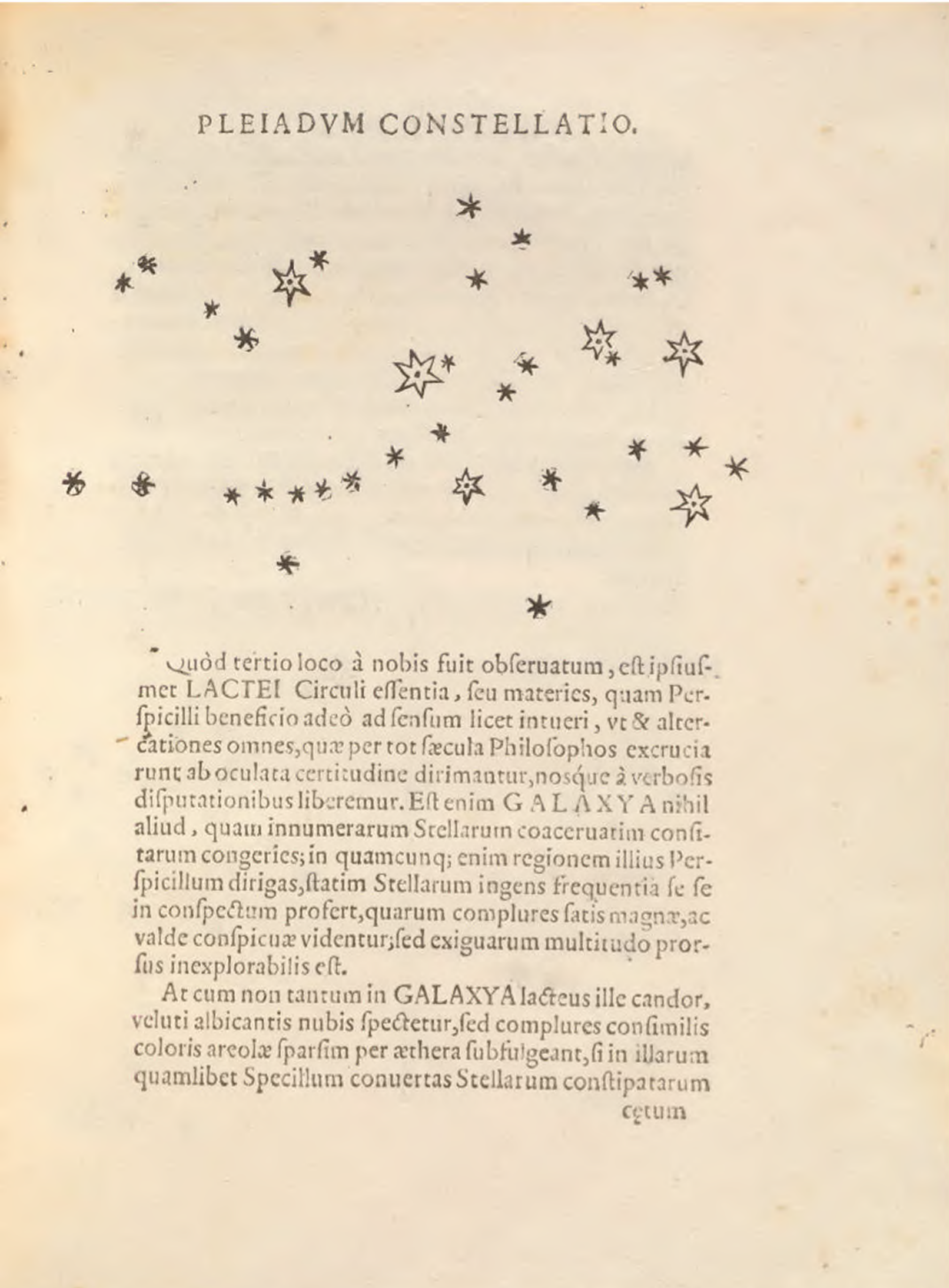
we now call inertia, investigated the strengths of various materials, and developed the modern science of mechanics.

All of these facts paint the traditional picture of "Galileo the scientist." But he was also a skilled artist, drawing in part from knowledge that he acquired at the Accademia delle Arti del Disegno (Florentine Design Academy), where painters, sculptors, and architects gathered to discuss the intricacies of their profession. Galileo is believed to have studied there in 1585 and was elected to its membership in 1613. At the Academy, he would have been exposed to key ideas such as linear perspective — the technique employed by artists to render objects in three dimensions, developed a century earlier by the architect and designer Filippo Brunelleschi (1377–1446). Artist and polymath Leon Battista Alberti (1404–72) had produced two lavishly illustrated treatises in which he expounded on the importance of realism and three-dimensionality; it's likely that Galileo absorbed these ideas.

Galileo also appears to have struck up lasting friendships with some of the leading artists of his day. They often sought out his opinions, recognizing his skill as a draftsman and as a master of perspective. Galileo collected paintings and loaned money to artists, as well. "He really thought of himself as being deeply involved in the art world," says Eileen Reeves, a professor of comparative literature at Princeton University and the author of *Painting the Heavens: Art and Science in the Age of Galileo* (Princeton University Press, 1997). "I see Galileo as being very interested in the arts and in visual representation in general."

SCIENCE THROUGH ART

This specialized knowledge paid off when Galileo first aimed his telescope at the Moon, although he initially struggled to interpret what he saw. While light and dark areas on the Moon are visible to the naked eye, his telescope revealed what appeared to be mountains and valleys. But how could he be sure? After all, he was viewing them from above, as well as from about a quarter of a million


PLEIADVM CONSTELLATIO.

Quòd tertio loco à nobis fuit obſeruatum, eſt ipſiuſmet LACTEI Circuli eſſentia, ſeu materies, quam Perſpicilli beneficio adeò ad ſenſum licet intueri, vt & altercationes omnes, quæ per tot ſæcula Philoſophos excruciarunt ab oculata certitudine dirimantur, noſque à verboſis diſputationibus liberemur. Eſt enim GALAXYA nihil aliud, quam innumerarum Stellarum coaceruatim conſitarum congeries; in quamcunq; enim regionem illius Perſpicillum dirigas, ſtatim Stellarum ingens frequentia ſe ſe in conſpectum profert, quarum complures ſatis magnæ, ac valde conſpicuæ videntur; ſed exiguarum multitudo prorſus inexplorabilis eſt.

At cum non tantum in GALAXYA lacteus ille candor, veluti albicantis nubis ſpectetur, ſed complures conſimilis coloris areolæ ſparſim per æthera ſubfulgeant, ſi in illarum quamlibet Specillum conuertas Stellarum conſtipatarum

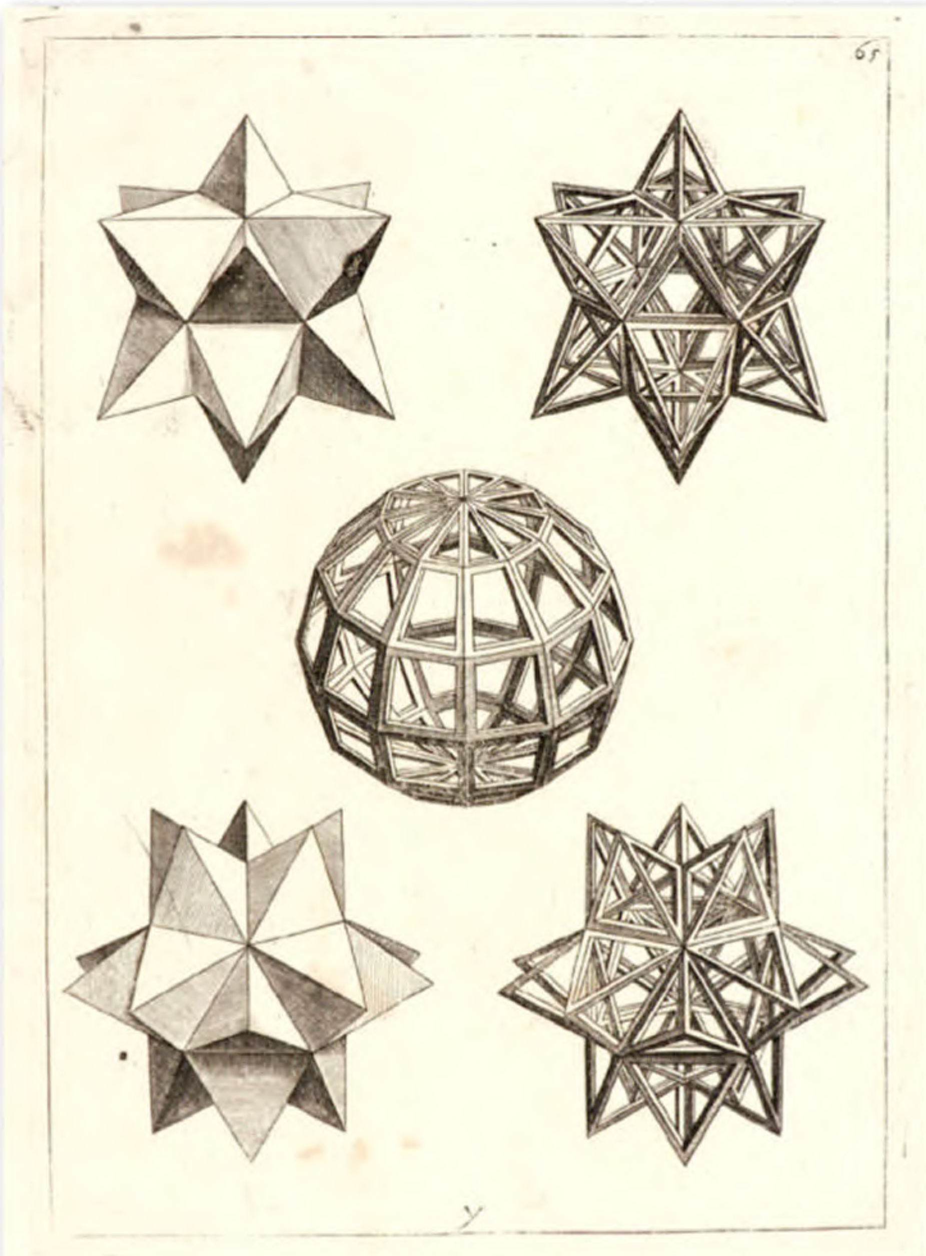
cętum

ABOVE: These engravings of the Moon (top), based on Galileo's wash drawings, show a crater on the terminator larger than any that truly exists. It may be the crater Albategnius (indicated by an arrow on the bottom photo), clearly embellished by Galileo or his engraver. GALILEI, GALILEO. *SIDEREUS NUNCIUS*. APUD THOMAM BAGLIONUM, 1610. COURTESY OF THE SMITHSONIAN LIBRARIES (HTTPS://DOI.ORG/10.5479/SIL.95438.39088015628597); NASA'S SCIENTIFIC VISUALIZATION STUDIO

miles (384,400 kilometers) away. So, he sketched what he saw and tried to make sense of it. "He must have drawn on the tricks of perspective that he had learned years before," says Reeves. For Galileo, "drawing was a means of discovery, a form of thinking."

Galileo paid particular attention to the features visible along the terminator, the line that divides the light and dark parts of the Moon. He noticed how the peaks of mountains on the dark side are lit up first, with the sunlight slowly making its way down their sides. As he observed the play of sunlight on those lunar mountains, Galileo was reminded of familiar sights on our own planet. As he wrote in *Sidereus Nuncius*, "There is a similar sight on earth about sunrise, when we behold the valleys not yet flooded with light though the mountains surrounding them are already ablaze with glowing splendor on the side opposite the sun. And just as the shadows in the hollows on earth diminish in size as the sun rises higher, so these spots on the moon lose their blackness as the illuminated region grows larger and larger."

One likely source of inspiration for these insights was a book by Daniele Barbaro called *La Pratica della Perspettiva*, published in 1569. It contained, among other things, lessons on how to draw spheres — not only perfectly smooth spheres, but also spheres with various protuberances. Another book, Lorenzo Sirigatti's *La Pratica di Prospettiva*, published in 1596, contained similar practical instructions. Galileo also sat in on lessons on Euclidean geometry taught by the Florentine mathematician Ostilio Ricci (1540–1603).



LEFT: References such as Lorenzo Sirigatti's *La Pratica di Prospettiva*, a page from which is shown here, guided Galileo's understanding of perspective. Such books taught how to draw geometric shapes with various surface features. This knowledge likely helped Galileo understand that he was looking down at mountains and crater walls on the Moon. ARTOKOLORO/ALAMY STOCK PHOTO

RIGHT: Galileo made these watercolors from observations of the Moon through his telescope in late 1609. They are the first realistic depictions of the Moon ever created, and later served as a basis for the engravings in *Sidereus Nuncius*, although the engraver likely took some artistic liberties. FIRENZE, BNC, GALILEIANO 48, F. 28R; BY PERMISSION OF MINISTERO PER I BENI E LE ATTIVITÀ CULTURALI E PER IL TURISMO/BIBLIOTECA NAZIONALE CENTRALE DI FIRENZE. THIS IMAGE CANNOT BE REPRODUCED WITHOUT PERMISSION FROM THE NATIONAL LIBRARY OF FLORENCE.

These innovations certainly helped artists render the world around them more vividly — but some scholars argue they also could have helped pave the way for the Scientific Revolution itself. Writing in *Art Journal* in 1984, Samuel Edgerton, an emeritus professor of art history at Williams College in Massachusetts, claimed there is "a clear case of cause and effect between the practice of Italian Renaissance art and the development of modern experimental science." Edgerton, now 94, says he "absolutely" stands by that assessment more than 30 years later. The key, he says, was the discovery of the idea of "viewpoint" by Renaissance artists. When we look at a set of railway tracks converging toward the horizon, the convergence is not a property of the tracks (which are, after all, parallel), but a property of our minds. The effect "is in your head and in your eyes," Edgerton says, "and the artists knew that."

And only someone as skilled as Galileo could see that mountains on the Moon were just like the mountains here on Earth — once he understood the viewpoint from which they were being seen.

A TRAINED ARTIST

Galileo's depiction of the lunar surface, as rendered in a series of engravings, are one of the highlights of *Sidereus Nuncius*. Instead of the perfect Moon imagined by the ancients, we see the rugged, pockmarked Moon that we know today. The book's engravings were preceded by a series of wash drawings — paintings made with a technique in which brown ink is diluted in water so the brushstrokes are nearly invisible, often allowing the underlying paper or canvas to be seen. These drawings, along with some of Galileo's original notebooks, are now housed in the Biblioteca Nazionale Centrale in Florence. Astronomers and historians agree that the drawings are based on observations of the Moon carried out between November 30 and December 18, 1609.

The wash drawings are more than just instructions for the engraver — they are works of art in their own right, says Roberta Olson, an art historian and Curator of Drawings at the New York Historical Society. She describes the wash drawings as "illusionistic studies" that are "artistically superb." Galileo's skill at applying the wash, carefully revealing the paper below only in specific areas, required enormous talent, Olson says. "Only a very highly trained and sophisticated artist would know how to do that."

Edgerton, too, has praised the artistic nature of Galileo's lunar sketches. In his book *The Heritage of Giotto's Astronomy* (Cornell University Press, 1991), he writes: "With the deft brushstrokes of a practiced watercolorist, he laid on a half-dozen grades of washes, imparting to his images an attractive soft and luminescent quality." Galileo's use of an "almost impressionistic technique" in rendering lighting effects "reminds us of Constable and Turner, and perhaps even Monet."

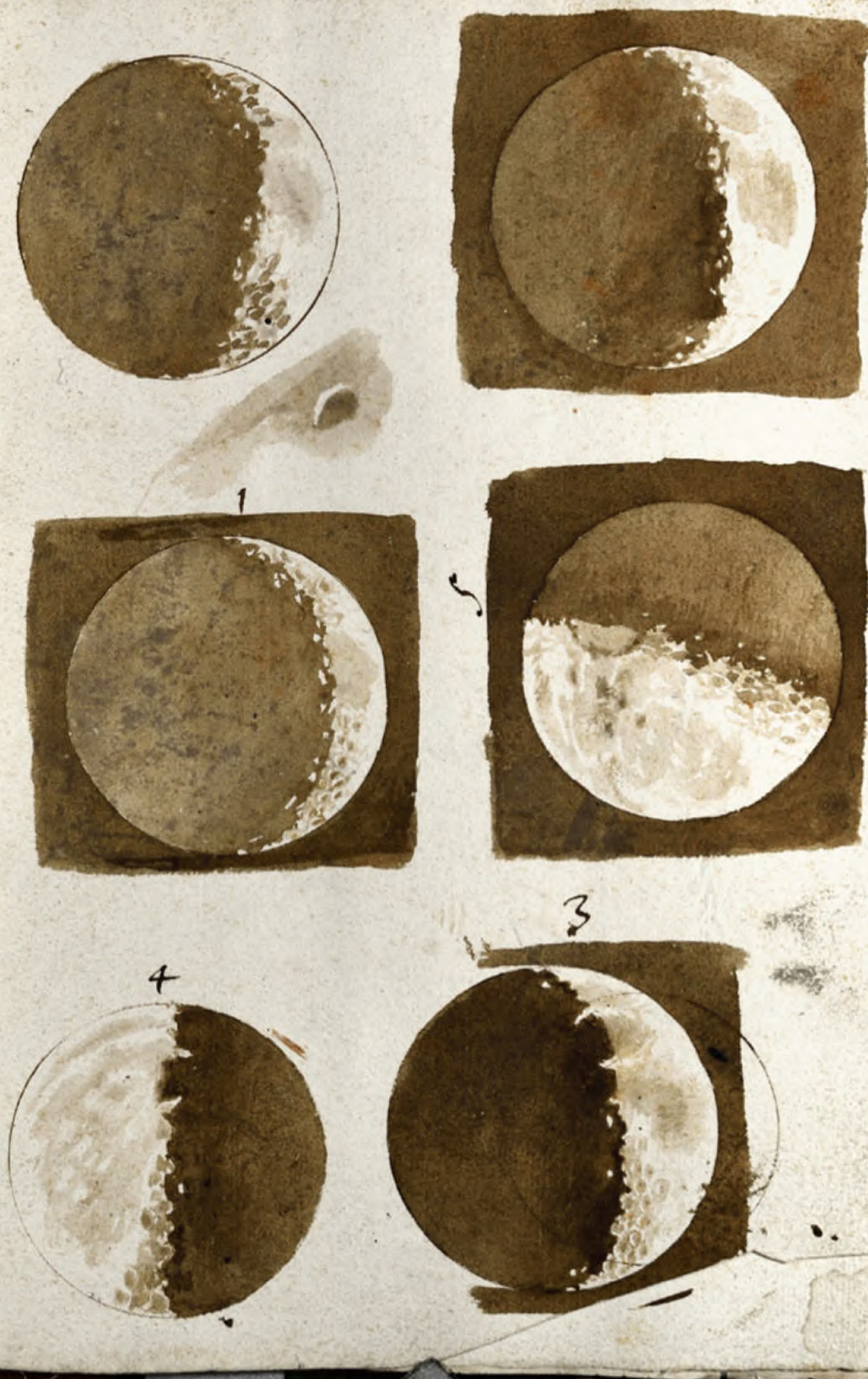
Interestingly, the published drawings that appear in *Sidereus Nuncius* are quite different from the wash drawings. Most obviously, a gigantic crater larger than any that actually exists on the Moon's surface figures prominently on the Moon's terminator as depicted at First Quarter or Last Quarter. (The closest real-life candidate for this oversized feature is a medium-sized crater known as Albategnius; however, either Galileo or his engraver seems to have embellished it almost beyond recognition.) Historians speculate that Galileo gave his drawings to the engraver as a guide but also encouraged him to employ his artistic license, exaggerating certain features to support the accompanying text.

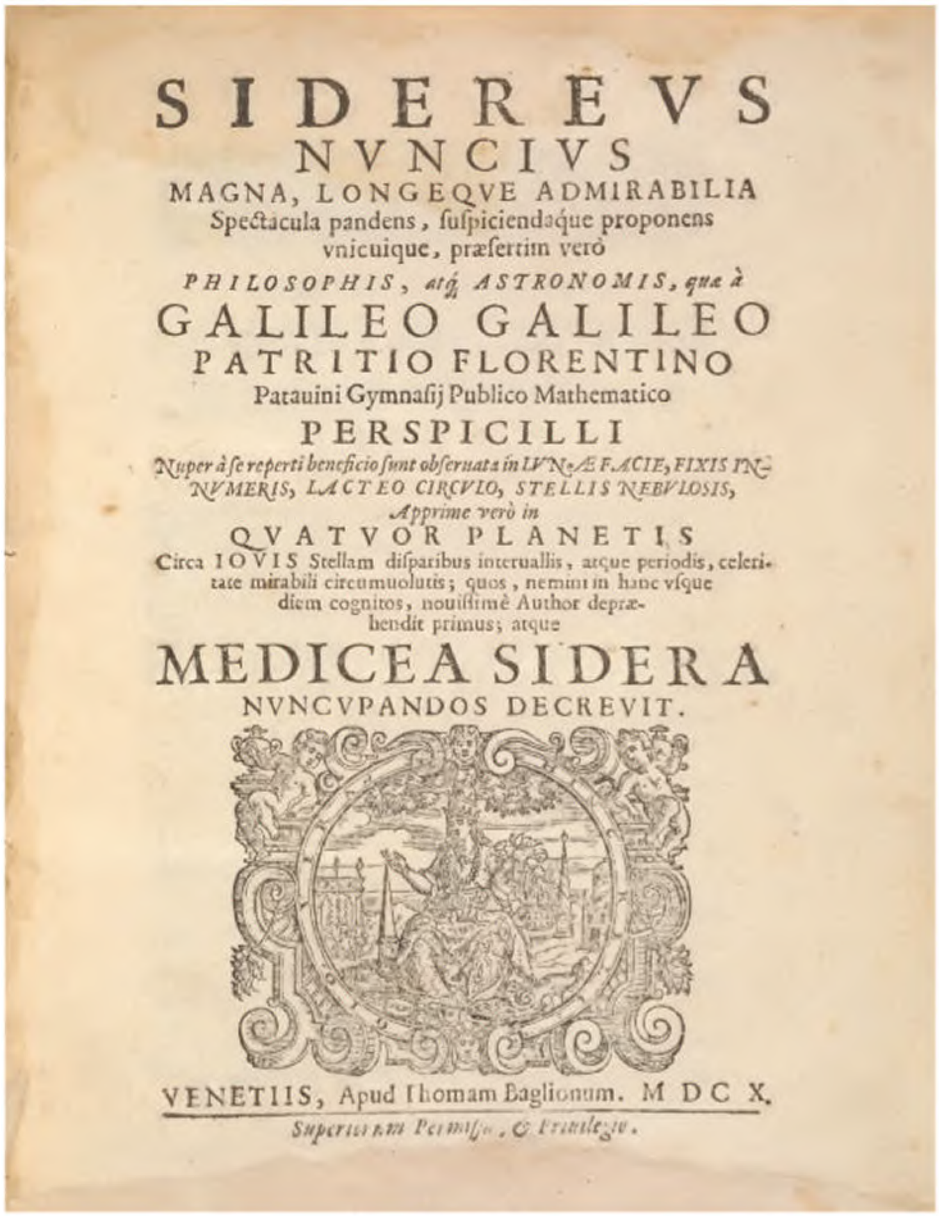
IN ANOTHER LIGHT

Another phenomenon that challenged Galileo as both an artist and a scientist was earthshine — the faint illumination of the dark part of the Moon's face caused by light from the Sun reflecting off of Earth. It is most readily seen in the first few days following New Moon. In Galileo's time, this ghostly shine, which he referred to as the Moon's "secondary light," was far more mysterious.

As he described it in *Sidereus Nuncius*, "When the moon is not far from the sun, just before or after new moon, its globe offers itself to view not only on the side where it is adorned with shining horns, but a certain faint light is also seen to mark out the periphery of the dark part which faces away from the sun … This remarkable gleam has afforded no small perplexity to philosophers."

Adi 7. di Gennaio 1610 Giove si vedeva col Cannone con 3. stelle fisse così * * ♃ * delle quali senza il cannone niuna si vedeva. à dì 8. appariva così ♃ * * * era dunq[ue]

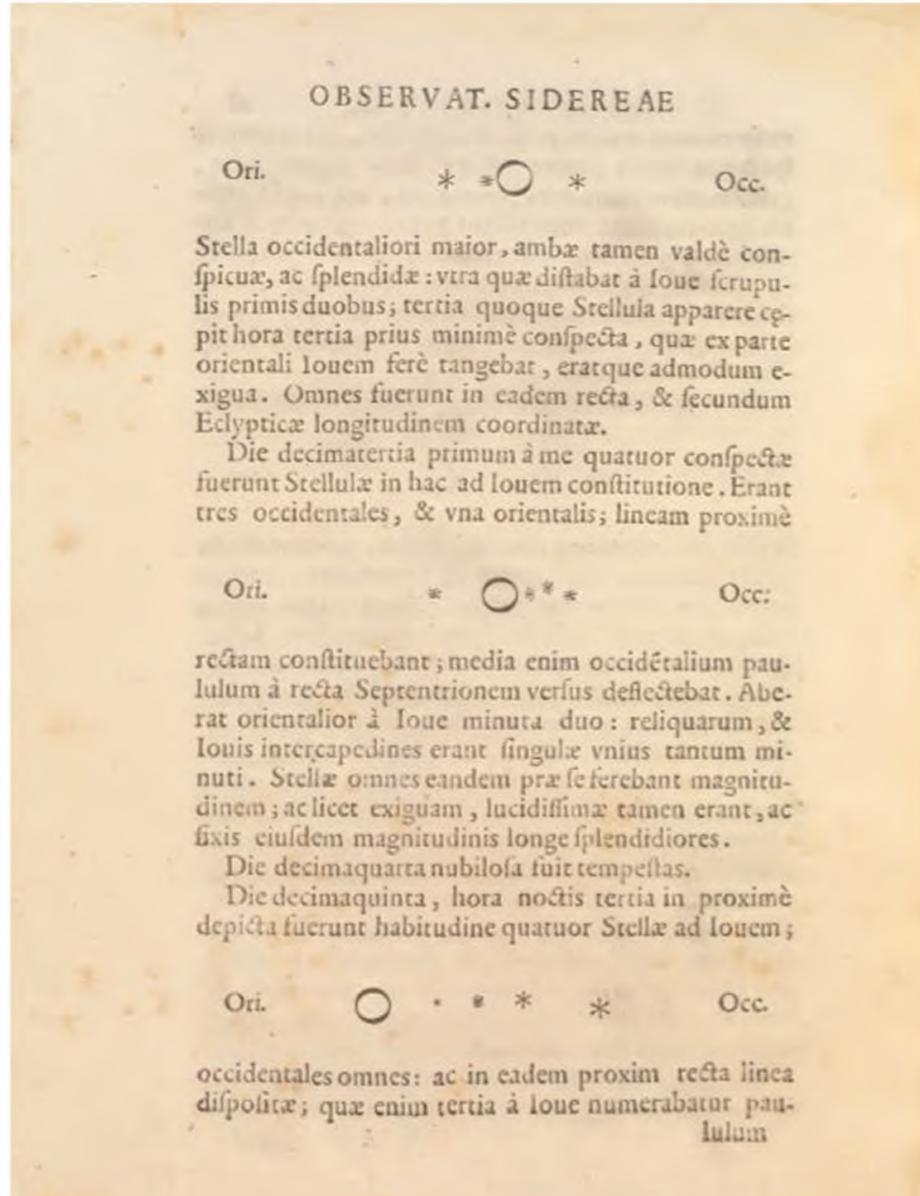




SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS IN-
NVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeri-
tate mirabili circumuolutis; quos, nemini in hanc vsque
diem cognitos, nouissimè Author depræ-
hendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

VENETIIS, Apud Thomam Baglionum. M D C X.
Superiorum Permissu, & Priuilegio.

Galileo published *Sidereus Nuncius*, whose title page appears here, in 1610. The book contained results of his telescopic observations of the skies and included drawings of the Moon, star clusters, constellations, and Jupiter's four largest moons, later christened the Galilean moons. GALILEI, GALILEO. *SIDEREUS NUNCIUS*. APUD THOMAM BAGLIONUM, 1610. COURTESY OF THE SMITHSONIAN LIBRARIES (HTTPS://DOI.ORG/10.5479/SIL.95438.39088015628597)



OBSERVAT. SIDEREAE

Ori. * *○ * Occ.

Stella occidentaliori maior, ambæ tamen valdè conspicuæ, ac splendidæ: vtra quæ distabat à Ioue scrupulis primis duobus; tertia quoque Stellula apparere cœpit hora tertia prius minimè conspecta, quæ ex parte orientali Iouem ferè tangebat, eratque admodum exigua. Omnes fuerunt in eadem recta, & secundum Eclypticæ longitudinem coordinatæ.
Die decimatertia primum à me quatuor conspectæ fuerunt Stellulæ in hac ad Iouem constitutione. Erant tres occidentales, & vna orientalis; lineam proximè

Ori. * ○** Occ.

rectam constituebant; media enim occidẽtalium paululum à recta Septentrionem versus deflectebat. Aberat orientalior à Ioue minuta duo: reliquarum, & Iouis intercapedines erant singulæ vnius tantum minuti. Stellæ omnes eandem præ se ferebant magnitudinem; ac licet exiguam, lucidissimæ tamen erant, ac fixis eiusdem magnitudinis longe splendidiores.
Die decimaquarta nubilosa fuit tempestas.
Die decimaquinta, hora noctis tertia in proximè depicta fuerunt habitudine quatuor Stellæ ad Iouem;

Ori. ○ · * * * Occ.

occidentales omnes: ac in eadem proxim recta linea dispositæ; quæ enim tertia à Ioue numerabatur paululum

With his telescope, Galileo observed four "stars" that appeared to orbit the planet Jupiter. In reality, these are moons: Io, Europa, Ganymede, and Callisto. *Sidereus Nuncius* contains numerous pages of observations showing the moons in various configurations around the gas giant. GALILEI, GALILEO. *SIDEREUS NUNCIUS*. APUD THOMAM BAGLIONUM, 1610. COURTESY OF THE SMITHSONIAN LIBRARIES (HTTPS://DOI.ORG/10.5479/SIL.95438.39088015628597)

Galileo eventually concluded that the phenomenon originates in light reflected from our own planet, and again, his interpretation may have leaned on his artistic knowledge. The principles of reflected light were already quite familiar to artists. Edgerton points out that Alberti offered a description of the phenomenon not for the Moon specifically, but in terms of general principles, in his treatise *Della Pittura* (*On Painting*). Alberti noted that the "reflection of rays always takes place at equal angles" and that such rays "assume the color they find on the surface from which they are reflected. We see this happen when the faces of people walking about in meadows appear to have a greenish tinge." Artists had long applied Alberti's logic to depicting terrestrial objects, but Galileo may have been the first to apply it to the heavens.

Galileo faced a very different challenge when he aimed his telescope at the great planet Jupiter. He saw four small bodies that appeared to change their positions from night to night, but always remained close to the planet itself. The only reasonable conclusion was that these were moons revolving around Jupiter. But his notebooks reveal that he was struggling to make sense of what he was seeing. For starters, the moons didn't always appear in a straight line. "At first, Galileo 'corrects' his drawings," says Reeves. "He figures they should be lined up." But eventually, Galileo concluded that the moons' orbits around Jupiter must be inclined to our line of sight, and drew the moons as they actually appear in the sky.

Galileo was always drawing, sketching, and painting. "I think he found it hard to think without drawing," Reeves says. If he was unsure how something ought to be treated, he would ask his artist friends — and they would likely consult him, too. This back-and-forth "was a constant process with Galileo, and with his friends."

IN GOOD COMPANY

Evidence that artists held Galileo in the highest regard can be found in a painting by the Flemish artist Peter Paul Rubens. In his *Self Portrait in a Circle of Friends from Mantua*, dating from about 1604, we see six figures: Rubens; his brother; the son of a merchant; the son of a nobleman; a Flemish scholar; and a young man near the center of the canvas, pegged by some historians as Galileo. We know that Galileo was friendly with both Rubens and his brother and that "they probably shared similar philosophical ideas," says Reeves. It's also possible that they shared the Copernican view of the cosmos, though this is much harder to prove. If they did, however, then this intriguing painting could be "a sly way of doing it," without overtly identifying oneself as a Copernican, she says.

Artists were also inspired by Galileo's astronomical discoveries. Most notable is the painter Lodovico Cardi, better known as Cigoli (1559-1613). Cigoli's most important commission came when he was asked to paint the chapel of Pope Paul V in the Basilica of Santa Maria Maggiore in Rome. He began the work that would adorn the inside of the cupola, often called the *Immacolata*, in September of 1610, and completed it by 1612. The biblical scene it depicts, based on the book of Revelation, shows the Virgin Mary as the Queen of Heaven standing on the Moon, wearing a multicolored robe and carrying a scepter in her right hand. A halo of 12 stars looms above her head; at the bottom we see a coiled serpent.

The fresco's most striking feature is the lunar surface, clearly pockmarked with craterlike features. Scholars have concluded that Cigoli's depiction of the Moon is directly indebted to one of the lunar images published in *Sidereus Nuncius*, in which the Moon is seen at its First Quarter phase. But it is also possible that Cigoli made his own observations, perhaps peering through one of Galileo's telescopes. "I would think that [Cigoli] had, at the very least, access to a telescope," says Reeves.

Interestingly, while the traditional Aristotelian view of the Moon was that of an unblemished, perfectly spherical body, Cigoli appears to have had no hesitation in depicting it as irregular and mountainous, just as Galileo had. While Galileo would be hauled before the Inquisition some 20 years later in 1633 — in part for his vocal support of Copernican astronomy — the Catholic authorities do not seem to have been particularly bothered by Cigoli's bold depiction of the Moon.

Clearly, Galileo was much more than a single-minded man of science; rather, he was a polymath with artistic leanings that deserve greater attention. Those artistic skills helped him beyond measure as he struggled to comprehend the sights revealed by his telescope and to communicate those sights to a mass audience.

"It was all about discovery," says Olson. "Discovery of the physical world, discovery of the principles that make it work." The scientists of Galileo's day, as well as the artists, wanted "to see how the cosmos worked."

Dan Falk *(@danfalk) is a science journalist based in Toronto. His books include* The Science of Shakespeare *and* In Search of Time*.*

In his *Immacolata* fresco adorning the Basilica di Santa Maria Maggiore in Rome, Cigoli painted the Moon beneath the Virgin Mary's feet as it appeared through his friend Galileo's telescope. Previous paintings with similar imagery depicted our satellite as smooth and featureless, rather than its true pockmarked and cratered form. LIVIOANDRONICO2013/WIKIMEDIA COMMONS

Flemish artist Peter Paul Rubens completed *Self Portrait in a Circle of Friends from Mantua* around 1604. In addition to himself, seen looking toward the viewer, Rubens painted his brother, the sons of a merchant and a nobleman, and a Flemish scholar. Some historians identify the sixth figure — the bearded man, third from the left, with the prominent white collar — as Galileo. RUBENS, PETER PAUL; *SELF PORTRAIT IN A CIRCLE OF FRIENDS FROM MANTUA*, WALLRAF-RICHARTZ-MUSEUM & FONDATION CORBOUD (DEP. 0248, KÖLN). RHEINISCHES BILDARCHIV KÖLN, WALZ, SABRINA, RBA_D038880

THE SOLAR SYSTEM'S CHANGING LANDSCAPE AS IT APPEARS IN EARTH'S SKY.

BY MARTIN RATCLIFFE AND ALISTER LING

NOVEMBER 2020

Planets shine morning and night

A spectacular fireball lights up the Michigan sky in this 2018 shot. Fast-moving Leonid meteors may leave similar trains of ionized gas in the sky when the shower peaks this month. TONY HEBERT

With the seven major planets on display, this month is a busy time for observers. Jupiter and Saturn continue their dramatic pairing in the southern sky. Mars remains near its peak and begins its retreat from Earth; catch it early in the month while you can. Neptune is near a bright star, while Uranus remains in a sparse region of sky and is up all night. The predawn sky hosts Venus and Mercury, a treat for early risers.

The window for observing Jupiter and Saturn is narrowing. In early November, the planets set an hour before midnight. Four weeks later, they're gone by 9:30 P.M. local time. The longer nights afford an early start — the best time to begin observing is as soon as twilight starts and the Sun has gone down.

On November 1, when daylight saving time ends, you can begin at 5:30 P.M. Jupiter and Saturn stand 27° and 29° high, respectively, in the south. Catch them early because at lower altitudes, their light passes through increasingly more of our atmosphere. Refraction worsens, too, causing color fringes around the planets.

Jupiter and Saturn start November 5.1° apart. Both have resumed direct easterly motion relative to the background stars. By virtue of being closer, Jupiter appears to move more quickly than Saturn, catching up with the ringed planet. They end the month only 2.3° apart. The pair makes a stunning spectacle in binoculars. Mount them on a tripod and soak in the sight. Some of Jupiter's moons are visible in binoculars as well.

A waxing crescent Moon stands west and then east below the duo on November 18 and 19, respectively.

Jupiter is a spectacular magnitude –2.2 on November 1 and dims by 0.1 magnitude in one week. The disk spans 37" and shrinks to 34" by November 30, as the planet's distance from Earth increases. November opens with a fine transit of Ganymede's shadow underway. Not long after the moon's shadow makes it halfway across the disk, Io reappears from Jupiter's huge shadow. Watch the empty space some 20" from Jupiter's eastern limb for Io's reappearance at 7:43 P.M. EST. Ganymede's shadow leaves Jupiter's face at 9:06 P.M. EST. There are several more transits and occultations in the first half of November, but progressively fewer throughout the month.

Saturn sits east of Jupiter, shining at magnitude 0.6. At nearly twice the distance of Jupiter, Saturn's disk — in reality comparable in size to Jupiter's — appears half the size in our telescopes: 16".

Saturn's atmospheric features are more subtle than Jupiter's. Use a good-quality eyepiece with well-corrected color transmission to see subtle details.

Bright lights before sunrise

A thin crescent Moon joins planets Mercury and Venus in Virgo the morning of November 13. Virgo's bright alpha star, Spica, shines nearby. ALL ILLUSTRATIONS: *ASTRONOMY*: ROEN KELLY

OBSERVING HIGHLIGHT

VENUS, MERCURY, and the crescent Moon share the November 13 predawn sky. The trio hangs near the bright star Spica in Virgo.

(The same goes for Jupiter.) The northern side of Saturn's rings is tilted toward us by 22°. This value diminishes over the next few years until the next ring plane crossing in 2025.

Titan shines at 8th magnitude. It is due north of Saturn November 3 and 20, and due south of Saturn November 11 and 27. Look also for a trio of fainter, 10th-magnitude moons closer in: Tethys, Dione, and Rhea. Closer to the rings' edge is 12th-magnitude Enceladus.

Iapetus reaches greatest western elongation November 4. This is the brightest Iapetus can appear, glowing near magnitude 10.2, 8' due west of Saturn. The moon dims to near magnitude 11 as it swings to superior conjunction on November 25.

November evenings are a great time to try imaging dwarf planets. Pluto is in the southern sky near Jupiter, Ceres is in the south, and Eris is in the east.

Pluto shines near 15th magnitude in Sagittarius and is a mere 41' due south of Jupiter on November 12. A one-minute guided exposure through an 80mm refractor should catch it. Ceres is a binocular object at magnitude 8.7. Find it in southern Aquarius all month. You'll want to catch Ceres as it cruises within 1° of the Helix Nebula (NGC 7293) between November 18 and 24. Eris is a challenge

— Continued on page 38

RISING MOON | Swinging between opposites

GLIDING QUIETLY across the solar system's dance floor is the endearing couple of Terra and Luna. From our earthly perspective, the latter appears to circle us, at times leading and other times following. But our Moon never actually moves backward relative to the audience of stars. We simply elegantly swap places while always moving forward around the broad circle we call the ecliptic.

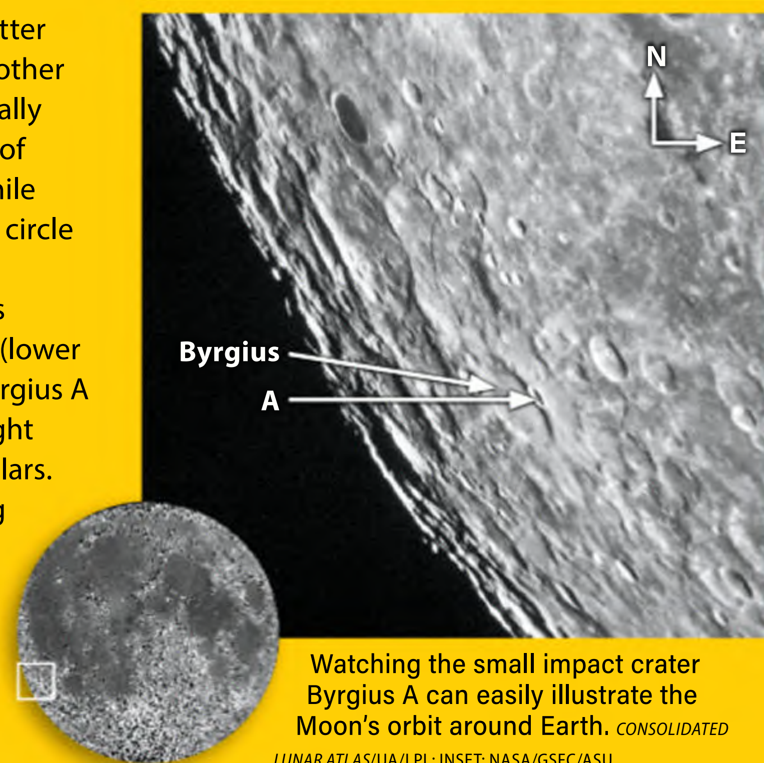
Concentrate on Luna's face to notice its monthly rise and dip. In the far southwest (lower left for observers north of the equator), Byrgius A is small impact crater surrounded by a bright apron and rays, quite prominent in binoculars. From night to night immediately following the Full Moon on Halloween, this dazzling dimple lifts to the upper right as Luna rises slightly "above" us in its orbit, which is tilted 5.1° to the ecliptic.

During the passage through New Moon, we swap places. Arriving at First Quarter, we find ourselves leading while peering "down" at Luna in the bottom of its dip. With binoculars on the 25th or 26th, look for a trio of dark spots at the upper right of its face: Lacus Spei, Endymion, and, at the very edge, Mare Humboldtianum. (See last month's "Rising Moon" for more details on this region.)

With each step toward Full, Luna spins a bit too fast while rising. As a result, that trio of braids rotates to the upper right and Mare Humboldtianum disappears from view in the last nights of the month. The remaining two dark spots are tucked right against the limb when we reach Full phase on the 30th. In December, you can watch the dimple of Byrgius A climb up from the lower left once again.

We've come back face-to-face, relative to the spotlight of our Sun, but Luna's graceful spin, rise, and dip combination does not repeat exactly. That grander cycle takes some 18 years, a saros, to complete.

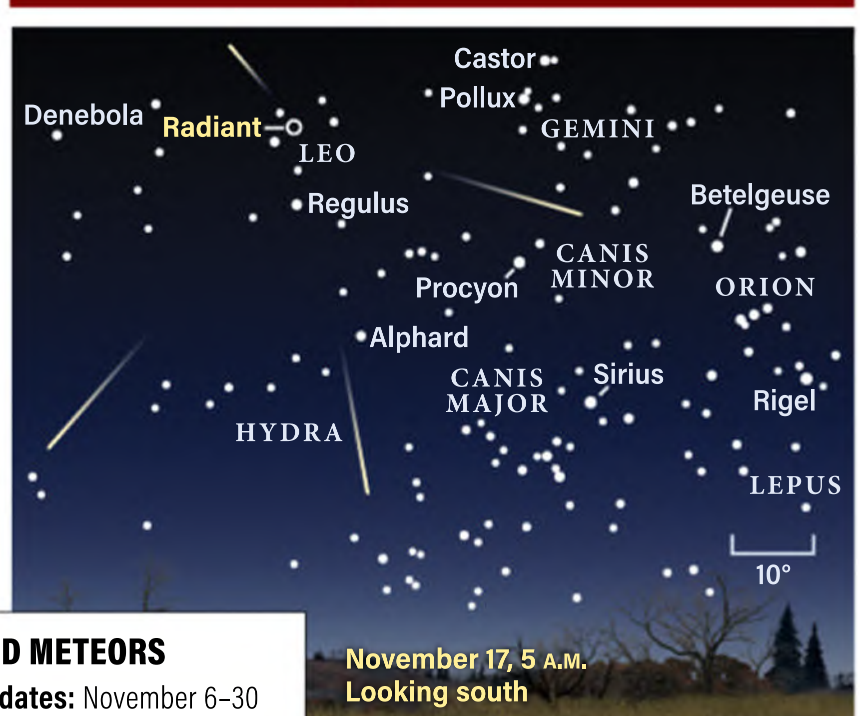
Byrgius A



Watching the small impact crater Byrgius A can easily illustrate the Moon's orbit around Earth. *CONSOLIDATED LUNAR ATLAS/UA/LPL; INSET: NASA/GSFC/ASU*

METEOR WATCH | A lion of a shower

Leonid meteor shower



The Leonids' radiant lies in the sickle of Leo the Lion, which rises shortly after midnight. Wait a few more hours for the greatest meteor rates.

LEONID METEORS
Active dates: November 6–30
Peak: November 17
Moon at peak: Waxing crescent
Maximum rate at peak: 15 meteors/hour

THE LEONID METEOR SHOWER is active between November 6 and 30, peaking the morning of November 17 with a projected zenithal hourly rate of 15 meteors per hour. It's a favorable year with the Moon out of the way.

Meteor rates increase as the radiant climbs higher, so early morning hours from 3 A.M. to 6 A.M. offer the best views. The Leonids produce fast-moving meteors, many of which show persistent trains — luminous trails of ionized gas that can take many seconds to fade away. Sometimes trains are caught by high-level winds, producing intriguing shapes. The Leonid meteor shower is associated with Comet 55P/Tempel-Tuttle, which last reached perihelion in 1998.

STAR DOME

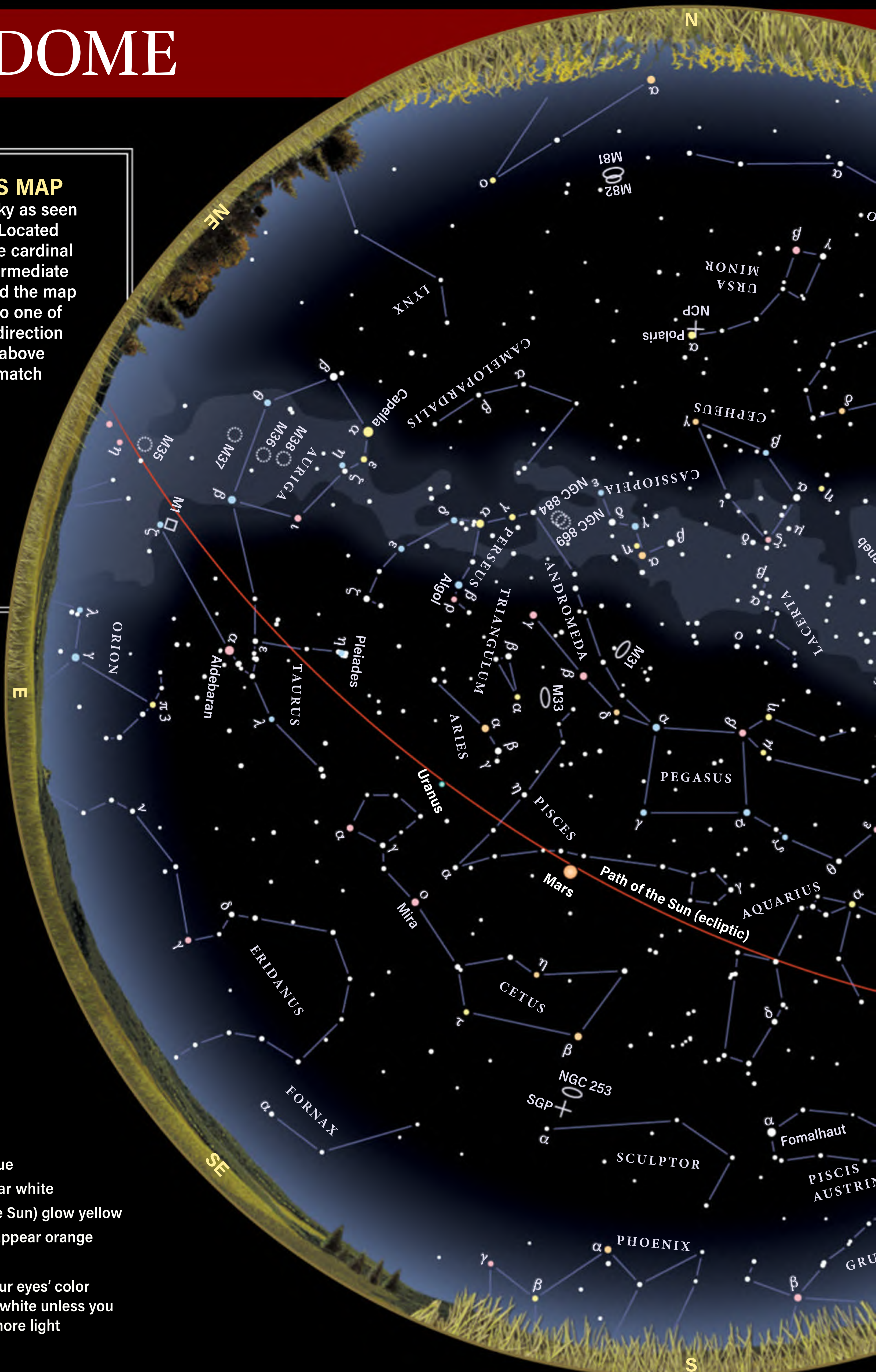
HOW TO USE THIS MAP

This map portrays the sky as seen near 35° north latitude. Located inside the border are the cardinal directions and their intermediate points. To find stars, hold the map overhead and orient it so one of the labels matches the direction you're facing. The stars above the map's horizon now match what's in the sky.

The all-sky map shows how the sky looks at:

9 P.M. November 1
8 P.M. November 15
7 P.M. November 30

Planets are shown at midmonth



MAP SYMBOLS

- Open cluster
- Globular cluster
- Diffuse nebula
- Planetary nebula
- Galaxy

STAR MAGNITUDES

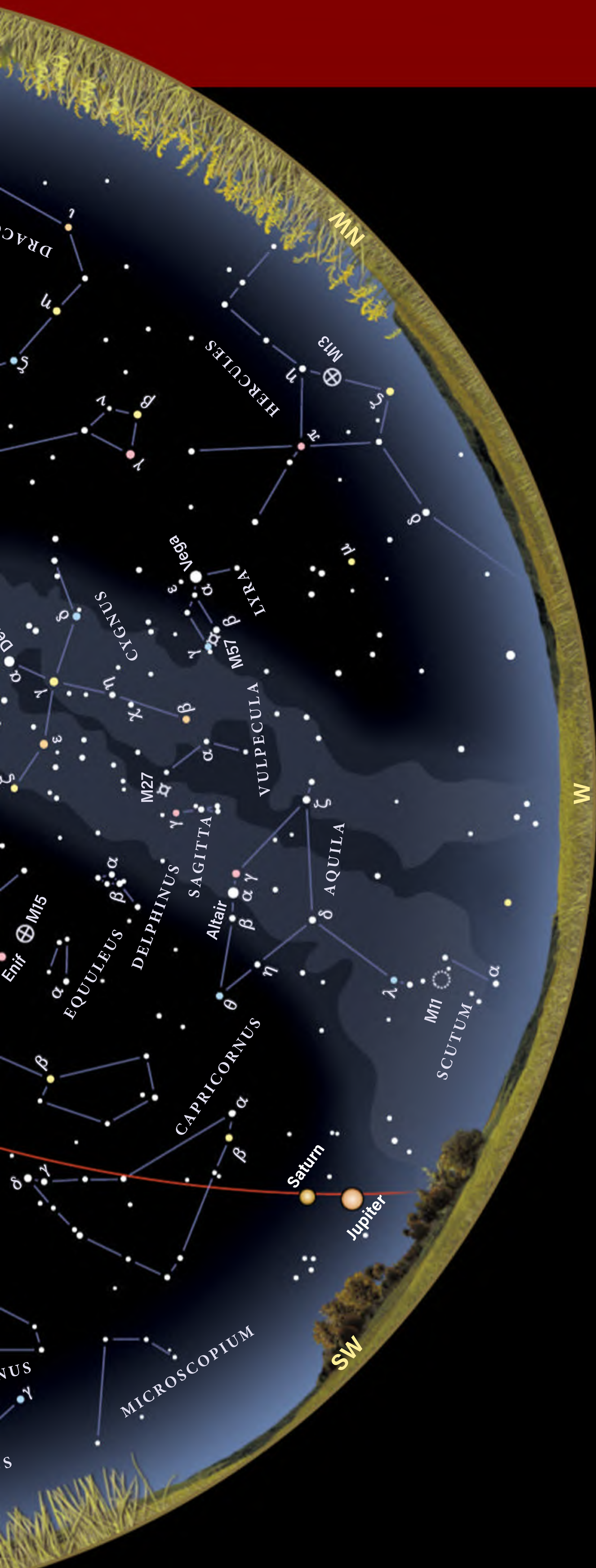
- Sirius
- 0.0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0

STAR COLORS

A star's color depends on its surface temperature.

- The hottest stars shine blue
- Slightly cooler stars appear white
- Intermediate stars (like the Sun) glow yellow
- Lower-temperature stars appear orange
- The coolest stars glow red
- Fainter stars can't excite our eyes' color receptors, so they appear white unless you use optical aid to gather more light

BEGINNERS: WATCH A VIDEO ABOUT HOW TO READ A STAR CHART AT **www.Astronomy.com/starchart.**



NOVEMBER 2020

SUN.	MON.	TUES.	WED.	THURS.	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					

ILLUSTRATIONS BY *ASTRONOMY*: ROEN KELLY

Note: Moon phases in the calendar vary in size due to the distance from Earth and are shown at 0h Universal Time.

CALENDAR OF EVENTS

1 Asteroid Flora is at opposition, 2 A.M. EST

3 Mercury is stationary, 3 A.M. EST

8 Asteroid Juno is in conjunction with the Sun, 4 A.M. EST

Last Quarter Moon occurs at 8:46 A.M. EST

10 Mercury is at greatest western elongation (19°), noon EST

12 The Moon passes 3° north of Venus, 4 P.M. EST

13 The Moon passes 1.7° north of Mercury, 4 P.M. EST

14 The Moon is at perigee (222,350 miles from Earth), 6:43 A.M. EST

15 New Moon occurs at 12:07 A.M. EST

Venus passes 4° north of Spica, 8 A.M. EST

Mars is stationary, 2 P.M. EST

17 Leonid meteor shower peaks

19 The Moon passes 2° south of Jupiter, 4 A.M. EST

The Moon passes 3° south of Saturn, 10 A.M. EST

21 First Quarter Moon occurs at 11:45 P.M. EST

23 The Moon passes 5° south of Neptune, 7 A.M. EST

25 The Moon passes 5° south of Mars, 3 P.M. EST

26 The Moon is at apogee (252,211 miles from Earth), 7:29 P.M. EST

27 The Moon passes 3° south of Uranus, noon EST

29 Neptune is stationary, 4 A.M. EST

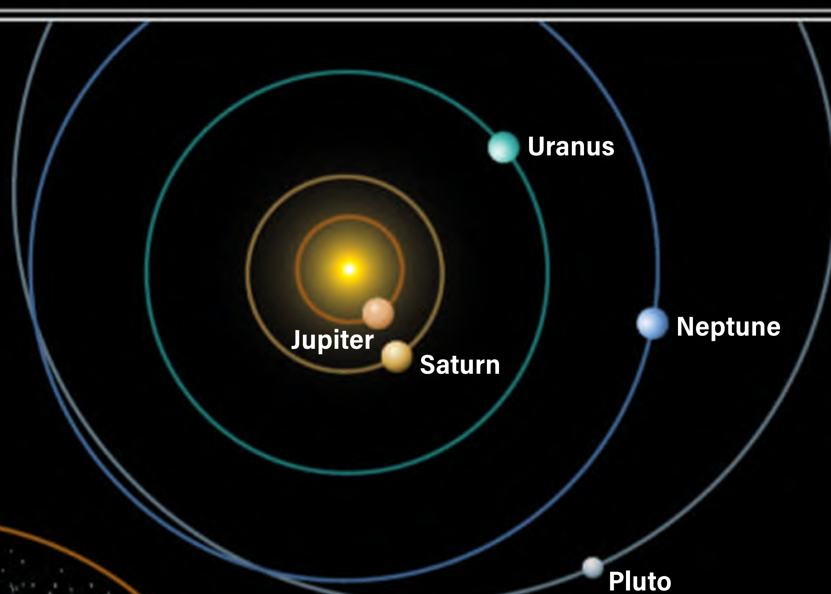
30 Full Moon occurs at 4:30 A.M. EST; penumbral lunar eclipse

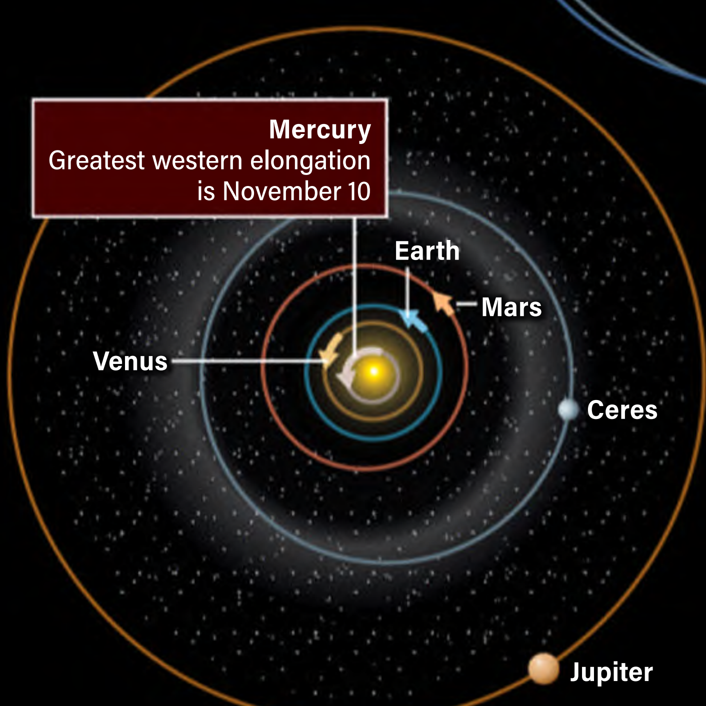
PATHS OF THE PLANETS

To locate the Moon in the sky, draw a line from the phase shown for the day straight up to the curved blue line.

THE PLANETS IN THEIR ORBITS

Arrows show the inner planets' monthly motions and dots depict the outer planets' positions at midmonth from high above their orbits.



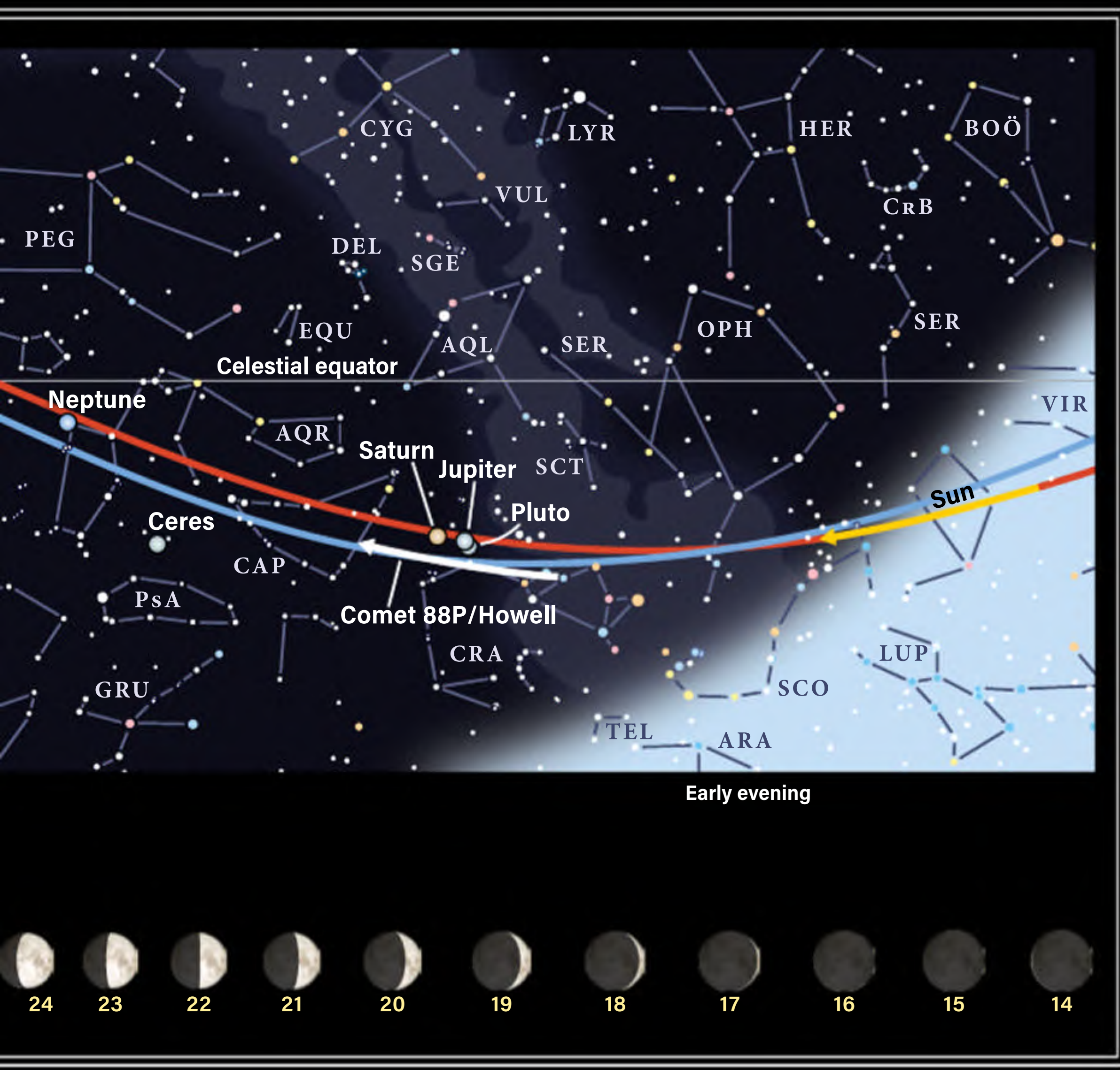


THE PLANETS IN THE SKY

These illustrations show the size, phase, and orientation of each planet and the two brightest dwarf planets at 0h UT for the dates in the data table at bottom. South is at the top to match the view through a telescope.

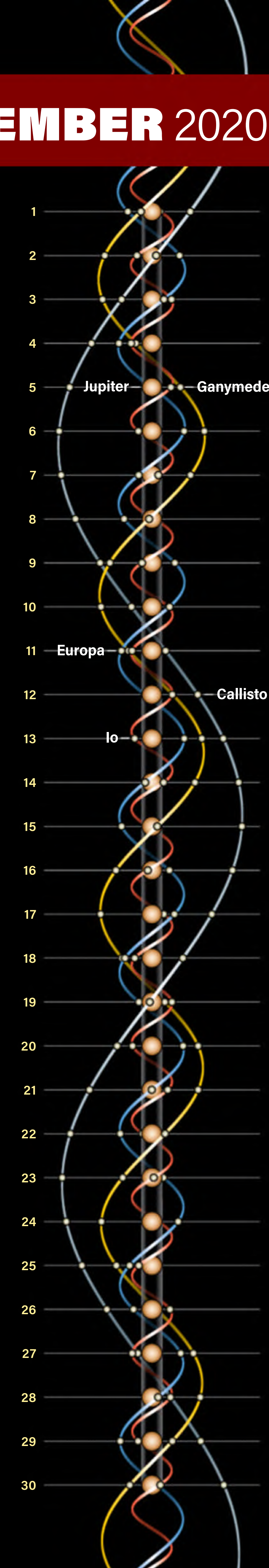
PLANETS	MERCURY	VENUS
Date	Nov. 15	Nov. 15
Magnitude	–0.7	–3.9
Angular size	6.1"	12.4"
Illumination	73%	85%
Distance (AU) from Earth	1.101	1.350
Distance (AU) from Sun	0.351	0.719
Right ascension (2000.0)	14h12.1m	13h22.6m
Declination (2000.0)	–11°00'	–6°47'

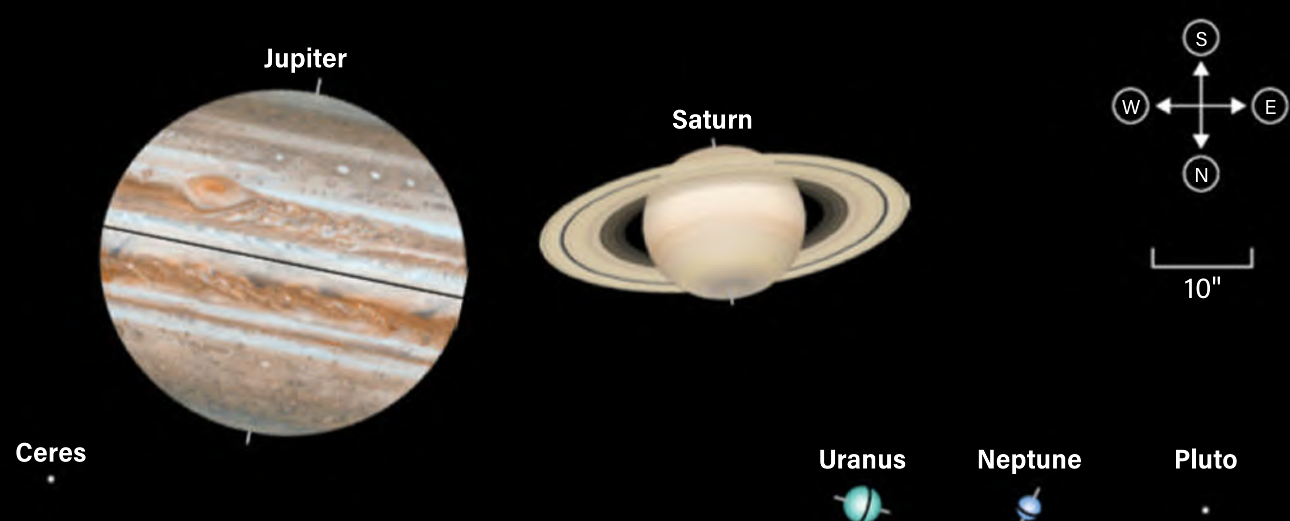
This map unfolds the entire night sky from sunset (at right) until sunrise (at left). Arrows and colored dots show motions and locations of solar system objects during the month.



JUPITER'S MOONS

Dots display positions of Galilean satellites at 8 P.M. EST on the date shown. South is at the top to match the view through a telescope.





MARS	CERES	JUPITER	SATURN	URANUS	NEPTUNE	PLUTO
Nov. 15	Nov. 15	Nov. 15	Nov. 15	Nov. 15	Nov. 15	Nov. 15
–1.7	8.9	–2.1	0.6	5.7	7.9	14.8
17.5"	0.5"	35.6"	16.0"	3.7"	2.3"	0.1"
95%	97%	99%	100%	100%	100%	100%
0.536	2.677	5.532	10.388	18.821	29.494	34.647
1.450	2.972	5.112	9.994	19.778	29.928	34.161
0h56.4m	22h27.9m	19h39.3m	19h55.7m	2h22.4m	23h17.3m	19h38.5m
5°06'	–22°17'	–21°56'	–21°08'	13°40'	–5°47'	–22°40'

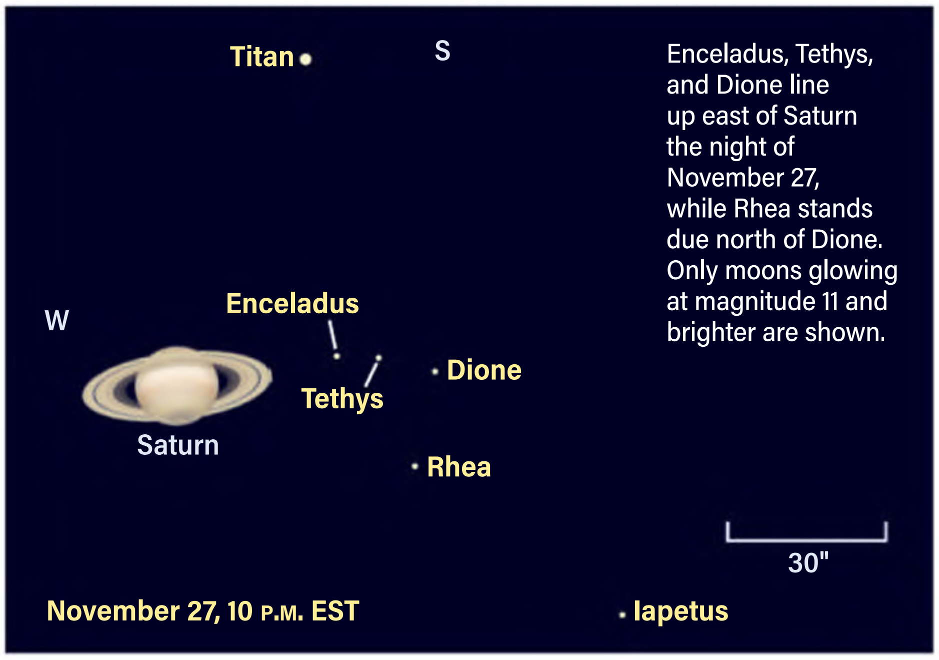
WHEN TO VIEW THE PLANETS

EVENING SKY
Mars (east)
Jupiter (south)
Saturn (south)
Uranus (east)
Neptune (southeast)

MIDNIGHT
Mars (southwest)
Uranus (southwest)
Neptune (west)

MORNING SKY
Mercury (east)
Venus (east)
Uranus (west)

Saturn's small moons get in line



reserved for larger telescopes (14 inches or greater) and longer exposures with a camera. If you can reach magnitude 19, give it a shot. It lies about 12° southeast of Mars in a bland region of sky 2° due north of a 5th-magnitude field star, HIP 7999, in northern Cetus.

Mars is stunning, high in the east an hour after sunset. It stands out at magnitude –2.1, equivalent to Jupiter's glow, in the dim constellation Pisces the Fish. Now a few weeks past its mid-October opposition, Mars continues westward for half the month, halting against the background stars November 15 before resuming its eastward direct motion.

As Mars recedes from Earth, its brightness dips, reaching –1.1 by month's end. Its diameter shrinks from 20" to 15", so make the most of early November for your best views of the planet. You'll also see its phase change from 98 to 92 percent lit. The next time the planet achieves an apparent diameter over 20" will be 2033, when it will be best seen from the Southern Hemisphere. Northern hemisphere observers will have to wait until 2035.

This month, **Neptune** is an easy target within 1° of the 4th-magnitude star Phi (ϕ) Aquarii all month long. If you can center the bright star in binoculars, you're also looking at Neptune. The ice giant drifts westward against the starry background until November 29, when it reaches its stationary point 44' east-northeast of Phi. Shining at magnitude 7.9, a pair of 7x50 binoculars will snag it. With a wider field of view, you'll notice two 6th-magnitude stars forming a triangle with Phi; they're located twice as far from the star as the planet, with Neptune in the center of the triangle. A telescope will reveal its bluish disk, spanning 2".

Uranus is only one day past opposition on November 1 and visible all night at magnitude 5.7. It lies in a bland region 10.5° southeast of Hamal, Aries' brightest star. With binoculars, follow a meandering line of 5th-magnitude stars until you reach 19 Arietis. Uranus stands 3° southeast of this star on November 1. The gap shrinks to 2.5° by November 30. A telescope reveals a bluish-green 4"-wide disk.

Soon after 4 A.M. local time, **Venus** appears above the eastern horizon. On November 1, it rises among the stars of Virgo the Maiden nearly three hours before the Sun. Mercury rises later, 20° farther east along the ecliptic. The two planets maintain their social distance during November.

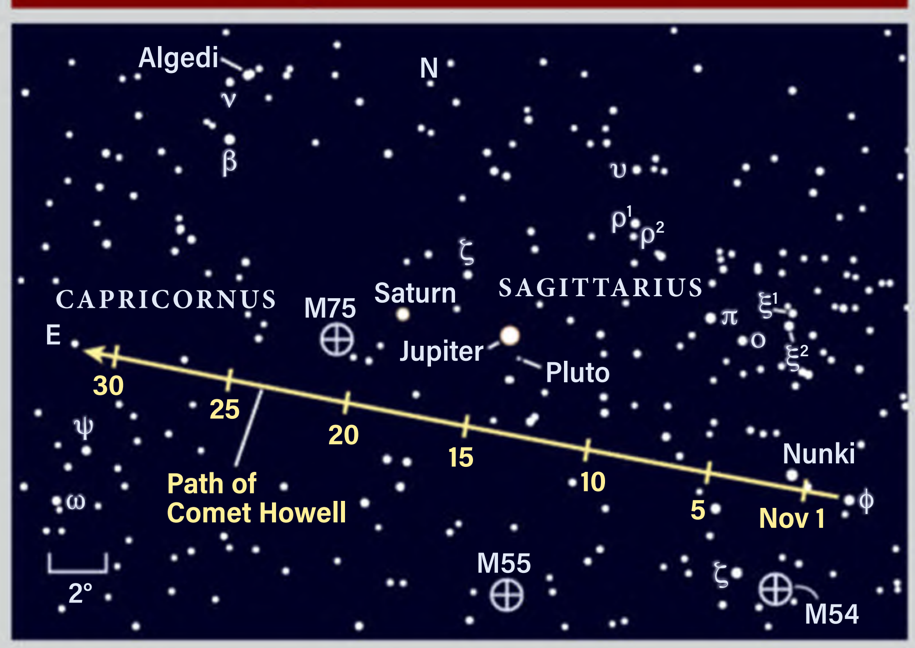
Venus is a bright magnitude –4. Grab a pair of binoculars

COMET SEARCH | A fuzzy familiar

THE EARLY EVENING COMET CRUISE continues. Unlike the narrow loops of most icy visitors, Comet 88P/Howell's 5.5-year orbit is nestled between that of Mars and Jupiter. Like Mars after opposition, it runs on the racetrack just outside ours, barely losing speed. As a bonus for northerners, Howell climbs higher in the sky, thanks to Earth's tilt.

Ensure you're set up early with an unobstructed southwest horizon. As time ticks past nautical twilight, Howell is only 20° high. The dark sky window opens for one hour on November 4th, but widens thereafter. At midmonth, it glides 3.5° beneath gas giants Jupiter and Saturn at almost 1° per day. By the 18th, the Moon's light becomes an issue once again.

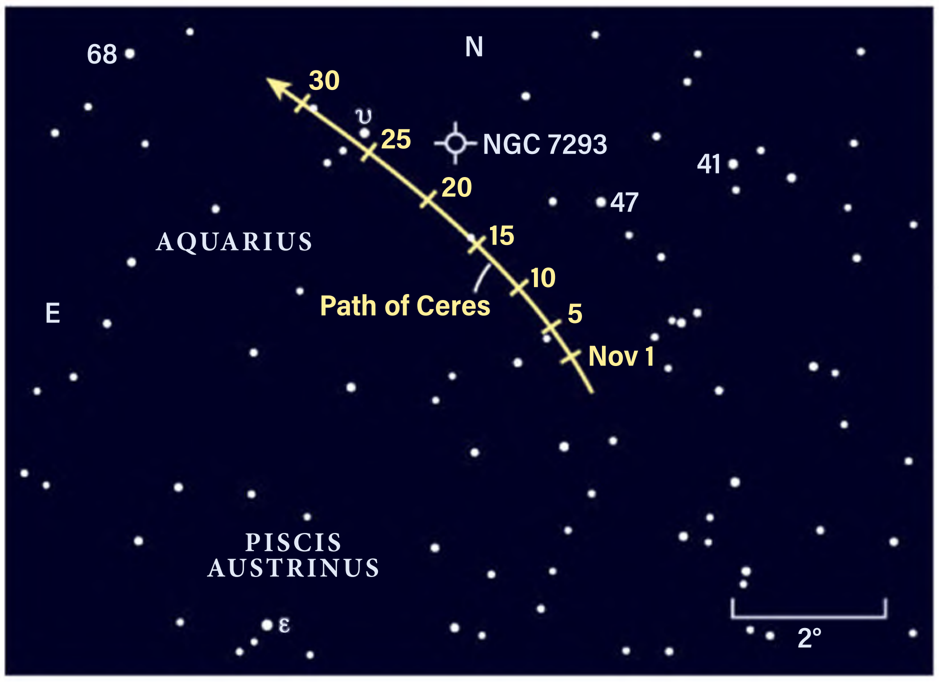
Comet 88P/Howell



Comet Howell passes several objects this month. Jupiter, Saturn, and Pluto are shown as they will appear on November 15, when Howell glides beneath them. While you're exploring the region, compare Howell's appearance to M75, described by discoverer Pierre Méchain as a "nebula without a star."

Flex your observing muscles by comparing the comet's appearance to the nearby globular star cluster M75. At magnitude 8.6 and 6' across, M75 will masquerade as a near twin. Push the magnification past 150x to see if one is more oblong than the other. Does each brighten at the center to a starlike core? Do their edges have similar softness?

A picture-perfect pairing



Dwarf planet Ceres is a binocular target that stays in Aquarius all month. Astrophotographers will want to take note, as it spends several days near the Helix Nebula (NGC 7293).

and center the planet on the first morning of the month to spy Zaniah (Eta [η] Virginis) just 20' away. It's almost as if Venus has a satellite.

Venus moves more than 1° along the ecliptic each day. By November 5, it's adjacent to Porrima (Gamma [γ] Virginis), with just 1° between them. A crescent Moon enters Virgo on November 11 and is 6.5° from Venus an hour before sunrise on November 12. At the same time, Venus lies 18' from 4th-magnitude Theta (θ) Virginis.

Venus sits 4° due north of Spica, Virgo's brightest star, on November 15. Both Venus and Mercury are moving in tandem, now separated by 13°. As Mercury is lost in twilight, Venus maintains its brilliance, dimming by only 0.1 magnitude. It quickly crosses the rest of Virgo to reach neighboring Libra November 28.

Venus changes little this month. On November 1, the 13"-wide disk is lit 82 percent. By November 30, it is 12" wide and 89 percent lit.

Mercury appears in the morning sky of early November, joining Venus as two morning "stars." It is magnitude 1.6 on November 1 and brightens to match Spica at magnitude 0.9 the next morning. Mercury and Spica stand side by side, separated by 4°, rising an hour before the Sun. The rapidly brightening sky offers a narrow window to catch the pair. To find the elusive planet, draw a line in your mind's eye from Venus east toward the horizon, where you expect the Sun to rise. Look for two specks of light in the twilight glow. Mercury and Spica stand a little less than 5° high 45 minutes before sunrise.

Mercury increases in elevation and brilliance through November 10, when it achieves greatest elongation (19°) from the Sun. Now an easy magnitude –0.5, Mercury stands 13° high at 6:15 A.M. local time for mid-northern latitudes in the U.S. Venus is nearly 25° high.

Following greatest elongation, Mercury continues to brighten even though its distance from Earth is increasing because its phase is also increasing. With a telescope, you can follow it from 16 percent lit on November 1, through 50 percent on November 8, to 85 percent lit by November 20. The disk's diameter shrinks from 9" to 6" over the same period.

Don't miss the stunning view of a slender crescent Moon standing 5° above Mercury (now magnitude –0.7) in the predawn sky November 13. Spica shines 7° southwest of the Moon, while Venus is 8.5° west of our satellite.

See how far you can follow Mercury as it sinks lower each morning. By November 20, it stands about 10° high in the eastern sky 45 minutes before sunrise. That elevation drops to 7° five days later, As November closes, the winged messenger flies into the brilliant glow of the Sun, advancing into the evening sky in late December.

Martin Ratcliffe *provides planetarium development for Sky-Skan, Inc., from his home in Wichita, Kansas.* **Alister Ling**, *who lives in Edmonton, Alberta, has watched the skies since 1975.*

LOCATING ASTEROIDS

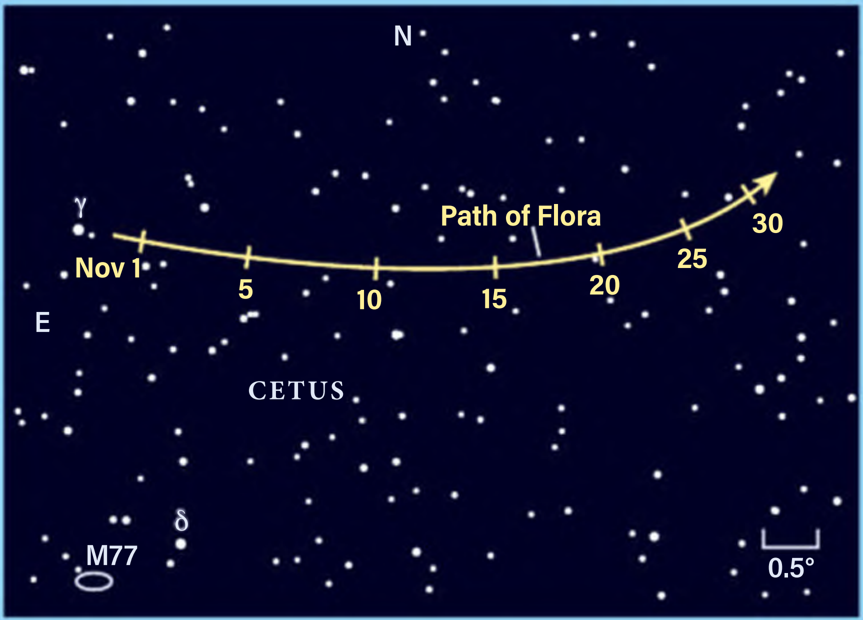
The Bull noses a flower

ASTEROID 8 FLORA starts the month in the same field of view as magnitude 3.5 Gamma (γ) Ceti, the middle of three modest points of light in a lonely eastern sky at midevening. The face of Taurus, made of the V-shaped Hyades, points right at it. Ruddy Aldebaran lights the trailhead.

Night by night, Flora appears to shift westward by nearly half the apparent width of the Moon each evening. Shining with reflected sunlight, the magnitude 8.3 dot outshines many of the field stars of the celestial whale. From the 8th to the 10th, Flora passes just above an upside-down triangle of 8th- to 9th-magnitude stars, perfect for catching its displacement with a simple sketch — everyone can draw four dots, right?

Flora orbits between Mars and Jupiter in the main belt. It's an 80-mile-wide, out-of-round planetesimal. It took four decades to double the asteroid count up from 4 Vesta, with Flora's discovery by Englishman John Hind in 1847. By then, the evidence opposing the theory that asteroids were the leftovers of an exploded planet had begun piling up.

Flora floats through the celestial whale



Asteroid Flora is not only relatively bright this month, but located against a backdrop of easy-to-spot stars as well.

GOLD FROM THE

Humanity's fascination with this precious metal is increased by knowing it comes from the stars.

BY RAYMOND SHUBINSKI

Two neutron stars collide somewhere in the depths of space in this artist's concept. In addition to generating gravitational waves, such an event can produce many heavy elements, including gold.
UNIVERSITY OF WARWICK/MARK GARLICK

STARS

“Gold is a child of Zeus; neither moth nor rust devour it; but the mind of man is devoured by this supreme possession.”

— Pindar, Greek poet, 5th century B.C.

In a remote galaxy, two neutron stars circled one another in a ballet of ultimate destruction and inevitable creation. Both objects were the remnants of massive stars, probably from a binary system, that had become supernovae long before. Each was incredibly massive, with neutrons so closely packed that their cores became diamond. The dance, alas, could not go on forever and the stars collided, releasing unimaginable energy and sending gravitational waves speeding through the fabric of space-time.

In 2017, 1.3 billion years later, astronomers detected those waves with the Laser Interferometer Gravitational-wave Observatory. Albert Einstein’s prediction that the universe should be filled with such faint ripples caused by gravity from massive objects included sources such as neutron star mergers. Yet finding a disturbance in the fabric of space-time from this kind of event had proven elusive until then. When news of the detection of gravitational waves broke, the media wanted to know what else happens when neutron stars collide. Astronomers explained that, beyond the destruction of the stars and the ripples in space, such events also create all the heavy elements we know in the blink of an eye. But what did the media key into? That gold comes from outer space.

This Minoan gold bead was made between 2300 and 2100 B.C. METROPOLITAN MUSEUM OF ART

Gold-plated history

It’s not surprising that of the many elements formed in the cataclysmic destruction of massive stars, gold should be the one that captures our imaginations the most.

ABOVE: The mask of the Egyptian pharaoh Tutankhamun is one of the most famous ancient artifacts on Earth. Made mostly of gold decorated with semiprecious stones, it weighs 22.6 pounds (10.23 kg). ROLAND UNGER/WIKIMEDIA COMMONS

RIGHT: This gold coin from the First Persian Empire was struck around 420 B.C. It honors King Darius II. DEFLIM/WIKIMEDIA COMMONS

Elements necessary for life, such as carbon, oxygen, potassium, and sulfur, should rank higher on a list of favorites. But we have an emotional connection with gold.

Thousands of years ago, someone may have seen a shiny object in a stream and picked up a piece of gold. It must have looked intriguing — though, because the metal is so soft, it's not very useful. Archaeologists have found a 6,500-year-old gold bead in Bulgaria and recovered a nearly 3,000-year-old gold coin from the Black Sea. The oldest known gold artifacts in England were found buried at Stonehenge, part of the grave goods belonging to a mysterious individual from Europe.

The ancient Egyptians had vast gold mines far south of their capital of Thebes, allowing them to encase the mummy of Tutankhamun in the precious metal. Few other ancient civilizations had such wealth. When the mummy was unwrapped, archaeologists found two daggers. One was made of what is now known to be meteoritic iron, and the other was made of pure gold.

Gold was treasured, though useful only as decoration or for trade, and not much else. But its scarcity made it desirable, and its unchanging nature made it alluring: Unlike silver, which turns black, copper that goes green, or iron that rusts, gold never changes. It seems to be immortal — a gift from the gods.

It took 20th-century science to unravel this mystery. Iron, silver, and copper rust or turn colors due to reactions with oxygen. Oxygen is always hungry for electrons. Iron will give up two or three electrons to oxygen and will oxidize (rust) as a result. Other elements also fall victim to oxygen. But not gold. It's the most nonreactive of all metals because it refuses to share electrons with oxygen.

Elemental facts

Like all the heavy elements on the periodic table, there just isn't much gold to be found. If all the gold mined in human history were formed into one solid cube, it would measure about 70 feet (21.3 meters) on a side. That would be around 183,000 tons of gold. Sounds like a lot, but if melted, it would fill only three and a half Olympic-size swimming pools. In 2018, Barrick Gold Corporation's mines in Nevada processed millions of tons of ore to recover just 4 million ounces (125 tons) of gold.

Because it is so dense and heavy, most of Earth's gold sank to the core of our planet. Australian geologist Bernard Wood estimates that 99 percent of the world's gold is buried thousands of miles below our feet. He also estimates that 1.6 quadrillion

The 1933 Saint-Gaudens double eagle is one of the rarest U.S. coins. Most of the more than 445,000 minted were melted into gold bars. Only 13 specimens remain. NATIONAL NUMISMATIC COLLECTION, NATIONAL MUSEUM OF AMERICAN HISTORY

tons of gold lie within the core. Wood calculates that all this gold, if brought to the surface, would form a layer of the shimmering metal just 16 inches (40.6 centimeters) thick. Compared to Earth's total size, that's not much gold. There is actually six times more platinum in our planet's core, which contains about 1 part per million of gold. Gold is, in fact, quite rare.

Our golden Sun

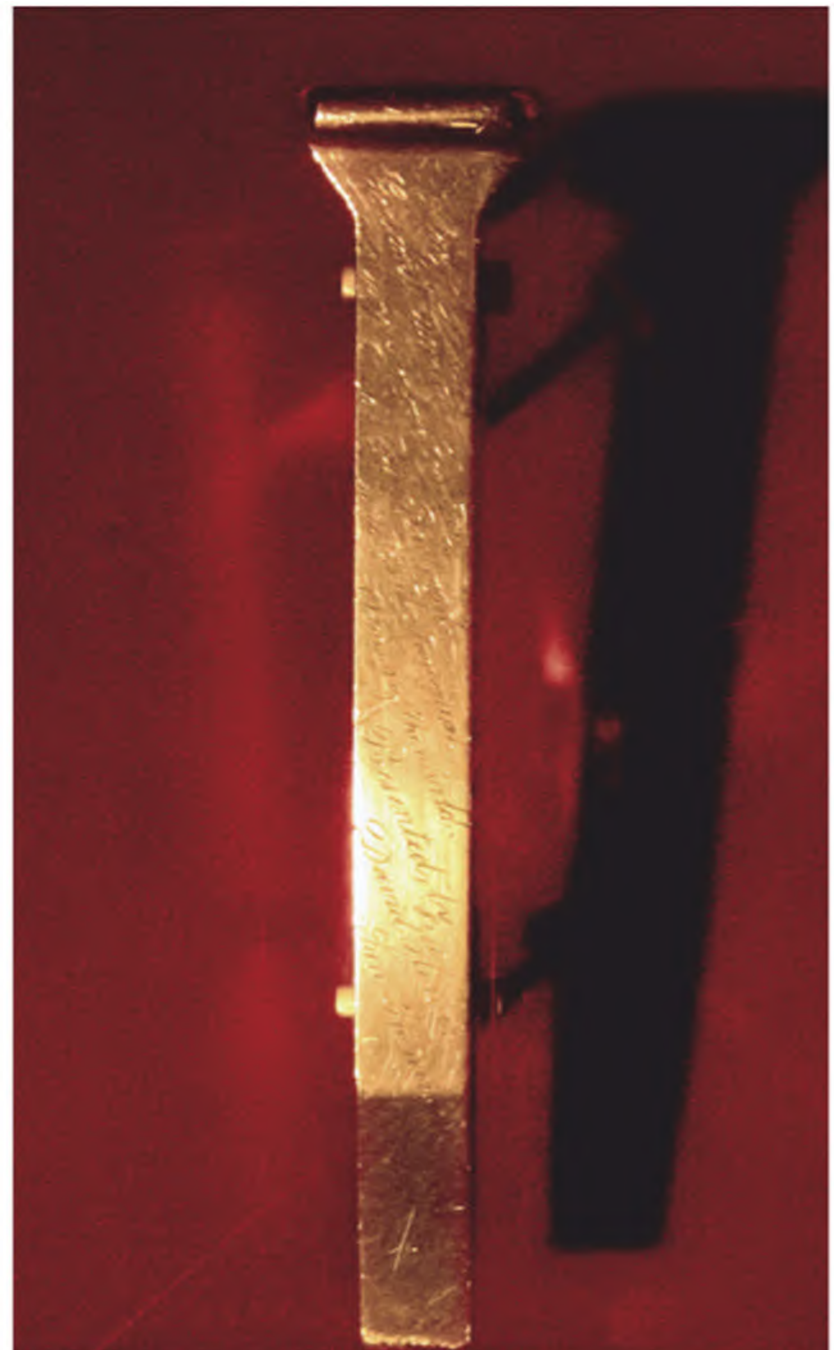
Working one night in 1859, chemists Robert Bunsen and Gustav Kirchhoff saw a fire raging in the town of Mannheim, Germany, about 10 miles (16 km) from their Heidelberg University laboratory. They rolled their newly improved spectroscope (a device they invented that breaks light into its component wavelengths, which allows chemical elements to be identified) to the window and quickly detected the elements barium and strontium within the bright glow given off by the flames. Bunsen wrote that the "same mode of analysis must be applicable to the atmospheres of the Sun and the bright stars." The second half of the 19th century saw an explosion of discoveries using this powerful tool.

During the total solar eclipse on August 18, 1868, several astronomers using spectroscopy detected a new element — and, it turned out, the universe's second most abundant one — in the Sun: helium. Carbon, nitrogen, iron, and all the heavier elements of the periodic table — including gold — were eventually identified in a gaseous state in the Sun's atmosphere.

In the late 18th and early 19th centuries, rock and mineral collecting became the science of geology. Men and women such as Charles Lyell, James Hutton, and the great fossil collector Mary Anning, discoverer of the first *Ichthyosaurus* skeleton, clearly demonstrated that Earth was far older than the 6,000 years suggested by many contemporary theologians. Lyell and Hutton said Earth must be millions or even billions of years old. If this was true, what could keep the Sun and stars shining for such an incredibly long time?

German physicist Julius Robert Mayer strongly favored the meteoric theory of solar heat. He had calculated that, lacking an external source of energy, the Sun could shine for only 5,000 years. In 1848, he suggested the Sun was fueled by billions of meteorites raining down on it, which provided its energy. This material also, supposedly, would have brought heavy elements to our star.

During the 1878 total solar eclipse, Cleveland Abbe, America's first U.S. Weather Bureau meteorologist, suggested that the Sun's corona, visible at totality, was in fact this swarm of meteors plunging into the Sun. But scientists soon proved that the corona was made of ultra-thin gas and demonstrated that meteors would be an insufficient source of solar energy.



The original Golden Spike, driven in by Leland Stanford, connected the Union Pacific and Central Pacific railways in 1869 near Ogden, Utah. It is on display at the Cantor Arts Center at Stanford University. WJENNING/WIKIMEDIA COMMONS

Eventually, scientists calculated that the Sun contains almost 2.5 trillion tons of gold, enough to fill Earth's oceans and more. Still, that's just eight atoms of gold for every trillion atoms of hydrogen — a tiny amount when compared to the mass of the Sun. But how did gold come to be in the Sun and Earth?

Science is golden

For more than a millennium, alchemists struggled to transmute one element into another. They were in search of the philosopher's stone, which could turn base metals like lead and mercury into gold. Even the great Isaac Newton was fascinated

During the total solar eclipse July 29, 1878, Cleveland Abbe, America's first U.S. Weather Bureau meteorologist, suggested that the solar corona was a swarm of meteorites that provided the energy for the Sun to shine. MICHAEL E. BAKICH LIBRARY

by the idea of transmutation. Indeed, some historians refer to him as "the last great alchemist." But the tremendous forces of nature that create the elements were beyond the grasp of these early experimenters.

The origins of heavy elements started to come into focus with the publication of Einstein's general theory of relativity in 1905. It was in this seminal work that the equation $E=mc^2$ first appeared. It wasn't obvious at first just how important this equation was to our understanding of the universe, but its application to the problem of the Sun's immense energy output would have far-reaching implications. Not only did it explain why the Sun and other stars could shine for billions of years, but it also helped show how elements heavier than hydrogen form.

Most of us think of the first atomic bomb and splitting atoms — the process of nuclear fission — when $E=mc^2$ comes to mind. In 1920, however, Sir Arthur Eddington, then at Cavendish Laboratory in Cambridge, England, thought that the fusing of hydrogen into helium could be the powerhouse of the Sun. Einstein's famous equation showed that incredible energy would be released in such a process.

Almost two decades after Eddington and others began to explore fusion, German-American physicist Hans Bethe described the now famous proton-proton chain reaction that explains how hydrogen fuses into helium. Deep within the Sun is a vast "soup" of hydrogen atoms consisting of one proton and one electron each, which are in constant, rapid motion. Most of the time, the electromagnetic force repels any collisions. Trying to stick similar poles of two magnets together gives a feel for such repulsion. But collisions happen, and protons fuse together. When four protons eventually fuse, helium–4 forms, releasing energy and making the Sun shine.

Our Sun contains enough hydrogen to continue this fusion process for another 5 billion years. Eventually, helium will begin to fuse, forming the final products of carbon, nitrogen, and oxygen (element No. 8). Within more massive stars, whose stronger gravity creates more pressure and heat, elements beyond oxygen can fuse. But this process can continue only until iron (element No. 26) forms at the center of giant stars, and that's when fusion shuts down. Finally, the star's core will collapse and then rebound in a supernova explosion.

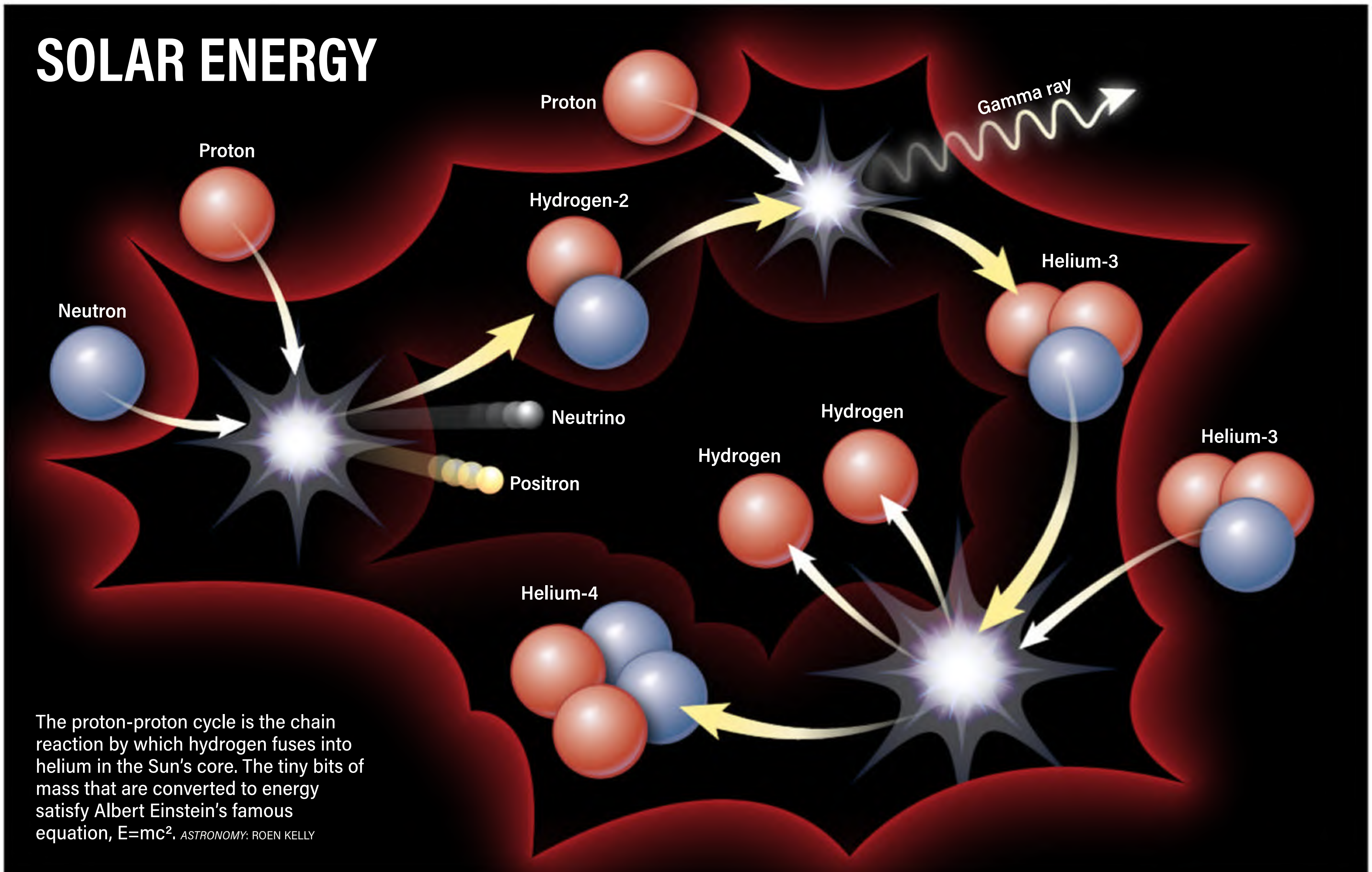
As the outer layers of the star are blasted into space, one of two neutron capture reactions takes place. In both, free neutrons penetrate the nuclei of nearby atoms and are "captured" by elements released in the explosion. Slow neutron capture (called "slow" because radioactive decay into other elements can occur before other neutrons are captured) creates about half of the elements heavier than iron. But that still leaves a lot of heavyweights on the periodic table. To make the rest, you need massive colliding stars that produce rapid neutron capture.

Once astronomers had pinpointed the source of the 2017

GOOD AS GOLD

The spectrum of gold shows the element's unique fingerprints, which are used to identify its presence. MCZUSATZ/WIKIMEDIA COMMONS

Atomic number	79
Atomic weight	196.96657
Density	19.3 grams/cm^3
Melting point	1,947.52° F (1,064.18° C)



The proton-proton cycle is the chain reaction by which hydrogen fuses into helium in the Sun's core. The tiny bits of mass that are converted to energy satisfy Albert Einstein's famous equation, $E=mc^2$. *ASTRONOMY*: ROEN KELLY

gravitational waves, researchers at the Max Planck Institute for Astronomy were able to detect strontium in the maelstrom of matter expanding into space at nearly 30 percent the speed of light. This element and others were formed by the rapid neutron capture reaction. The merger of these stars sent 10^{22} free neutrons flying through just 1 cubic centimeter of space every second.

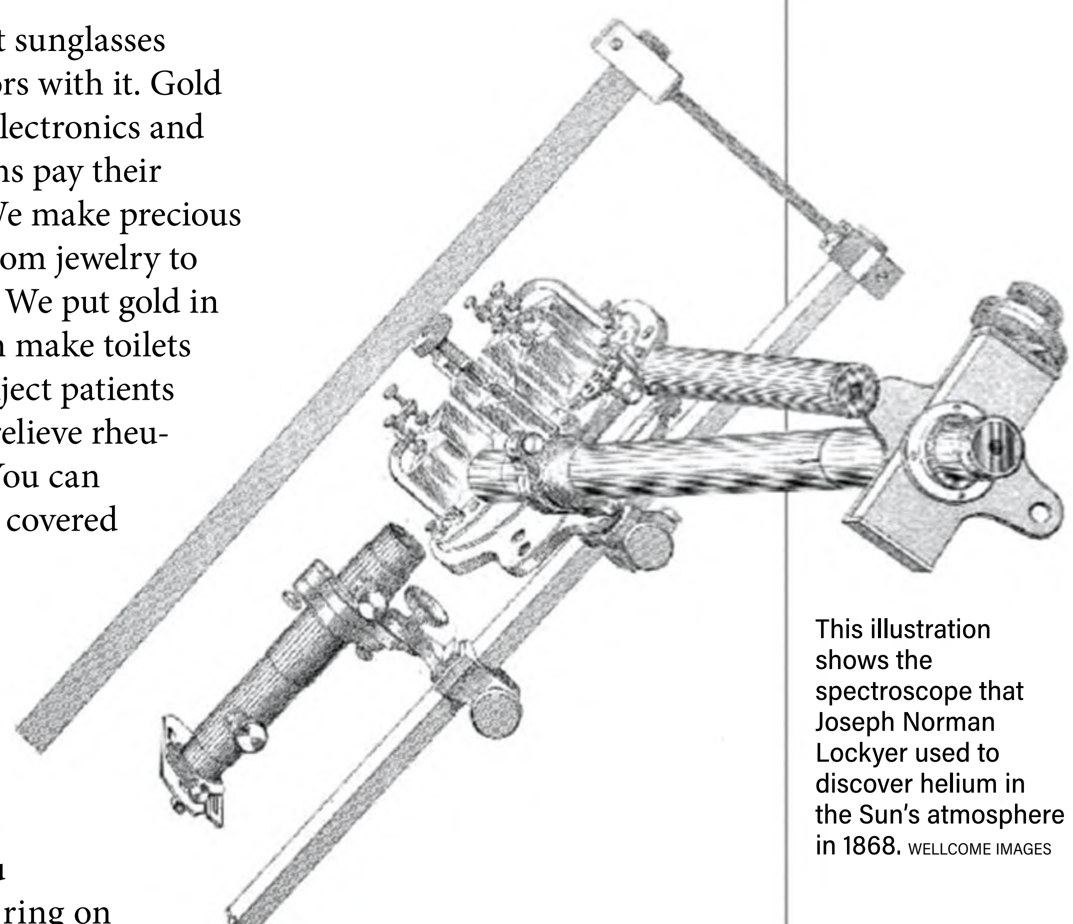
Such a high density of neutrons creates conditions that allow existing elements to quickly capture free neutrons. Strontium, thorium, uranium, and even gold form in a literal flash. And off they go into the depths of space. During the nearly 14-billion-year life span of our universe, this has happened enough times to seed the nebulae that eventually collapse to form solar systems such as ours with gold — and all the other heavy elements, too.

Gold standard

Gold pervades our lives. The element is in every cellphone and computer. We coat sunglasses and astronaut visors with it. Gold thread is used in electronics and in clothing. Nations pay their debts with gold. We make precious objects out of it, from jewelry to religious artifacts. We put gold in our teeth and even make toilets with it. Doctors inject patients with gold to help relieve rheumatoid arthritis. You can even eat chocolate covered in gold.

Carl Sagan famously said we are made from the stuff of stars. So is the world around us. The next time you glance at the gold ring on your finger or feel the gold chain around your neck, remember that they are indeed a gift from the stars.

Raymond Shubinski *is a contributing editor of* Astronomy *who enjoys items made of gold.*



This illustration shows the spectroscope that Joseph Norman Lockyer used to discover helium in the Sun's atmosphere in 1868. WELLCOME IMAGES

Observations of Jupiter's moons

These remote satellites have revealed scant details to earthbound observers for more than 400 years, and offer a great observing challenge.

BY KLAUS BRASCH AND LEO AERTS

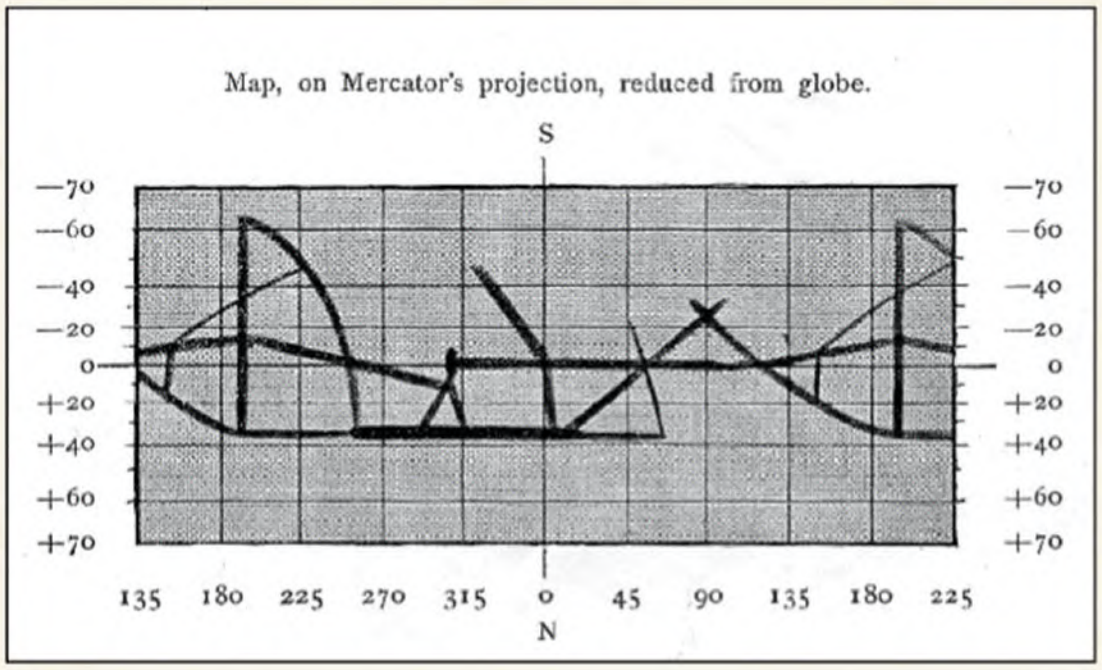
THE FOUR LARGE satellites of Jupiter, discovered in 1610 by Galileo Galilei, have been viewed by more people than any other planetary satellites besides the Moon. They are favorites at star parties and make an attractive sight alongside Jupiter. The famous moons also comprise a distinctive association of bodies which individually would qualify as planets in their own right. But, linked with Jupiter, they are instead considered a small analog of the larger solar system.

If the seeing (atmospheric steadiness) is good, a 6-inch or larger telescope at high magnification will reveal the tiny but distinct disks of all four Galilean moons. Moreover, under really steady seeing with a medium-size scope, experienced observers can occasionally glimpse elusive markings on Ganymede, Jupiter's largest moon.

Observational history

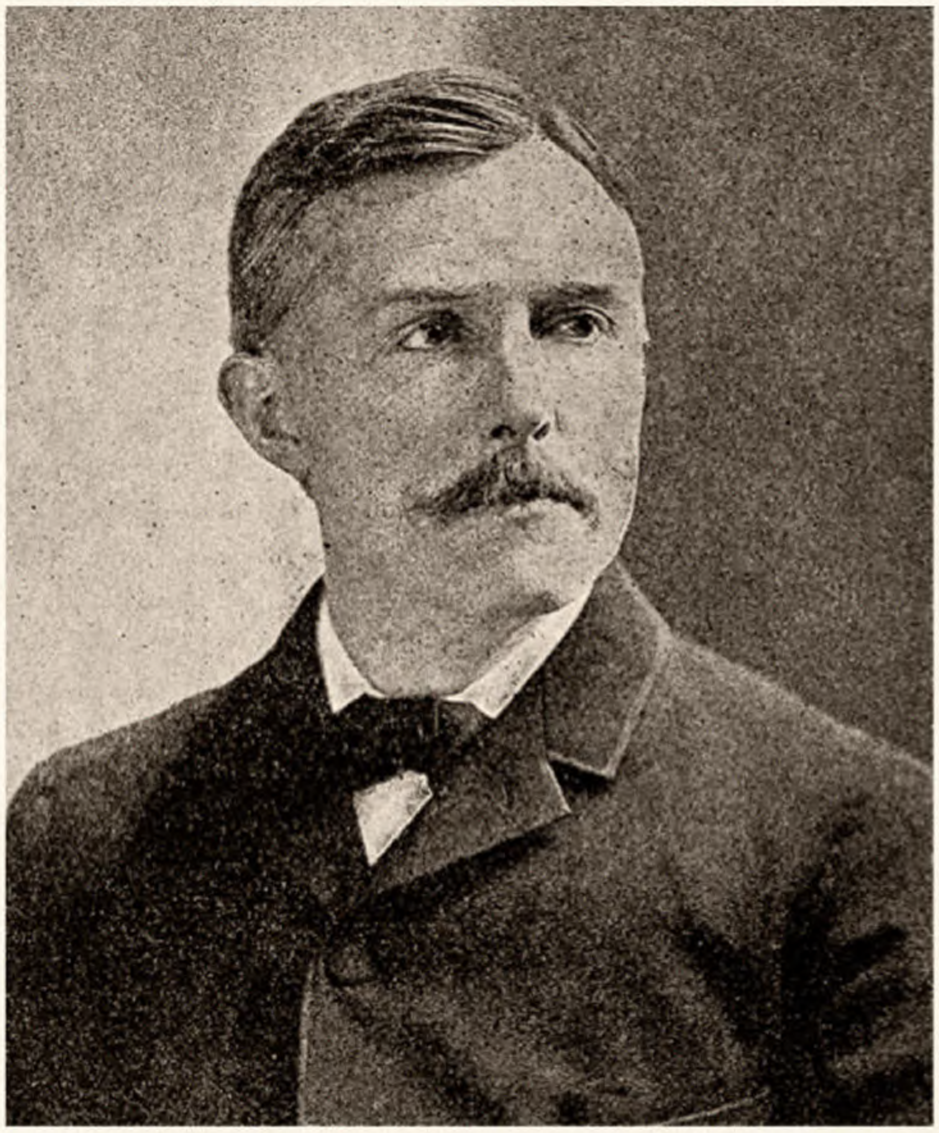
Exactly what could be observed on the jovian moons was a topic of considerable dispute in the late 19th and early 20th centuries. In 1900, astronomers Andrew E. Douglass and William H. Pickering published an extensive monograph in the *Annals of Lowell Observatory, Volume II*, detailing observations of Jupiter and its

ABOVE: William H. Pickering, along with Andrew E. Douglass and Percival Lowell, founded Lowell Observatory in Flagstaff, Arizona. While there, Pickering made extensive observations of planetary satellites. LOWELL OBSERVATORY ARCHIVES

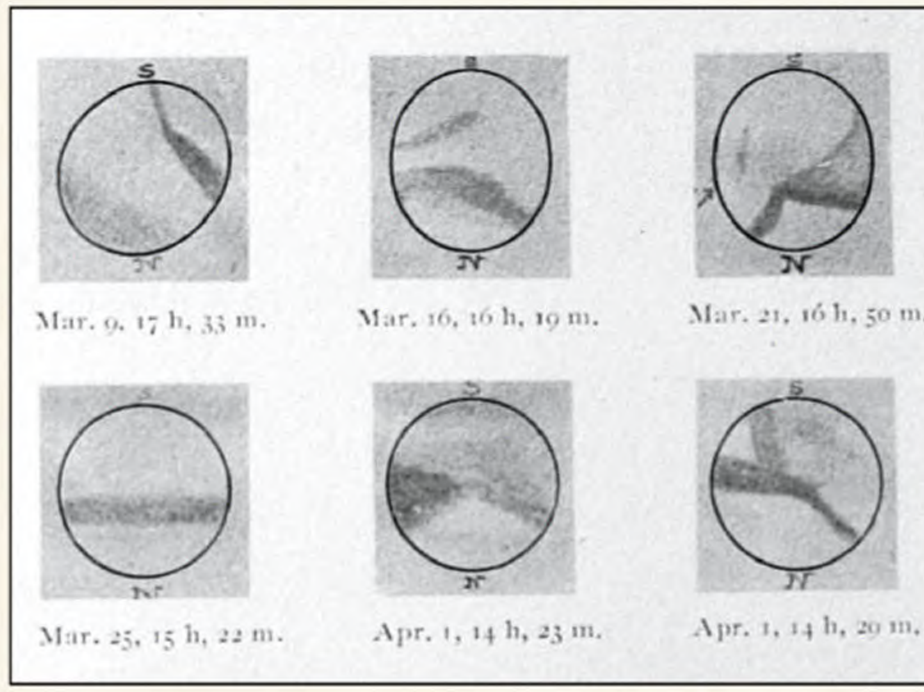


LEFT: Douglass made this map of Ganymede showing the general locations of features he observed through Lowell Observatory's 24-inch Clark refractor. LOWELL OBSERVATORY ARCHIVES

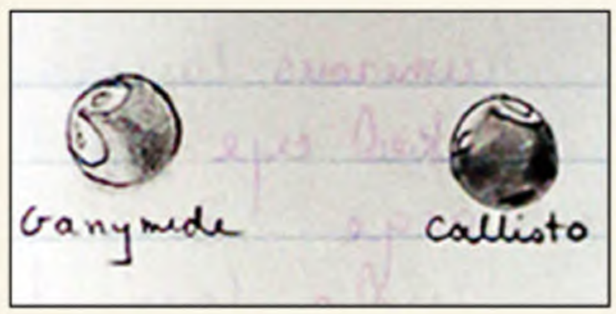
ABOVE: Douglass discovered a relationship between the sunspot cycle and tree rings, thus establishing the science of dendrochronology. He was also instrumental in founding the Steward Observatory at the University of Arizona. LOWELL OBSERVATORY ARCHIVES



Edward E. Barnard was an American astronomer best known for discovering Barnard's Star, unique for having the highest proper motion, and for creating a catalog of dark nebulae within the Milky Way. INTERNET ARCHIVE BOOK IMAGES



Douglass made these drawings of Ganymede at Lowell Observatory in 1894 and 1895, as he observed through 12-, 18-, and 24-inch refractors.
LOWELL OBSERVATORY ARCHIVES



These sketches of Ganymede and Callisto were made in 1983 by *Astronomy* columnist Stephen James O'Meara, using the 9-inch refractor at Harvard College Observatory.
STEPHEN JAMES O'MEARA

moons that they made in 1894 and 1895.

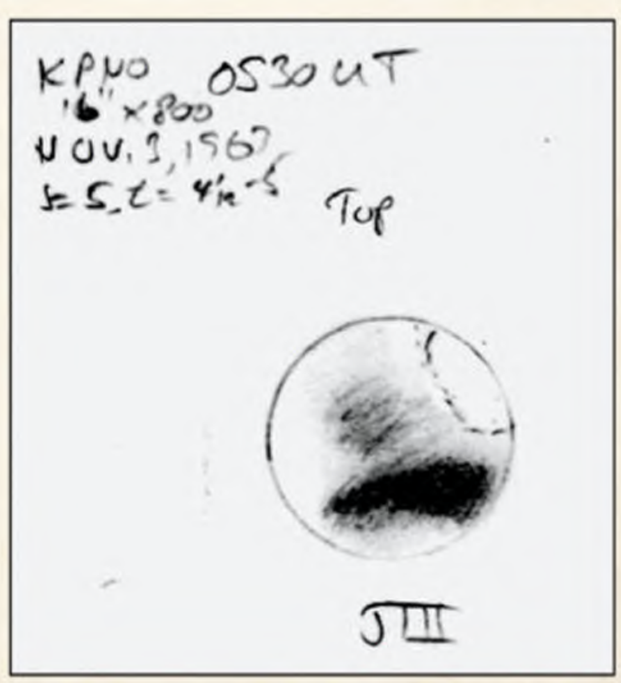
Working in Mexico and at Lowell Observatory in Flagstaff, Arizona, with two refractors — an 18-inch Brashear and a 12-inch Clark — mounted in tandem, the astronomers undertook an ambitious visual program. Their goal was to estimate the ellipticity, rotational periods, and surface features of what they called satellite I (Io), II (Europa), III (Ganymede), and IV (Callisto). The common names, originally assigned by Galileo's contemporary Simon Marius, did not become official until the 20th century.

Douglass subsequently undertook a more detailed study of Ganymede with the newly commissioned 24-inch Clark refractor at Flagstaff. He published the results in the prestigious journal *Astronomische Nachrichten* in 1897, including a map of the features he recorded.

Pickering was a rather eccentric individual; among other extraordinary theories, he believed that Jupiter's moons were not solid bodies but low-density aggregates of dust and meteoric debris. That undoubtedly colored his impressions that they appeared elliptical through the telescope, as well as accounts for his obsession with measuring their "ellipticity." Other observers subsequently showed that the presumptive ellipticity of the moons reported by Pickering was illusory, likely due to contrast or astigmatic effects.

Douglass, a talented astronomer and botanist, was at that time strongly influenced by his boss, Percival Lowell, regarding his views of Mars and its putative network of canals. He was later dismissed by Lowell for doubting their reality. After moving to the University of Arizona in 1906, Douglass became head of Steward Observatory and founded the new science of dendrochronology, which dates historic events using the annual growth rings of trees.

At Lick Observatory, near San Jose, California, renowned astronomer Edward E. Barnard used the then-largest telescope in the world, the 36-inch Clark refractor, to undertake similar observations of Ganymede and Callisto from 1893 through 1895. His results were also published in *Astronomische Nachrichten* in 1897, in a paper



Dale P. Cruikshank reported seeing detail on Ganymede on November 3, 1963, while observing through a 16-inch reflector at 800x at Kitt Peak National Observatory. D.P. CRUIKSHANK

Compare the images of Ganymede above, taken May 5, 2016, to the one generated by JPL's Solar System Simulator (this page, top right). All were taken through a 14-inch Celestron with a 1.8x Barlow lens, and an ASI 120MM-S webcam. LEO AERTS

Co-author Aerts took the image of Ganymede on the left through a DMK webcam attached to a 14-inch Celestron with a 2.5x PowerMate, with the addition of a red filter. The comparative image of Ganymede on the right was generated using the Solar System Simulator provided by Jet Propulsion Laboratory (JPL). LEO AERTS

titled "On the Third and Fourth Satellites of Jupiter."

Differences arise

The Lowell observations show predominantly banded and crossed streaks on all four satellites, and also provide detailed descriptions of each. Ganymede is summarized as: "The third satellite was observed with much greater ease and gave more satisfactory results. The detail is conspicuous, and consists of northern and southern belts parallel to the equator, and other markings. The northern belt becomes visible 2.2 [days] after superior conjunction. Its position is easily determined, and between 1894 and 1895 gives a means for measuring very exactly the rotation period. It shows that the rotation of detail agrees with revolution about Jupiter within 15 minutes. The north polar cap seen by some observers is immediately north of this conspicuous northern belt and is probably caused by contrast."

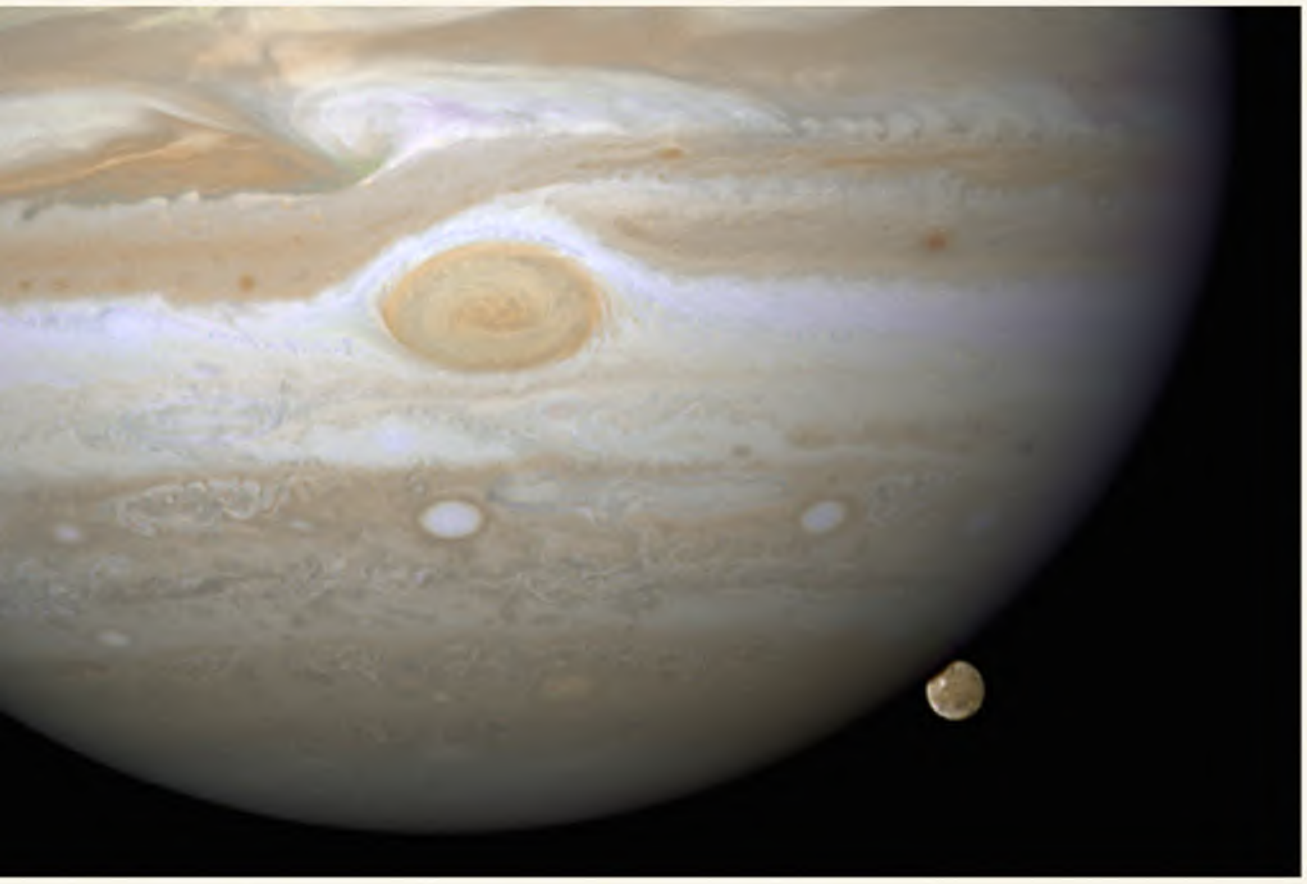
Other astronomers later showed that Jupiter's main moons are tidally locked and rotate synchronously with their planet like our Moon. In his subsequent 1897 paper, Douglass appears more certain of the key markings he described: "On February 20th … an interval of extremely good seeing revealed the Great Northern Belt in longitude 260° to 20°, with perfect distinctiveness and definition."

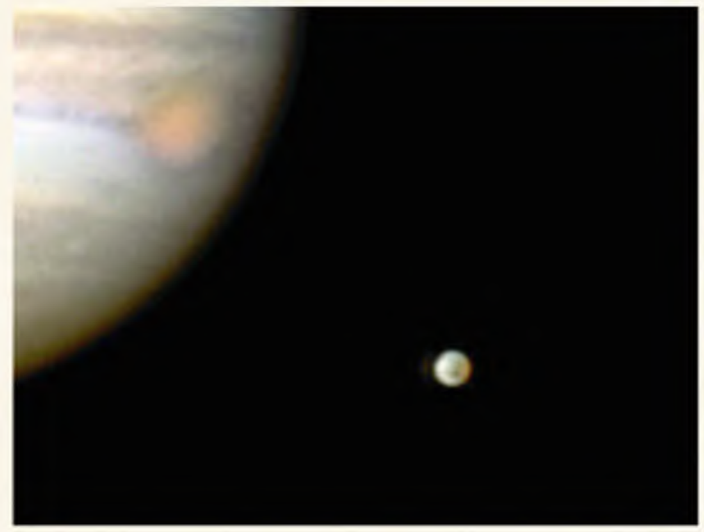
In sharp contrast to Douglass and Pickering, Barnard's drawings of Ganymede and Callisto show far more diffuse features: "Though conspicuous enough, they were so vague in form that at no two times was it possible to say definitely that the same marking was under observation." He goes on to say, "I have been very much interested in Mr. Douglass' paper on the third and fourth satellites of Jupiter." After Barnard mentioned that he used the much larger 36-inch Lick refractor to make his observations, he wryly added, "According to Mr. Douglass' drawings and statements, he finds these satellites covered by a series of fine dark lines, the maximum width being estimated at less than 0.1" or 200 miles. In appearance, from the drawings, these markings very much resemble those seen at the same observatory upon Mars, Venus and Mercury."

These strident comments, well documented in William Sheehan's memorable biography of Barnard, *The Immortal Fire Within*, point to the rivalry and disagreements between the two observatories. They were most glaring with respect to the putative martian canals and similar features as depicted by Percival Lowell and others. Much of the divergence hinged on Lowell's claims that while his telescopes were of smaller aperture, seeing conditions at the high and dry elevation of Mars Hill were unequaled.

To that, Barnard countered that it was his belief that no existing telescope, except the 40-inch Yerkes refractor, "is so capable of showing the surface features of these satellites

In 2015, co-author Aerts captured the webcam image at left of Ganymede transiting Jupiter with a 14-inch Celestron Schmidt-Cassegrain telescope. He also made a simultaneous sketch of the satellite, at right. LEO AERTS





A Hubble Space Telescope image of Ganymede emerging behind Jupiter is shown at left. Co-author Aerts took the comparable image at right through a 14-inch Celestron Schmidt-Cassegrain telescope. LEO AERTS

as the Lick 36-inch. I also believe there are brief intervals of good seeing at the Lick Observatory which are not excelled if indeed they are equaled at any other observatory."

Well over a century later, what can we conclude as to who was right and what in fact can be observed of the jovian moons' features using earthbound telescopes? Both authors of this piece have spotted vague detail on Ganymede through a 14-inch Schmidt-Cassegrain telescope on rare occasions of outstanding seeing. And one of us, Brasch, even saw ruddy patches on Io while observing with Lowell Observatory's 4.3-meter Discovery Channel Telescope. Well-known planetary scientist Dale P. Cruikshank likewise observed details as a student with the 82-inch Otto Struve telescope at McDonald Observatory, as well as with smaller instruments at Kitt Peak National Observatory (KPNO) and elsewhere.

In addition, in the 1940s, French astronomer Bernard Lyot and others reported visible details on all four Galilean moons. They were observing with a 24-inch refractor at Pic du Midi Observatory in France, known for its legendary steady seeing and clear skies.

Current observations

One can argue that jovian moon detail should be well within visual reach of large, professional telescopes, but what about smaller, more typical amateur instruments? Clearly, it depends on a number of factors: the quality of the optics, the seeing, the magnification, and perhaps most importantly, the observer's experience and visual acuity.

Before the Voyager spacecraft flybys of Saturn in 1980 and 1981, *Astronomy* magazine's eagle-eyed Stephen James O'Meara (then a student) spotted the spokes in the planet's B ring. He also accurately determined the rotation period of Uranus with the 9-inch Clark refractor at Harvard College Observatory. In 1983, O'Meara went on to spot mottled markings on Ganymede and Callisto with this same telescope. Regarding the latter, he advises, "Seeing detail on the jovian moons requires exceptional seeing, and the best views are [obtained] through astronomical twilight. Spend a minimum of 30 minutes looking, waiting for moments of perfect seeing, and confirm and reconfirm any initially suspected structure at least three times."

Likewise, during his student days, Cruikshank reported detail on Ganymede with his 12-inch reflector, a 16-inch reflector at KPNO, and the 40-inch refractor at Yerkes Observatory. More recently, co-author Aerts sketched and simultaneously imaged details on Ganymede with a 14-inch Schmidt-Cassegrain telescope.

These results once again raise questions as to the reliability of visual reports. In an effort to answer them, we undertook a side-by-side comparison of visual observations from several sources, with modern digital images of the Galilean moons. Making allowances for stylistic differences among observers, as well as instrumental and atmospheric variances, it seems clear that visual reports of features on Jupiter's largest moon, Ganymede, must be taken with considerable skepticism. While there is general agreement that the satellite exhibits diffuse dark and light regions, and there are references by several of the early observers to "bright polar caps," the notes of Barnard, O'Meara, and Cruikshank all urge caution in their accompanying notes: "extremely difficult"; "probably unreliable"; "seemed real, but …"; and so on.

On the other hand, today, thanks to the tremendous advances in digital imaging and processing, amateur astronomers with just medium-size telescopes can capture outstanding images of Jupiter and its moons, unheard of just a decade ago. It is indeed a golden age of amateur astronomy.

Klaus Brasch *is a retired bioscientist and volunteer at Lowell Observatory in Flagstaff, Arizona.* **Leo Aerts** *is a Belgian amateur astronomer specializing in solar system imaging.*

Collect the cosmos in stamps

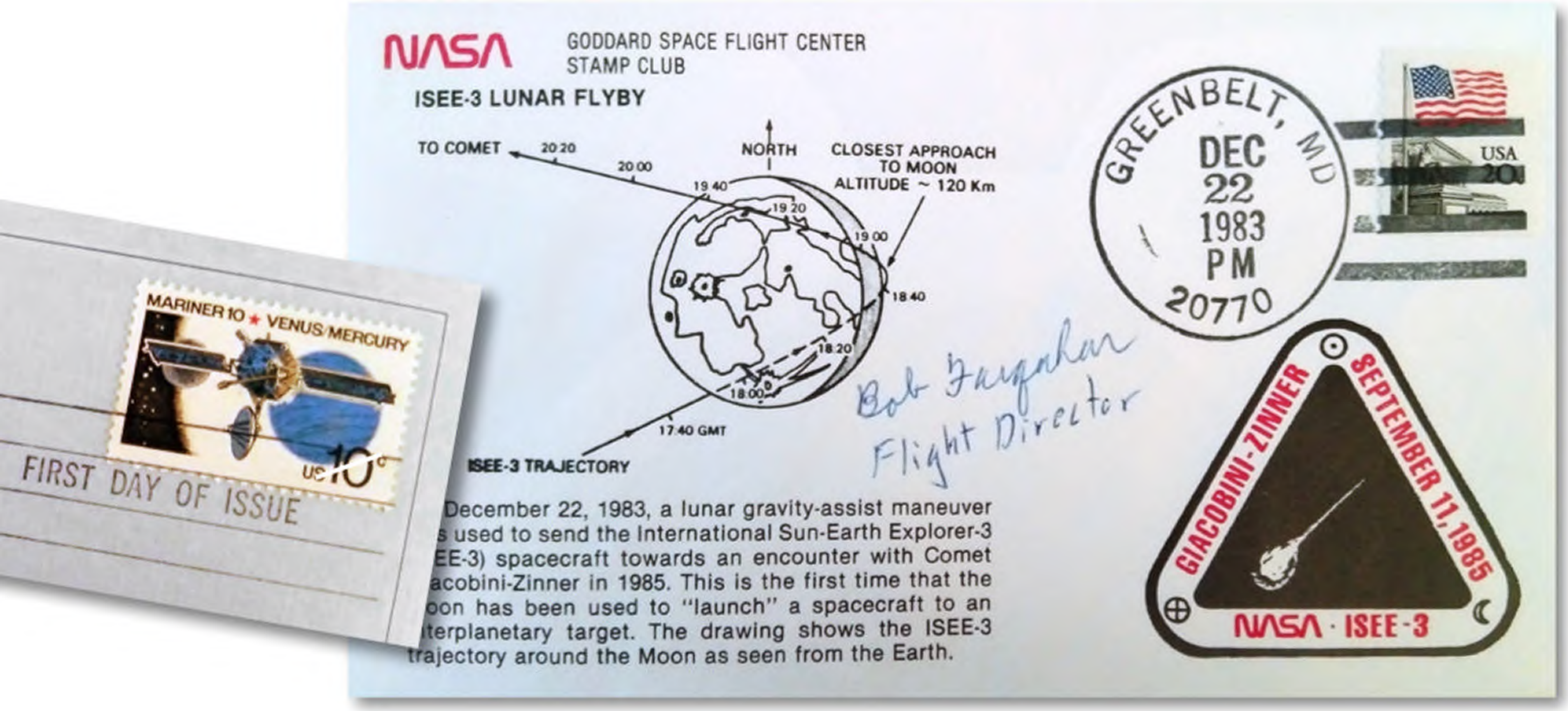
While the universe is vast, this selection of stamps can shrink it down to a manageable size.

BY KATRIN RAYNOR-EVANS

IMAGINE CARRYING the universe in your pocket before sending it halfway across the world. Of course, you can't actually carry the entirety of the universe, but you can carry a small, weightless surrogate that's just as beautiful. These could include a colorful array of astronauts, rockets, galaxies, and nebulae, on canvases about 1 inch in size.

You may have guessed that I'm talking about postage stamps. I've had a lifelong interest in astronomy, but I didn't turn my attention to stamp collecting until a few years ago. This new hobby ignited when, while leafing through my father's stamp collection, I spotted a science-fiction-themed stamp. I soon wondered what other topics

The author exhibits a collection of stamps and first day covers at a celebration of the 50th anniversary of the Moon landing, at National Museum Wales in Cardiff.



ALL IMAGES BY KATRIN RAYNOR-EVANS

stamps could pay tribute to — particularly, astronomical ones. After some research, I realized I could bring my love of the cosmos and this new hobby together. From then on, I was captivated.

Philately is the collection and study of postage stamps and associated materials, such as first day covers — an envelope or card with a stamp cancelled on the first day that stamp was sold. Postal stationery, miniature sheets, full sets of newly issued stamps, special handstamps, and autographs all contribute to the world of stamp collecting as well.

Small yet vibrant and educational, stamps are also a fantastic way of documenting and commemorating scientific discoveries, providing a unique historical record. Since the release of the first astronomy-themed stamp — a blue stamp issued in Brazil in 1887 depicting the constellation Crux the Southern Cross — countries all over the world have been issuing stamps to celebrate the wonders of the sky and the achievements made by humankind.

Remembering historical events is exciting and important to us. And what better way to recognize these milestones than to look at how the world has commemorated them with the simple postage stamp throughout time?

The Royal Astronomical Society's bicentennial

On January 12, 2020, the Royal Astronomical Society

(RAS) celebrated its 200th anniversary. Located in London, the RAS is an organization actively promoting the study of astronomy, cosmology, solar system sciences, and geophysics.

In February, the British postal service, the Royal Mail, issued a special set of stamps to commemorate the group's bicentenary. Designed in collaboration with the RAS, the images reflect scenes of discovery and research undertaken by British astronomers and astrophysicists including Stephen Hawking and Dame Jocelyn Bell Burnell.

"Visions of the Universe," comprises eight illustrated stamps with a colorful array of astronomical objects and phenomena, including the stunning Cat's Eye Nebula (NGC 6543), rapidly rotating neutron stars, black holes, and the rubber-duck-shaped Comet 67P/Churyumov–Gerasimenko.

This was not the first RAS anniversary celebrated with stamps. In 1970, the Royal Mail issued a stamp commemorating the

organization's 150th anniversary. It depicted the Society's first president, William Herschel, his son John, and Francis Baily, the founders of the RAS, standing in front of Herschel's famous 40-foot telescope. This probably won't be the last time RAS is remembered through these small pieces of art, as the society has been a part of the astronomical world for so long.

The world watches Hale-Bopp fly by

Continuing our honoring of historical astronomical events, Comet C/1995 O1 Hale-Bopp was the most observed comet of the 20th century, slowly traversing our skies over the course of approximately 18 months. Hale-Bopp shone bright at magnitude –1 and was visible to the naked eye, even in light-polluted towns and cities.

In 1997, the Dominican Republic issued a stamp depicting the comet positioned against a tropical pink and yellow sky. When a comet nears its closest approach to the Sun, it can develop two tails as dust particles are liberated from within its icy nucleus. Solar radiation blows gas and dust from the comet's center, forming an ion tail and a dust tail. The Dominican Republic stamp depicts this occurrence, as Hale-Bopp is shown with its two tails of gas and dust flying behind it.

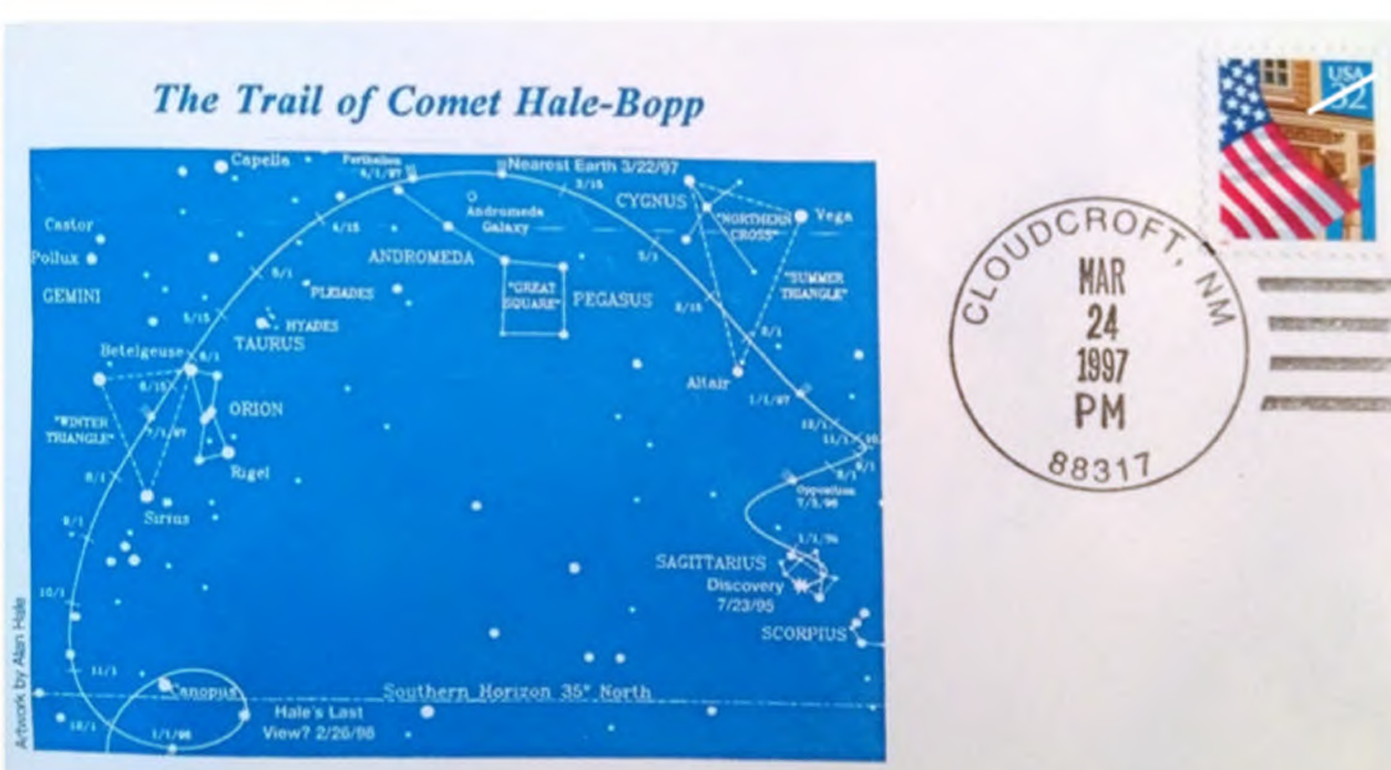
In 2007, the coastal African country of Guinea issued a set of miniature sheets to celebrate the 10th anniversary of Hale-Bopp's show. The collection of four stamps shows discoverers Alan Hale and Thomas Bopp set against various backgrounds, including images of the comet and an illustration of Charles Messier, a nod to one of the greatest comet hunters in history.

Some stamp collectors even made their own covers — an envelope covered in the desired stamps and mailed by the postal service with the intention of becoming a collectible — to celebrate the comet. Avid collectors mailed their covers to Cloudcroft, New Mexico, to have them hand stamped and mailed back from the location where Hale made the first discovery of the comet.

Comet Halley's 1986 return

Comet 1P/Halley, known to most as Halley's Comet, is perhaps the most famous short-period comet in history — its return time of 76 years has allowed some people to view this once-in-a-lifetime event twice. Although it's named after astronomer Edmond Halley, records of the comet date back as far as 240 B.C. in China. It was even embroidered into the Bayeux Tapestry, a famous cloth depicting hundreds of years of world events.

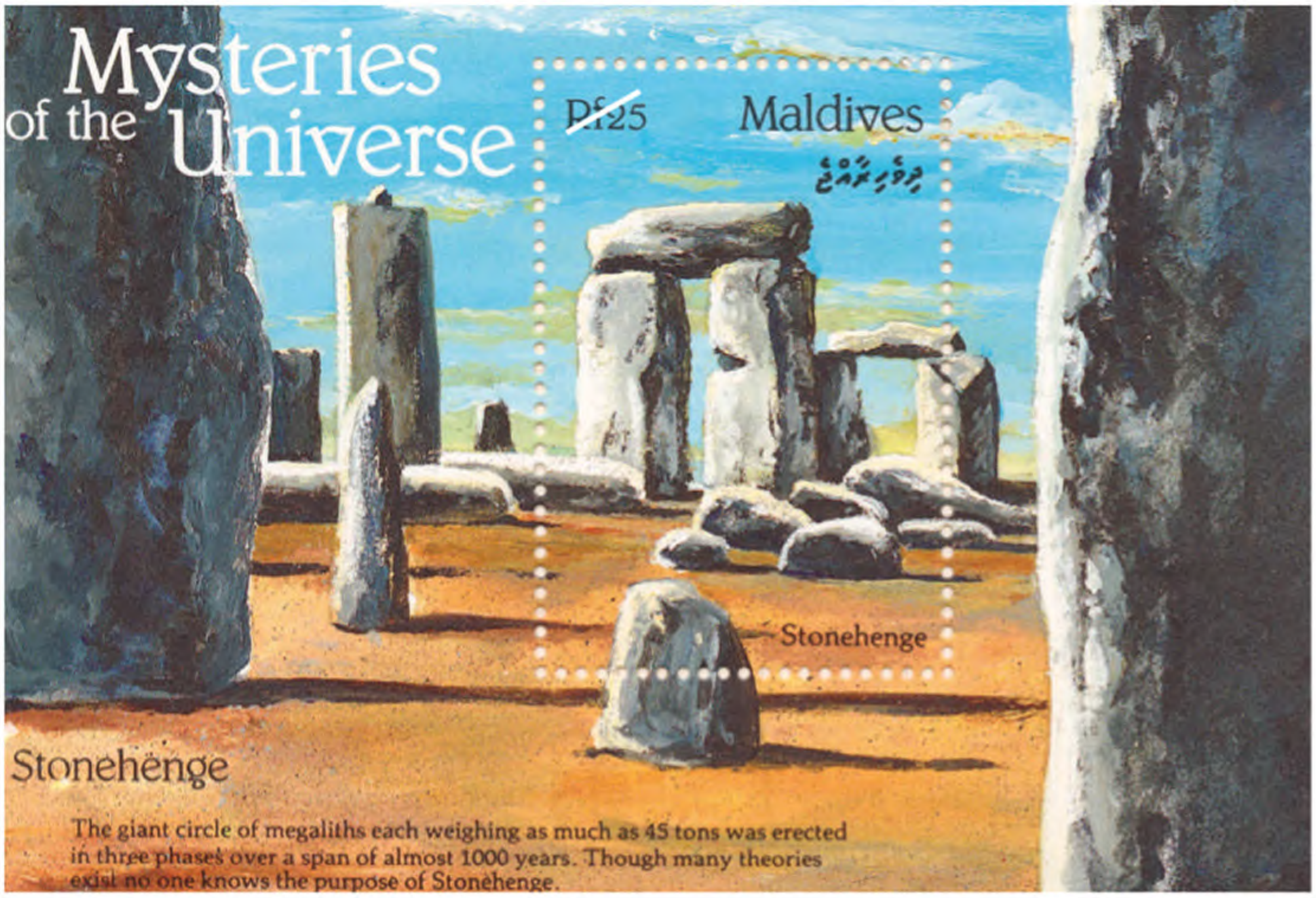
And on January 24, 1985, amateur astronomer and *Astronomy* columnist Stephen James O'Meara became the first person to visually observe Halley's Comet, then at magnitude 19.6, as it approached the Sun for its February 9, 1986 return. He used a home-built 24-inch telescope on top of Mauna Kea in Hawaii to spot it.

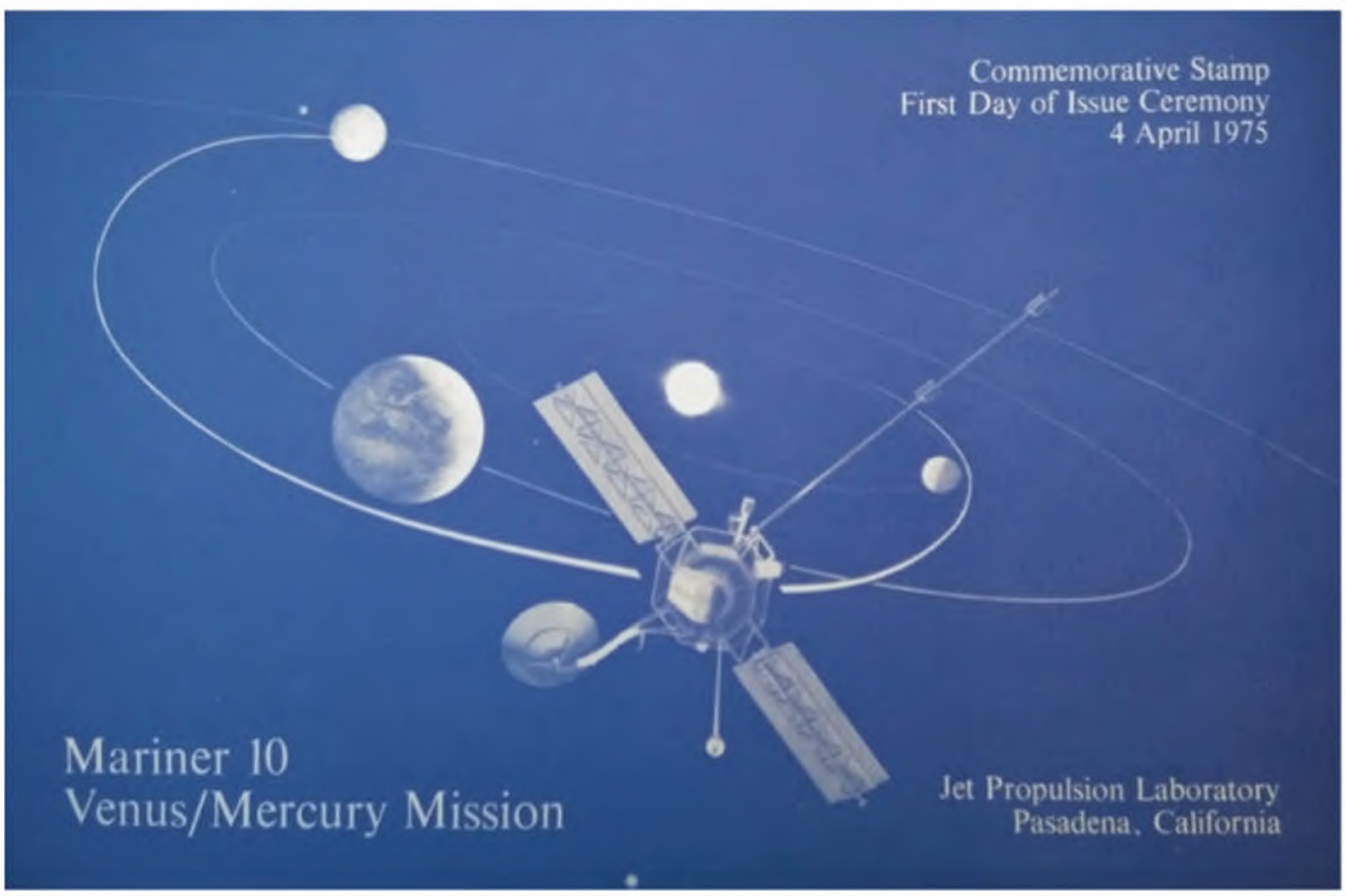


Also in 1985, on July 2, the European Space Agency launched the robotic Giotto spacecraft to get up close and personal with the infamous comet. The next year, between March 12 and 15, 1986, the spacecraft approached the comet to within 370 miles (596 kilometers) and collected an impressive amount of data.

To celebrate the comet's 1986 return to our night skies, countries around the world — from the Cook Islands in the South Pacific to Paraguay in South America — produced stamps. The Royal Mail issued a fantastic set of four stamps illustrated by the famous cartoonist Ralph Steadman. The selection is colorful and imaginative, depicting scenes such as discoverer Edmond Halley as a comically disgruntled comet; two comets in the sky (representing seeing Halley twice in a lifetime); the Giotto encounter; and the comet rounding the Sun.

In addition, cachet designs — illustrations or inscriptions stamped on an envelope — printed on first day covers included images of the





comet's orbit, as well as portraits of Halley and the Giotto spacecraft.

Commemorating the Apollo missions

Giotto wasn't the only spacecraft to receive the special honor of becoming a stamp. Achievements in spacecraft development and spaceflight have been celebrated on stamps for decades — and none more so than the Apollo missions. In 2019, the United States Postal Service (USPS) issued two Forever stamps to commemorate the 50th anniversary of humans landing on the Moon. The stamps illustrate the Apollo 11 landing site in Mare Tranquillitatis, or the Sea of Tranquility, and the iconic photograph of Buzz Aldrin taken by Neil Armstrong.

The 50th anniversary of Apollo 13's ill-fated flight in April 1970 was marked in 2020. Apollo 13 was supposed to be the third mission to land on the Moon, until Commander James Lovell, Command Module Pilot John Swigert, and Lunar Module Pilot Fred Haise lost power in their spacecraft after an oxygen tank exploded two days into their mission. The crew was left without oxygen and water supplies, forcing them and their NASA counterparts on the ground to think on their feet to get the group back to Earth. Instead of landing on the Moon, the three astronauts made it back home safely on April 17.

Romania issued a miniature stamp sheet in June of 1970 which shows four value stamps featuring the splashdown of the lunar module with its parachutes deployed. Bordering these are four non-value stamps showcasing portraits of the crew and the Apollo 13 emblem.

Also in 1970, the Republic of Rwanda issued a set of eight stamps to celebrate the accomplishments of the space race. The stamps tell the story of the race to the Moon, from humans reaching Earth orbit to the first Moon landing. While these stamps can't capture the exact wonder and amazement the Apollo era brought, they still serve as a nice reminder of this great human accomplishment.

Celebrating modern astronomical events

A number of astronomical events took place in 2020:

Eclipses, the summer solstice, meteor showers, and planetary observing all have a special place on our observational calendars, giving everyone a chance to look into the sky and spend a little less time on other worries. Annually, these events allow people to enjoy the wonders of the universe we live in, so much so that they also have been celebrated on stamps.

Six eclipses will have graced our skies by the end of the year. This includes the annular solar eclipse of June 21 and the total solar eclipse occurring December 14. Such rare astronomical events have been long been commemorated on stamps — for example, the Great American Eclipse, which was visible along a narrow path across the United States on August 21, 2017. A few months before, on June 20, 2017, the USPS issued their first Forever Stamp using thermochromic ink, which changes color in response to heat, to celebrate this eclipse. "The Total Eclipse of the Sun" stamps depict the Sun obscured by the Moon; when heat is applied to the stamp's surface, the eclipse image disappears, revealing the Full Moon.

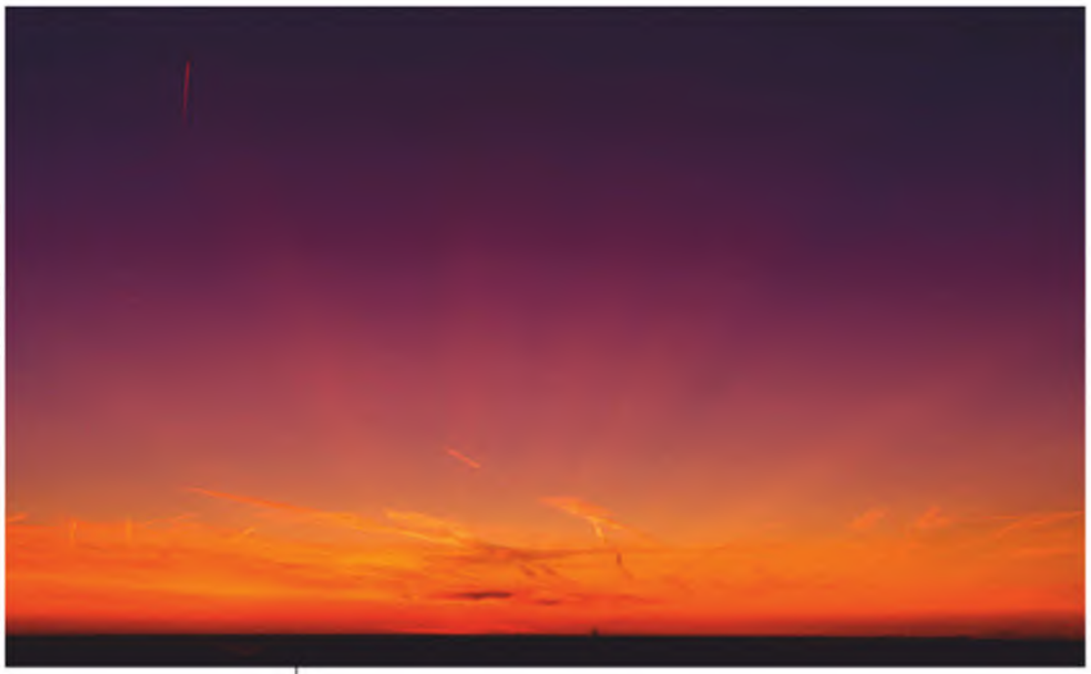
The summer solstice is celebrated across the globe, ushering in the first official day of the hot season. But it's also become a major holiday at the prehistoric astronomical site Stonehenge, where the Sun peers perfectly through the stone gates while rising on the morning of the summer solstice. The iconic stone circle itself is a favorite for astronomers and stamp collectors alike, as much a mystery as a feat of astronomical engineering. Stonehenge has been featured on a set British "World Heritage Site" stamps in 2005 and on the 1997 "Wonders of the World" stamps issued by The Republic of The Gambia.

From objects in space, such as comets, star clusters, and black holes, to the feats of human exploration, astronomy has been globally celebrated on stamps for over a hundred years. Philately is a wonderful and vibrant way to look back and catalog the exceptional discoveries made throughout history. The hobby allows us to celebrate our growing knowledge of this beautiful and dynamic universe, and even send it around the world so that someone else can capture the universe in a space as small as a postage stamp.

Katrin Raynor-Evans *has been a fan of the night sky her whole life, but she now keeps the universe close to her in stamp form.*

"Fire" in the sky

Let's examine volcanic and mock-volcanic twilights.



ABOVE: Dutch skywatcher Michiel de Boer captured this view of a volcanic twilight from the Dutch Dunes, complete with crepuscular rays. MICHIEL DE BOER

RIGHT: The mock volcanic twilight at lower right over Maun, Botswana, on May 20, 2020, was caused by smoke injected into the stratosphere by intense fires in southeastern Australia. STEPHEN JAMES O'MEARA

BY STEPHEN JAMES O'MEARA

Stephen is a globe-trotting observer who is always looking for the next great celestial event.

Lucky are those who have seen Mother Nature paint Earth with fire during twilight. A year ago, Northern Hemisphere twilights became infused with incendiary glows capped with simmering purple sheens. These colors were created by sunlight interacting with gases injected into the Earth's stratosphere by a potpourri of volcanic events: Ambae (July 2018, Vanuatu), Raikoke (June 2019, Russia), and Ulawun (July 2019, Papua New Guinea). And since their first known recording in 1553, they have inspired poets, artists, and skywatchers alike.

An example

In September 2019, Michiel de Boer of the Netherlands was driving home after watching a "fairly uneventful sunset" from the coastal Dutch Dunes. That's when a peculiar orange glow in the sky caused him to turn around. He made it just in time to watch the orange sky turn red. "This could only be a volcanic sunset," he thought, as the red glow combined with scattered blue light to create a mild purple hue. "As the eye adapts to colors," he said, "the purple was best seen when first looking in the other direction for half a minute."

Clouds below the horizon also caused shadow gaps in the higher volcanic aerosol layer, creating crepuscular rays, against which were projected colorful contrail cirrus. "Though I'm generally not a fan of man-made clouds, this was an exception," de Boer said. "The colors were so vivid it was hard to capture."

When powerful volcanic eruptions inject large amounts of ash or sulfur dioxide into Earth's stratosphere, thin veils of dust or sulfuric acid droplets can linger for years, spreading over the entire globe. Light Detection and Ranging (LIDAR) measurements have fingered Raikoke's 2019 eruption as the primary source for the sunset-boosting materials. Scientists are now seeing the strongest stratospheric enhancement in mid-northern latitudes since the 1991 eruption of Mount Pinatubo in the Philippines.

That event injected 20 million tons of sulfur dioxide into the stratosphere, and it created colorful volcanic twilights across the globe for some 18 months. Satellite observations from early 2020 show that Raikoke's plume ascended 16 miles (26 kilometers) and dispersed throughout the Northern Hemisphere. But at the time of this writing, many observers have already reported that the visual effects have greatly waned.

Southern skies aglow

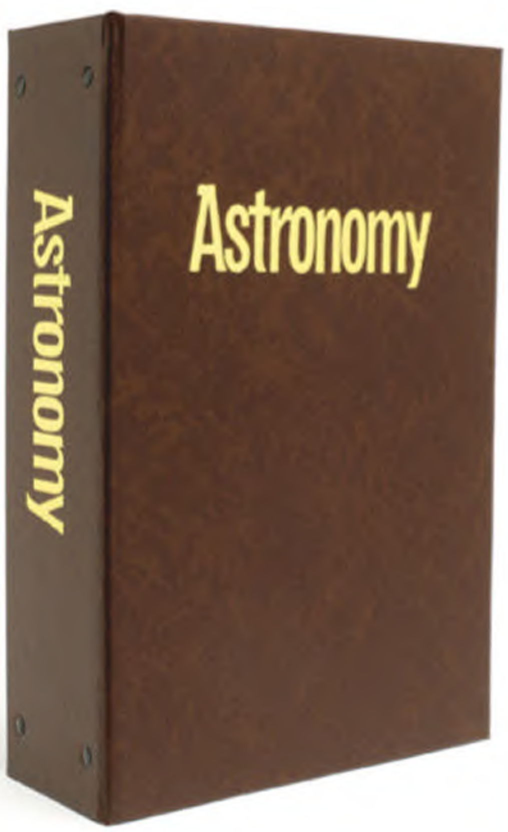
Intense fires in southeastern Australia during December 2019 and January 2020 led to an atmospheric phenomenon for the record books. Fires have been known to create an updraft of superheated, fast-rising air, which can turn into enormous pyrocumulonimbus clouds in the troposphere. On January 20, 2020, however, CALIPSO, a joint environmental satellite constructed by NASA and the French National Centre for Space Studies, observed smoke from the Australian fires continuing to rise into the stratosphere.

Three months later, mock volcanic twilights began occurring over Botswana. A check with NASA atmospheric scientist Colin Seftor confirmed that the colorful sunsets were due to smoke from Australia's "unprecedented fire activity." The fires lofted between 300,000 and 900,000 metric tons of smoke into the stratosphere.

Since the initial outbreak, the vast stratospheric smoke plumes have encircled the Southern Hemisphere, creating twilight glows that mimic volcanic events — but only minor ones. Indeed, to date, I have not observed any fiery reds in the afterglow with my unaided eyes. This may be related to the fact that wildfire smoke has a different composition than volcanic dust. Smoke is more sooty black carbon than lighter colored sulfates.

If you've made observations of either of these rare twilight effects, I'd love to hear from you. As always, send reports to sjomeara31@gmail.com.

BROWSE THE "SECRET SKY" ARCHIVE AT **www.Astronomy.com/OMeara**



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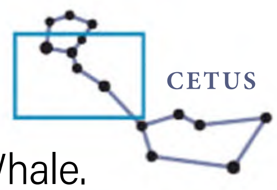
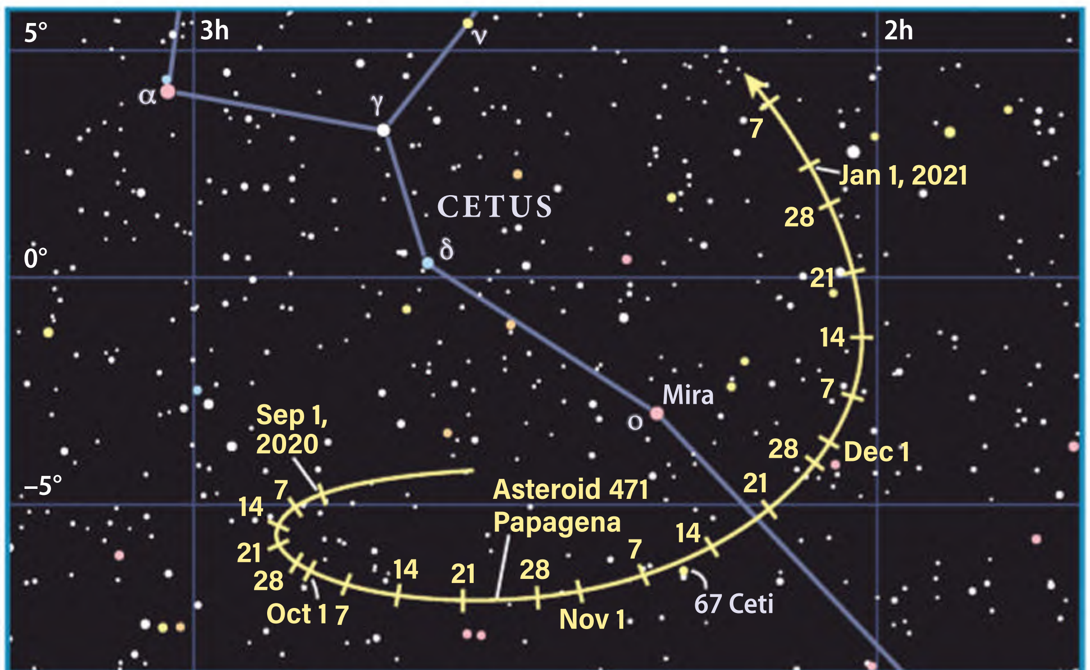
MAP
$2948.00
tripod not included

Target asteroid Papagena



Find the space rock in the belly of the Whale.



Often, the best way to spot an asteroid is to wait until its predicted path brings it near a bright star. Asteroid 471 Papagena comes within a degree of 5th-magnitude 67 Ceti around November 10, just a few weeks after it reaches opposition on October 27. *ASTRONOMY*: ROEN KELLY

BY GLENN CHAPLE

Glenn has been an avid observer since a friend showed him Saturn through a small backyard scope in 1963.

One of my favorite astronomical activities is observing asteroids. My first success was in the summer of 1971, when I spotted 4 Vesta. Since then, I've notched 126 asteroids — tracking most of them down with a modest, 3-inch f/10 reflector.

It's hard to explain my fascination with something that, through an eyepiece, looks like just another star. Maybe it's the knowledge that the "star" is in fact a huge space rock dozens to a few hundred miles in diameter. Maybe it's the pleasure I derive from following the night-to-night motion of an asteroid traversing the starry background. Who really knows?

If you've never seen an asteroid, though, it's time to get in the game. So, this month, your assigned target is asteroid 471 Papagena. As November begins, it is just days past opposition in the constellation Cetus, but it remains brighter than 10th magnitude all month. Here are the steps you'll need to take in order to move Papagena to your "observed" list.

It's time to get in the game.

Begin by assembling your asteroid-hunting gear. You'll need a telescope rigged with a low-power eyepiece that yields a field of view at least 1° (about twice the diameter of the Moon) across. A big scope isn't necessary; even a common 2.4-inch refractor will suffice. Add a clipboard, paper, a pencil, a red-filtered flashlight, and this finder chart, and you're ready to go!

The first thing you'll need to do once you're set up is locate Papagena. Point your scope toward the bright star nearest its predicted location. A favorable window of opportunity occurs around November 10, when Papagena is less than a degree from the 5th-magnitude star 67 Ceti. Alternate views between your finder chart and eyepiece to "star-hop" your way to the asteroid's predicted location. If you've done everything correctly, you should spot the 9th-magnitude space rock.

Don't start celebrating yet, though. You can never be 100 percent sure you've spotted an asteroid until you've detected its motion. I don't count an asteroid as observed unless I've seen it on two or three evenings to confirm its motion against the background stars. On more than one occasion, I was disappointed to discover that my suspect from the evening before hadn't moved, forcing me to renew my search.

To be sure you've found Papagena, refer to the finder chart to study where it should appear over the next few nights. Take out your sketch pad and draw the field, including your candidate and field stars within at least a degree of its future path. (The fewer field stars, the better, as you might mistake them for Papagena on a later night.)

Confirmation comes on the next clear night when you revisit the field. If you see nothing where your suspect was the previous night, raise your fist in triumph. Now turn to tonight's predicted location. If you see a "star" in that location and your sketch shows nothing was there the first night, raise both fists in triumph and write "Gotcha!" on the page. You've captured Papagena.

As is the case with its kindred asteroids, Papagena is much more than a stellar speck. With a diameter of over 90 miles (145 kilometers), it's roughly comparable in size to the state of Connecticut. Fortunately for us, Papagena will never get closer than its opposition distance of 120 million miles (193 million km). A main-belt asteroid (one whose orbit lies between Mars and Jupiter), Papagena circles the Sun once every 4.9 years.

In catalogs, asteroids are assigned a number that indicates the order of their discovery. Ceres, the first asteroid discovered, therefore bears the designation 1 Ceres. And as you might expect, the brightest asteroids tended to be discovered first, so they were assigned the lowest numbers. But some slipped through the cracks, only coming to light later. One such elusive asteroid was Papagena, hence its relatively high designation of 471 Papagena. In fact, Papagena eluded visual discovery until it was photographically found by German astronomer Max Wolf on June 7, 1901. He named it after a character in the Mozart opera *The Magic Flute*.

I hope your experience with Papagena spurs your interest in asteroids. And if so, you'll be glad to know that *Astronomy* features a bright, currently visible asteroid every month in our Sky This Month section. This month's selection is asteroid 8 Flora.

Questions, comments, or suggestions? Email me at gchaple@hotmail.com. Next month: More astronomy guides. Clear skies!

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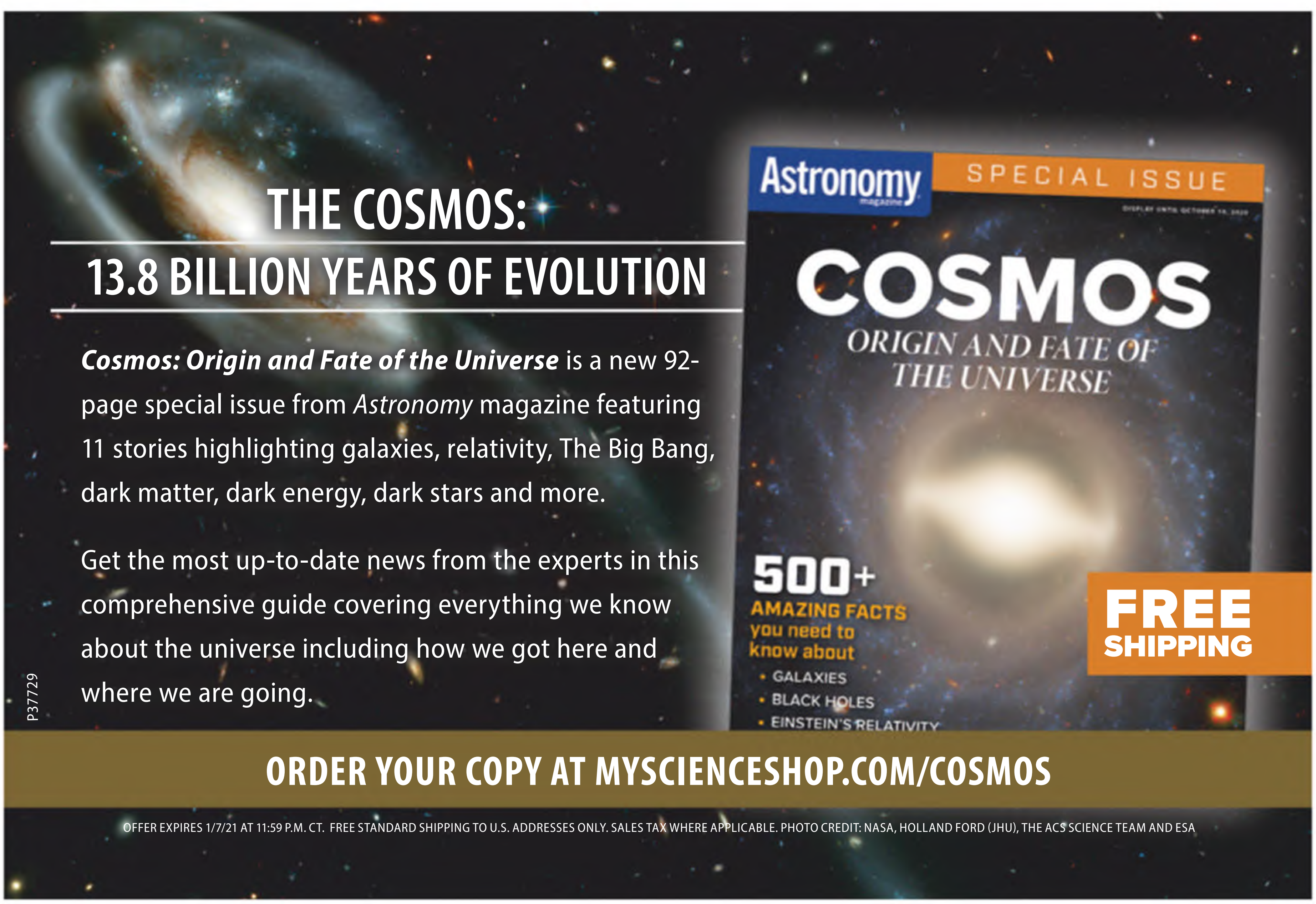

THE COSMOS:
13.8 BILLION YEARS OF EVOLUTION
Cosmos: Origin and Fate of the Universe is a new 92-page special issue from Astronomy magazine featuring 11 stories highlighting galaxies, relativity, The Big Bang, dark matter, dark energy, dark stars and more.
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A whale's tale

Return to Cetus to explore the other surprises this whale and its neighbors have to offer.

Bursting with new star formation, NGC 253 is one of the brightest galaxies for any observer armed with binoculars and a dark night sky.
R. JAY GABANY

BY PHIL HARRINGTON
Phil is a longtime contributor to Astronomy *and the author of many books.*

Last month, we visited the famous long-period variable star Mira. Although Mira's constellation, Cetus the Whale, is inconspicuous even under dark skies, it holds a few other surprises for binocular observers.

Let's begin with the constellation's brightest star, **Beta (β) Ceti.** That's right — just as Rigel (Beta Orionis) outshines Orion's alpha star, Betelgeuse, Beta Ceti beats Alpha (α) Ceti by half a magnitude (magnitude 2.0 versus 2.5). Although history is silent on how the German astronomer Johann Bayer made these errors when he was assigning Greek letter designations in his catalog of 1603, it might have been due to each star's southern position.

In addition to its Bayer discrepancy, Beta Ceti also has an identity crisis: It has two proper names. Traditionally, it is referred to as Deneb Kaitos, which means "tail of the whale" (or sea monster). But in 2016, the International Astronomical Union sanctioned an alternate name, Diphda, meaning "second frog." Brighter Fomalhaut (Alpha Piscis Austrini) to the west is the "first frog."

Beta Ceti puts on a colorful show through binoculars.

Call it what you will, Beta Ceti puts on a colorful show through binoculars. That's because Deneb Kaitos (I'm a traditionalist) is a type-K0 orange giant. In its prime, Beta Ceti was a type-A white main sequence star. But now, having exhausted its supply of fusible hydrogen in its core, it relies on helium fusion to generate energy. As it evolved, it also expanded in size and dropped in surface temperature to produce its golden glow.

From Deneb Kaitos, shift 7° southeastward into neighboring Sculptor to find spiral galaxy **NGC 253**. The dominant member of the Sculptor Galaxy Group — the closest galactic collection to our own Local Group — NGC 253 is a showpiece in the Southern Hemisphere's November sky, but proves challenging to spot from mid-northern latitudes.

Take the journey to NGC 253 in steps. First, place Deneb Kaitos along the northern edge of your field of view. Doing so should center a small triangle of 5th-magnitude stars. Then step again by moving that triangle to the field's northern edge. NGC 253 should then be just south of that field's center.

Location and sky conditions are important when it comes to viewing NGC 253. From my suburban yard, where the galaxy never gets higher than 25° above the light-polluted southern horizon, I can just make out a uniform glow through my 10x50 binoculars. But travel to a darker site and NGC 253 really pops. Through those same 10x50s, I spy a brighter central core surrounded by the galaxy's fainter galactic disk. Moving up to my 16x70s makes those features more evident, while my 25x100s begin to hint at some texture, or mottling — evidence of the disk's complexity, seen in images.

While you are admiring NGC 253, glance to the southeast without shifting aim. Do you see a soft, circular glow? That's the globular cluster **NGC 288**. It appears just 1¾° from NGC 253. Of course, their alignment is purely coincidental. NGC 253 is estimated to be 11.4 million light-years away, while NGC 288 is only 28,700 light-years from us.

Although few observers make the effort to find NGC 288, binoculars show it readily — again, provided the sky is dark and the air is clear and dry. My 10x binoculars reveal its soft, circular glow, about half as large as NGC 253 is long.

Finally, let's try for **NGC 246**, a great binocular challenge. This planetary nebula, 7° due north of Deneb Kaitos, is perfect for a Halloween stargaze because of its nickname, the Skull Nebula. The nebula's odd structure in images, likely caused by shock waves as the expanding cloud interacts with its surroundings, lends it the appearance of a human skull.

You'll have to strain to see this one. Sources list it as 8th magnitude, but that is deceiving. Its relatively large diameter cuts its surface brightness, and therefore visibility. It has always evaded my 10x50 binoculars. I have, however, spotted its dim, oval disk through my tripod-mounted 16x70s using averted vision — but only after I jury-rigged two narrowband filters over the eyepieces.

I would enjoy hearing your experiences with these and other targets. Contact me through my website, philharrington.net. Until next month, remember that two eyes are better than one.

BROWSE THE "BINOCULAR UNIVERSE" ARCHIVE AT **www.Astronomy.com/Harrington**

INDEX *of* ADVERTISERS

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MARKETPLACE

Much of the mass in the El Gordo galaxy cluster is actually dark matter, shown here artificially colorized in blue. Scientists determined the location and concentration of the cluster's dark matter by observing how its mass distorted the light from distant galaxies behind the cluster. NASA, ESA, AND J. JEE (UNIVERSITY OF CALIFORNIA, DAVIS)

Spotting dark matter

Q | IN YOUR MAY FEATURE, "IS THE BIG BANG IN CRISIS?" DARK MATTER IS CALLED INVISIBLE. HOW WAS THE DARK MATTER IN THE STORY'S IMAGE OF THE EL GORDO GALAXY CLUSTER DETECTED AND COLORIZED IF IT IS INVISIBLE?

William P. Gerhold
Hewitt, New Jersey

A | It is true that we cannot see dark matter directly. The blue color in the image of the El Gordo galaxy cluster (above) was artificially added to show where the cluster's dark matter resides. Similarly, you've probably seen composite images that include colorized X-rays, radio waves, and infrared light. Because the human eye can't see all these wavelengths of light, astronomers take data at different wavelengths and combine it into a single image using different colors to show where unseen material exists.

To colorize the location of the dark matter, astronomers looked at visible matter (i.e., distant galaxies) behind the El Gordo cluster. Dark matter neither absorbs nor gives off light, which is why astronomers have named it *dark*. But because dark matter has mass, it *does* interact with normal matter — including photons (light) — via gravity. This causes an effect called gravitational lensing, which occurs when light from a distant background object passes near a massive object, whose gravity bends it. On Earth, we see that the background object's image appears distorted — it may be spread out, smudged, magnified, or even duplicated. Based on the image we see, astronomers can calculate the amount and distribution of mass it took to create the distortion.

In the case of El Gordo, astronomers measured the mass of the galaxy's normal matter using data from many observations. These include optical and infrared light, which reveal the amount of mass in stars and dust, and X-rays, which show the amount of mass in hot gas that often permeates galaxy clusters. Researchers then observed how the light from background galaxies that traveled through and around the cluster is distorted, and calculated the mass required to reproduce any warping they saw. The difference in the total mass required and the mass observed shows where the dark matter resides in the galaxy cluster, as well as where it is most concentrated or spread out. The result is a map of the galaxy's dark matter, which was colorized (in this case, blue) and overlaid on an optical image to show where the dark matter is located.

Alison Klesman
Senior Associate Editor

Q | HOW MANY SATELLITE GALAXIES HAVE NOW BEEN DETECTED THAT ARE GRAVITATIONALLY BOUND TO OUR MILKY WAY GALAXY? ARE WE ABLE TO DETECT ANY AROUND THE ANDROMEDA GALAXY?

Patrick Clough
Wichita, Kansas

A | The largest satellite galaxies to our Milky Way are the Large Magellanic Cloud and the Small Magellanic Cloud, which are easily spotted with the naked eye from the Southern Hemisphere. But the exact number of satellite galaxies surrounding the Milky Way is still relatively unknown and has been a point of near-continuous study in astronomy since the discovery of the Sculptor Dwarf Galaxy in the 1930s.

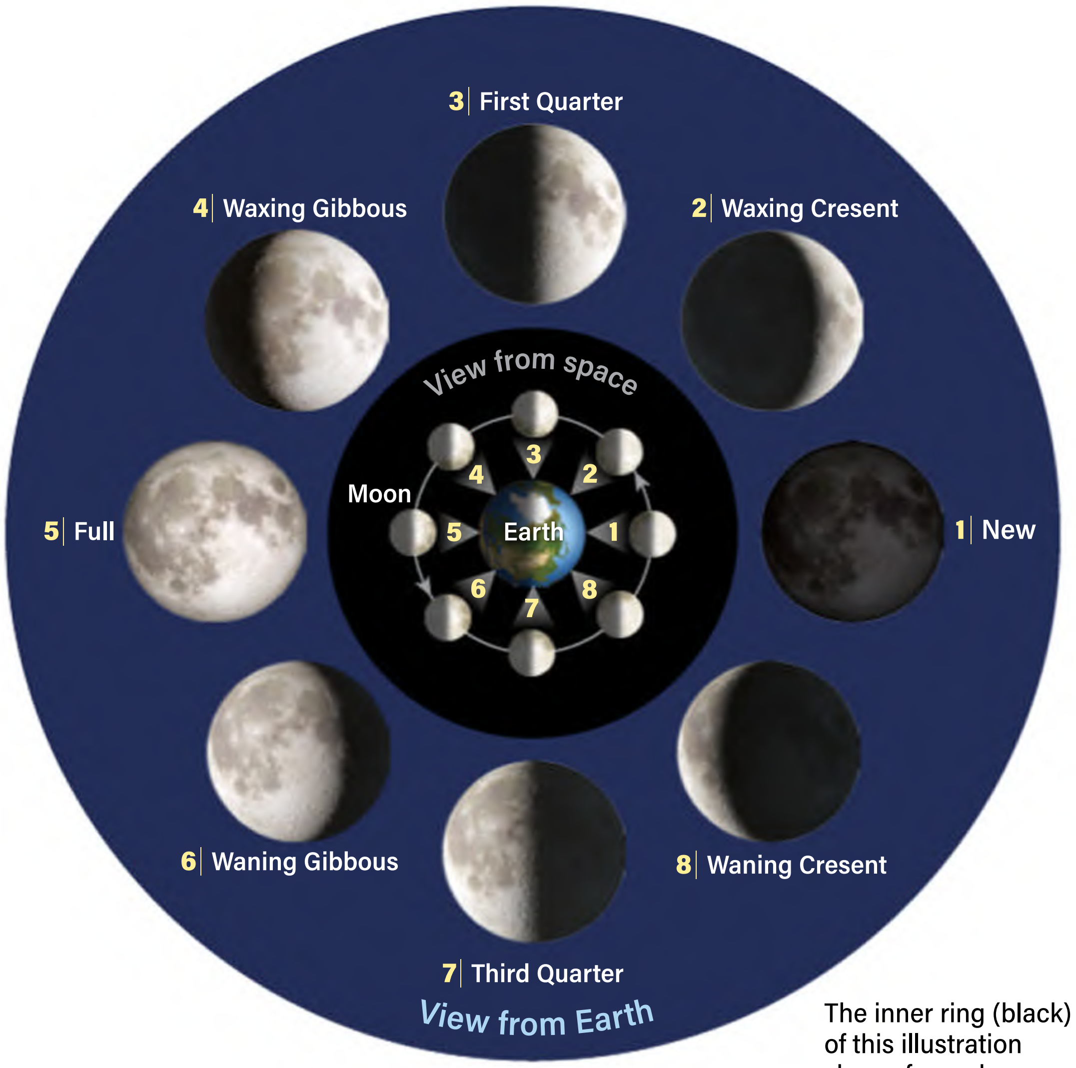
While the exact number is uncertain, astronomers have currently identified at least 14 satellite galaxies, thanks in large part to the Sloan Digital Sky Survey, the Dark Energy Survey, and the Panoramic Survey Telescope and Rapid Response System. Yet, astronomers think it is likely that even more satellite galaxies are waiting to be found with deeper imaging surveys in the future.

As with the Milky Way, the exact number of satellites that surround the Andromeda Galaxy is not certain. There are at least 19 confirmed dwarf galaxies orbiting our neighbor, the brightest and largest of which is NGC 205 (sometimes called M110).

Determining exactly how many satellite galaxies both the Milky Way and Andromeda have is crucial for testing current cosmological models. Recently, astronomers discovered that both galaxies are a bit surprising when it comes to the distribution and velocities of their satellites: While simulations predict a random distribution, observations show that both the Milky Way's and Andromeda's satellites lie in a narrow plane perpendicular to their respective disks and rotate within this plane. Co-rotating planes like these occur in less than 1 percent of simulations, so it brings into question whether cosmological predications are correct or if our Local Group of galaxies is weird. As it turns out, the same unexpected behavior occurs in a third galaxy, Centaurus A, making it likely that these satellite planes are not an exception and instead a rule.

Caitlyn Buongiorno
Associate Editor

The Andromeda Galaxy (M31) floats among satellite galaxies M32 (center, right below the galaxy) and NGC 205 (above and to the right of the galaxy's nucleus). ESA/HUBBLE & DIGITIZED SKY SURVEY 2. ACKNOWLEDGMENT: DAVIDE DE MARTIN (ESA/HUBBLE)



The inner ring (black) of this illustration shows from above how the Moon orbits Earth, with the Sun illuminating half the Moon at all times. (The Sun is located to the right of Earth and the Moon.) The outer ring (blue) shows the phases of the Moon as we see them from Earth as our satellite orbits around us. *ASTRONOMY*: ROEN KELLY, AFTER NASA/BILL DUNFORD

Q | WHAT HAPPENS TO THE MOON DURING NEW MOON?

Michael Gardner
Dublin, Ireland

A | From Earth, we only ever see one side of the Moon. This is because the time it takes the Moon to revolve around its own axis happens to be the same amount of time it takes for the Moon to orbit Earth: one month. This phenomenon is known as tidal locking. Since we only see one side of the Moon, how much of the Moon is visible to us over the course of a month depends on which part of the Moon is reflecting light from the Sun. And *that* depends on where the Moon is in its orbit around Earth.

In the image above, the Sun lights up only the half of the Moon that faces our star. From Earth, we see only the portion of the Moon that is both facing our planet and reflecting light.

In the case of a New Moon, the Moon is between Earth and the Sun, so the side of the Moon facing the Sun isn't facing us. We can't see any portion of the lit-up Moon during this phase. (When the Sun and Moon exactly line up, as viewed from Earth, we get a special experience known as a solar eclipse.)

You can simulate the phases of the Moon yourself at home with a lamp and baseball. Place the lamp (without its shade) on one end of a darkened room and stand on the opposite end of the room. By raising the baseball at arm's length in front of you (so it faces the lamp), you can move slowly in a circle and see it go through the same phases as the Moon.

Caitlyn Buongiorno
Associate Editor

SEND US YOUR QUESTIONS

Send your astronomy questions via email to askastro@astronomy.com, or write to Ask Astro, P.O. Box 1612, Waukesha, WI 53187. Be sure to tell us your full name and where you live. Unfortunately, we cannot answer all questions submitted.

Cosmic portraits

1. STELLAR ART
NGC 3572 is a star cluster and emission nebula in the constellation Carina the Keel. The intense radiation and stellar winds of the cluster's young stars are sculpting the gas into a variety of shapes. NGC 3572 lies some 9,000 light-years away. ▪ ***Kfir Simon***

2. DARK AND DUSTY
Although this cloud of interstellar dust and cold gas appears dark, it's actually the 468th object in a catalog of bright nebulae compiled by American astronomer Beverly T. Lynds. LBN 468 lies in the constellation Cepheus the King, near that pattern's border with Draco. ▪ ***Gerald Rhemann***


3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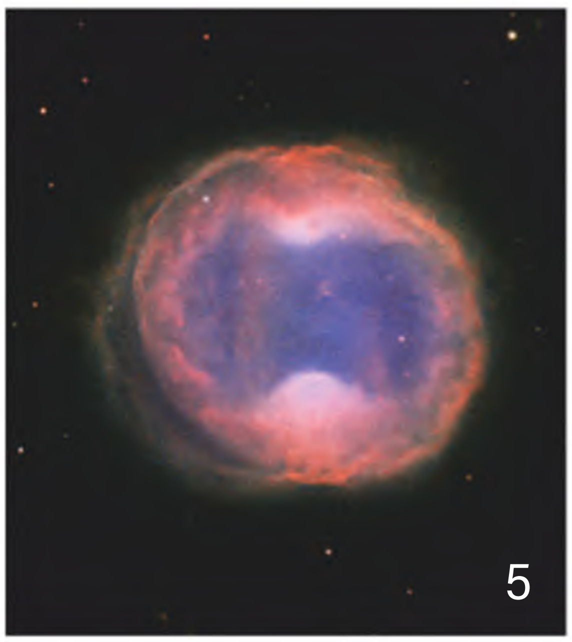
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7

3. FRIGID BEAUTY
Venus appears brilliant as always as it sets behind a house in Tatamagouche, Nova Scotia, on October 29, 2018. The photographer captured this 30-second exposure as the temperature dipped below 0 degrees Fahrenheit (-18 degrees Celsius).
• *Barry Burgess*

4. FACE OFF
NGC 2835 is a face-on spiral galaxy in the constellation Hydra the Water Snake. It lies within a rich star field some 35 million light-years away, spans 65,000 light-years, and glows at magnitude 10.5.
• *Adam Block/Telescope Live*

5. CRANK IT UP!
The Headphone Nebula, also known as Jones-Emberson 1 and PK 164+31.1, is a planetary nebula in the constellation Lynx. It glows meekly at magnitude 17, so creating this image required 36 hours of exposures. **• *Douglas J. Struble***

6. BARELY THERE
This ultra-thin crescent Moon, only 0.4 percent illuminated, was a scant 15 hours old when the photographer captured it April 23, 2020, at 11:30 A.M. MST. To image it so close to the Sun, he extended the tube of his 10-inch Newtonian reflector by 6 feet (1.8 meters) with chromed bubble wrap sheet stock.
• *Chris Schur*

7. REFLECTIONS
Jupiter (brightest), Saturn (farthest left), and Mars form a small triangle just to the left of the Milky Way in this 20-second exposure taken March 28, 2020, at 5:15 A.M. EDT from Chatham, Massachusetts. **• *Chris Cook***

SEND YOUR IMAGES TO:
Astronomy Reader Gallery, P.O. Box 1612, Waukesha, WI 53187. Please include the date and location of the image and complete photo data: telescope, camera, filters, and exposures. Submit images by email to **readergallery@ astronomy.com.**

ARE YOU OUT THERE, BATMAN?

If the Caped Crusader happened to glance at Serpens the Serpent, he would no doubt leap into action. Tucked into the constellation's northeastern corner is a striking silhouette that bears an uncanny resemblance to a bat's wings, the distress signal used to summon Batman. In reality, the feature (at upper right in this Hubble image) is the shadow of a planet-forming disk cast by the young star HBC 672 onto the surrounding Serpens reflection nebula. Starlight escapes perpendicular to the disk, but gets absorbed by the structure's gas, dust, and rock. Recent observations show the shadow moves like a bat flapping its wings; astronomers suspect a planet causes this motion as its gravity warps the disk. NASA/ESA/K. PONTOPPIDAN (STScI)

January 2021

Mars rules the evening sky

As the third decade of the 21st century gets underway, you can catch the solar system's two largest planets hanging low in the west-southwest during evening twilight. **Jupiter** and **Saturn** stand 10° above the horizon a half-hour after sunset. Jupiter shines at magnitude –2.0, some 10 times brighter than magnitude 0.6 Saturn, from its perch just 1.2° to the ringed planet's upper right.

The two worlds dip lower with each passing day and disappear into the Sun's glare by midmonth. Before they exit the evening stage, however, they have one final hurrah: As the giant planets descend, **Mercury** rises to meet them. January 9 finds the magnitude –0.9 inner planet 2° to Saturn's left. Two days later, Mercury passes 1.5° to Jupiter's upper left. Although you might have a hard time seeing the trio with your naked eye, binoculars should deliver nice views if you have a clear and unobstructed horizon. Unfortunately, the low altitude of the planets means a telescope won't deliver crisp views.

After these close passages, Mercury continues its ascent as it approaches a January 24 greatest elongation. On that date, the innermost world lies 19° east of the Sun and appears 6° above the western horizon 30 minutes after sundown. For Southern Hemisphere observers, this is one of Mercury's worst apparitions in 2021. But you won't have to wait long for a better view — the planet puts on a magnificent show in the predawn sky during late February and March.

After straining to see these three planets during twilight, **Mars** offers some welcome relief. The Red Planet shines prominently in the northwest as darkness falls. It begins January at magnitude –0.2 and dims to magnitude 0.4 by month's end, which still places it among the brightest objects in the night sky.

Mars continues to move eastward, crossing the border from Pisces the Fish into Aries the Ram on January 5. If you're looking for a viewing challenge, try to spy 6th-magnitude **Uranus** using Mars as a guide. On the evenings of January 21 and 22, the outer planet resides less than 2° south of Mars. You'll need binoculars to see Uranus and a telescope to discern its diminutive blue-green disk. Also plan to target the Red Planet through a telescope this month to get perhaps your final good view of the surface. Its disk spans 10.4" on the 1st but only 7.9" on the 31st.

You'll have to wait until morning twilight to see **Venus**. The inner world shines at magnitude –3.9 all month, so it's bright enough to pierce the twilight glow. But it sinks closer to the Sun's glare as the month progresses and becomes harder to see. By January 31, it rises only an hour before the Sun. A telescope doesn't help much, showing a disk that measures barely 10" across and appears nearly full.

The starry sky

I've spent decades observing through various telescopes, but I still love to explore the night sky with binoculars. That's the way I started as a child, using my father's 8x25 binoculars. I later acquired some 7x50s, a nearly perfect size for binocular astronomy.

The summer months provide some great binocular targets in Orion the Hunter. Even better, this magnificent constellation stands high in the north on January evenings.

There's no better place to start than Orion's Sword, which lies a few degrees south of the Hunter's conspicuous belt. The middle of the sword features the stunning Orion Nebula (M42), which is as much of a treat through binoculars as it is through a telescope.

M42 provides a wonderful illustration of the benefits of using averted vision. The technique involves looking slightly away from a dim source of light to let the rods in your eyes reveal more. If you gaze toward the edge of a field centered on M42, the nebula will appear brighter and more extensive.

Return now to the three belt stars, which fit quite nicely in a binocular field. This region boasts a profusion of 6th- to 8th-magnitude stars that makes for an attractive field. Once you've had your fill here, try to spot M78. French astronomer Pierre Méchain discovered this nebula in 1780 just 2.5° north-northeast of magnitude 1.7 Zeta (ζ) Orionis, the easternmost belt star. I find M78 to be a tricky object through binoculars if even a little light pollution intrudes on the sky.

The belt stars form a remarkable asterism — a recognizable pattern of stars separate from a constellation — but Orion harbors another superb example. Shift your gaze 11° north of the belt and you'll be face to face with the head of the celestial Hunter: a lovely little triangle comprised of the stars Lambda (λ), Phi^1 (ϕ^1), and Phi^2 (ϕ^2) Ori. Between Lambda and Phi^1 lies a beautiful short line of three stars. You'll need binoculars to track these down because they glow at magnitudes 7.6, 7.5, and 6.7, respectively, from north to south.

Our final object this month lies 12° west of this group, though it's easier to find by looking approximately halfway between Gamma (γ) Ori and Gamma Tauri, the star that marks the tip of the V-shaped Hyades star cluster in Taurus. English astronomer William Herschel discovered open cluster NGC 1662 in 1784. The object's description in the *New General Catalogue* is quite fitting: "cluster of large and small scattered stars." I can spot it through binoculars without much difficulty. At first glance, it appears as a patch of light about half the apparent diameter of the Full Moon.

STAR DOME

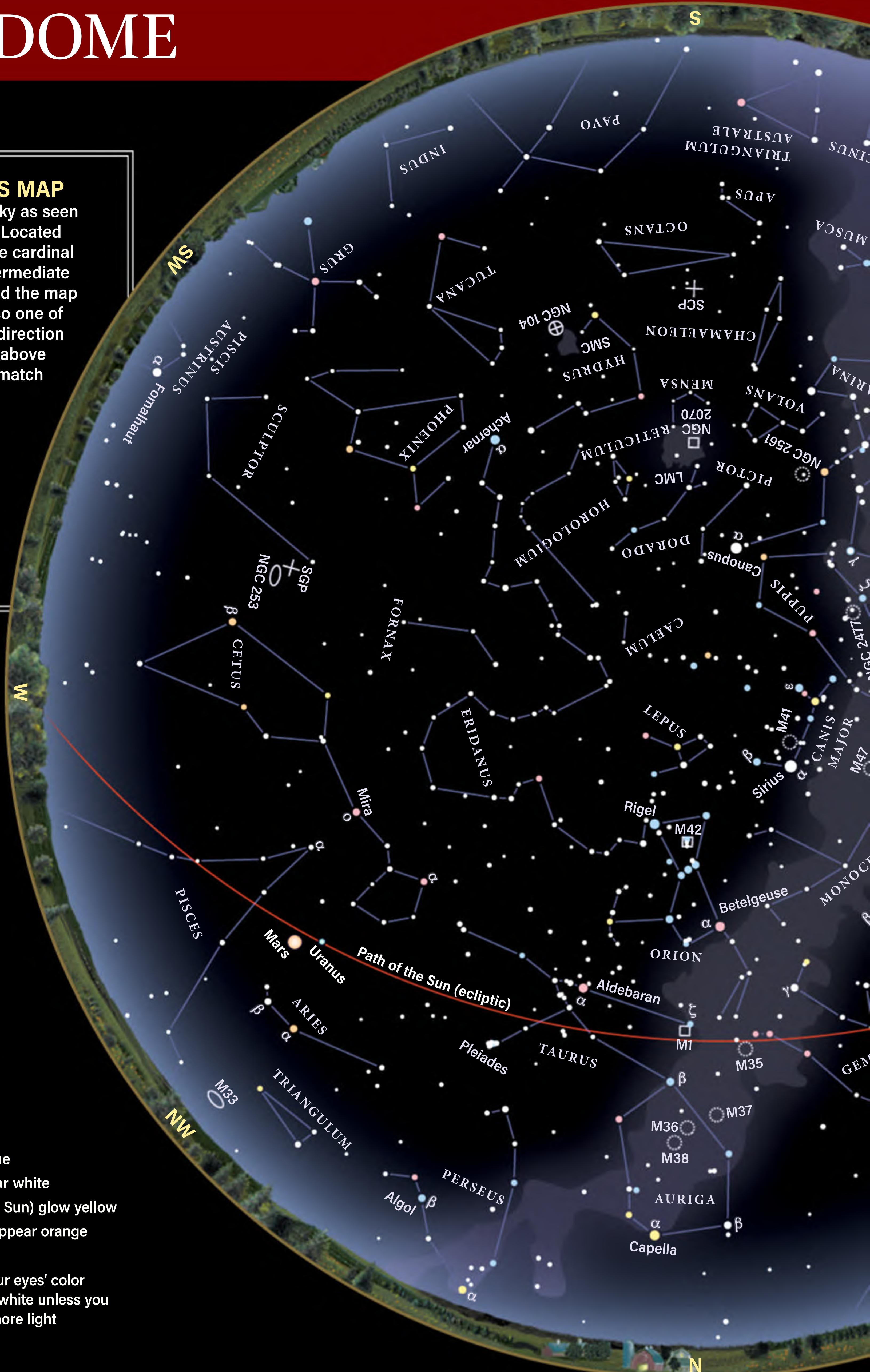
HOW TO USE THIS MAP

This map portrays the sky as seen near 30° south latitude. Located inside the border are the cardinal directions and their intermediate points. To find stars, hold the map overhead and orient it so one of the labels matches the direction you're facing. The stars above the map's horizon now match what's in the sky.

The all-sky map shows how the sky looks at:

11 P.M. January 1
10 P.M. January 15
9 P.M. January 31

Planets are shown at midmonth



MAP SYMBOLS

- Open cluster
- Globular cluster
- Diffuse nebula
- Planetary nebula
- Galaxy

STAR MAGNITUDES

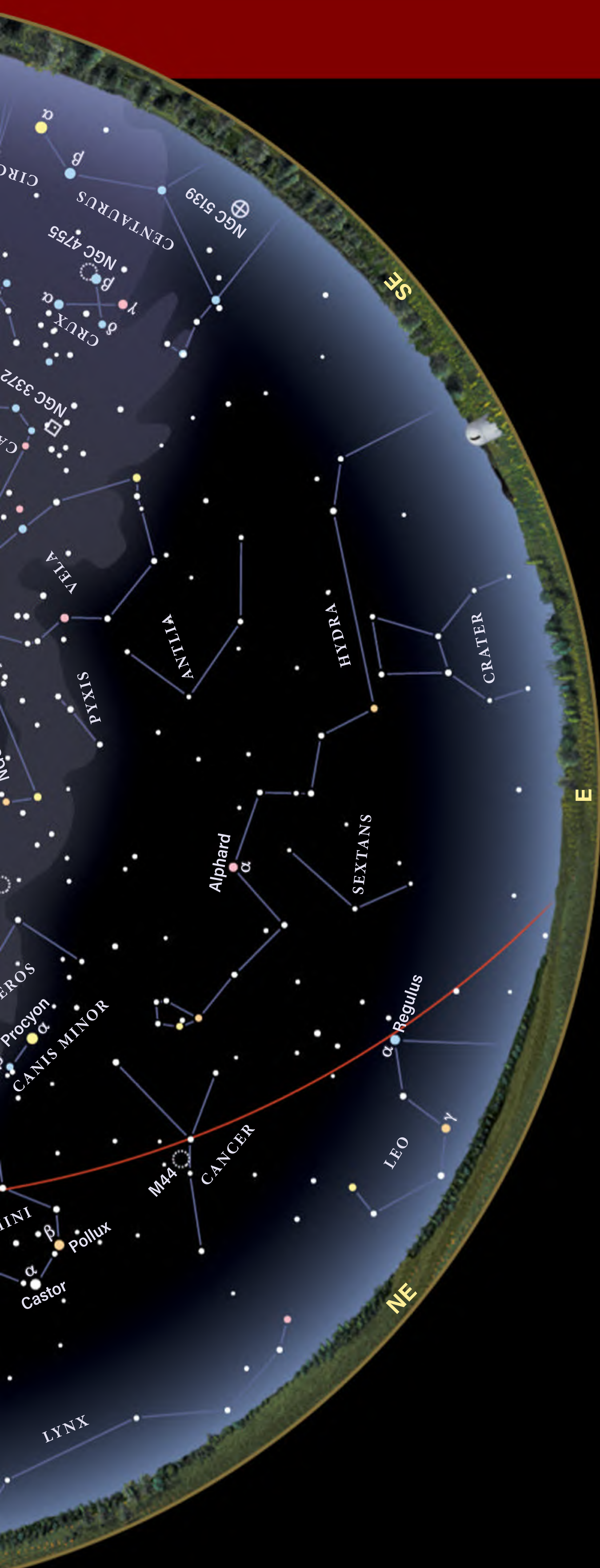
- Sirius
- 0.0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0

STAR COLORS

A star's color depends on its surface temperature.

- The hottest stars shine blue
- Slightly cooler stars appear white
- Intermediate stars (like the Sun) glow yellow
- Lower-temperature stars appear orange
- The coolest stars glow red
- Fainter stars can't excite our eyes' color receptors, so they appear white unless you use optical aid to gather more light

BEGINNERS: WATCH A VIDEO ABOUT HOW TO READ A STAR CHART AT **www.Astronomy.com/starchart.**



JANUARY 2021

SUN.	MON.	TUES.	WED.	THURS.	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
31						

ILLUSTRATIONS BY *ASTRONOMY*: ROEN KELLY

Note: Moon phases in the calendar vary in size due to the distance from Earth and are shown at 0h Universal Time.

CALENDAR OF EVENTS

2 Earth is at perihelion (147.1 million kilometers from the Sun), 14h UT

6 Last Quarter Moon occurs at 9h37m UT

9 The Moon is at perigee (367,387 kilometers from Earth), 15h37m UT

11 Mercury passes 1.5° south of Jupiter, 11h UT

The Moon passes 1.5° south of Venus, 20h UT

13 New Moon occurs at 5h00m UT

14 The Moon passes 3° south of Jupiter, 1h UT

The Moon passes 2° south of Mercury, 8h UT

Uranus is stationary, 14h UT

Pluto is in conjunction with the Sun, 14h UT

17 The Moon passes 4° south of Neptune, 6h UT

20 First Quarter Moon occurs at 21h02m UT

21 The Moon passes 5° south of Mars, 6h UT

The Moon passes 3° south of Uranus, 6h UT

The Moon is at apogee (404,360 kilometers from Earth), 13h11m UT

Asteroid Eunomia is at opposition, 19h UT

22 Mars passes 1.7° north of Uranus, 0h UT

23 Asteroid Vesta is stationary, 22h UT

24 Mercury is at greatest eastern elongation (19°), 2h UT

Saturn is in conjunction with the Sun, 3h UT

Asteroid Irene is at opposition, 17h UT

28 Full Moon occurs at 19h16m UT

29 Jupiter is in conjunction with the Sun, 2h UT

30 Mercury is stationary, 2h UT