DRAGONFLY:
48 Eyes on the Deep Sky
PAGE 64

EINSTEIN'S ECLIPSE:
Revisiting the 1919 Expedition
PAGE 28

BETELGEUSE:
A Stellar Time Bomb
PAGE 34

SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

ZOOM in on Jupiter's Majesty
PAGE 14

Join the Billion-Light-Year Club
PAGE 57

SEEING DOUBLE:
A Tour of Favorite Binaries
PAGE 22

TEST REPORT:
Omegon's Wind-up Star Tracker
PAGE 60

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CONTENTS

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May 2019 VOL. 137, NO. 5

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FEATURES

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S&T TEST REPORT

COLUMNS / DEPARTMENTS

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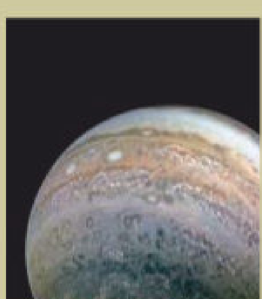

Jupiter's southern hemisphere delights with exotic storms.
NASA / MSSS / DAVID MARRIOTT

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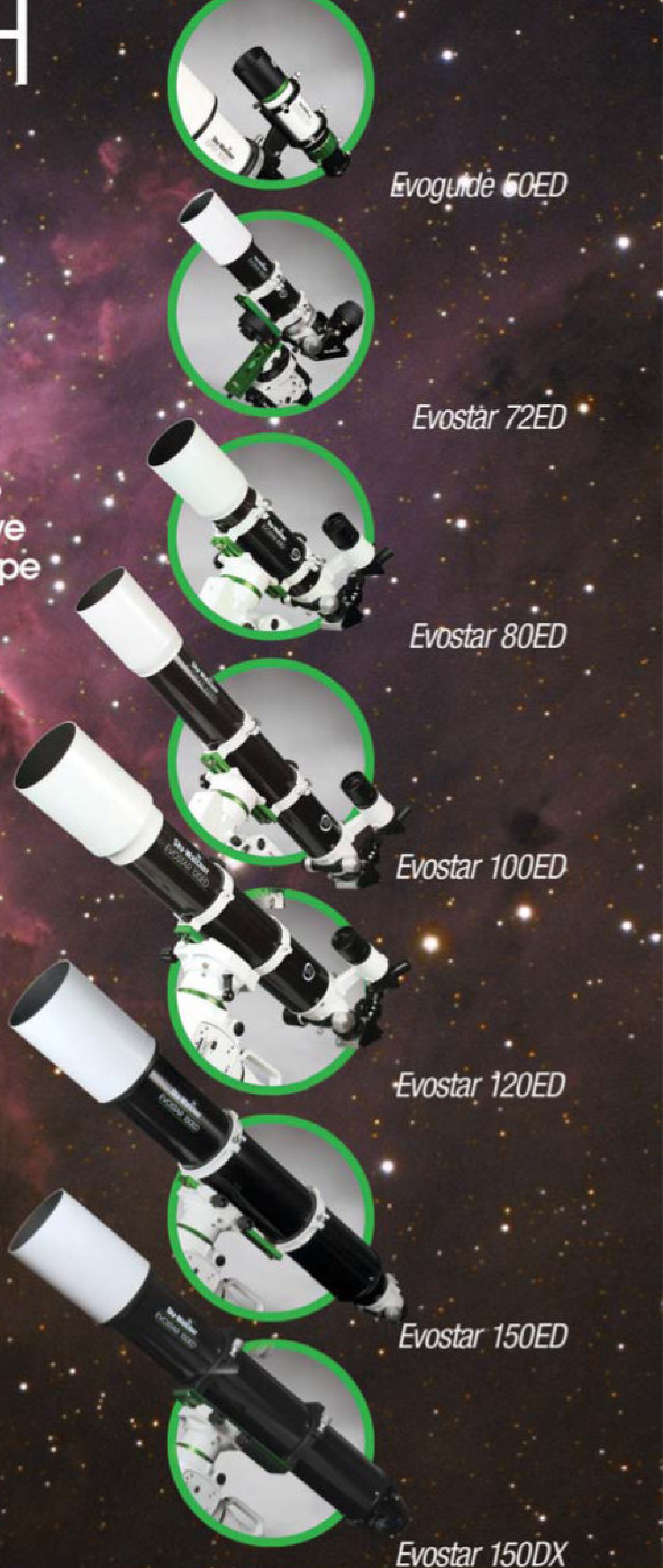

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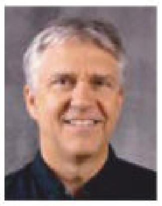
A Dolphin on Jupiter

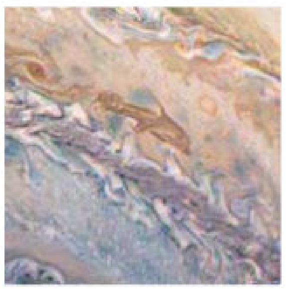


WHEN AMATEUR ASTRONOMERS, particularly those who enjoy image processing, first learned of NASA's plans for its JunoCam, their jaws likely dropped.

Here's NASA essentially saying, "We've got this spacecraft called Juno that we're putting into orbit around Jupiter. It'll have a hi-res color camera that's just for you, the general public. You can vote on what you'd like JunoCam to photograph on each of Juno's *perijove passes*, or closest approaches, and we'll direct the camera to take the highest-ranked choices. Once we receive the pictures back at Earth, we'll upload them raw or slightly processed to our website. You can then download them, process them to your eye's content, and upload them back to our site for the world to admire. Your images may help Juno scientists see things they might not otherwise have seen, and they'll even use some of them to illustrate their scientific papers."

Like kids in a candy shop? Oh yeah.

As our gallery of images starting on page 14 shows, it's been a richly fruitful pro-am collaboration since Juno went into its 53-day-long orbit around the gas giant in July 2016. These amateur-enhanced artworks might make a great exhibit at the Museum of Modern Art or the Guggenheim Bilbao. The pictures are sublime, mesmerizing, otherworldly. Some could serve as Rorschach tests: We readily discern the "dolphin" in our cover image, but what else? To me, one picture suggests an El Greco painting blended with a Blue Period Picasso, another a raging wildfire on Earth photographed from space. You'll have your own interpretations.



The "dolphin" seen on our cover

You may find yourself struggling to turn up anything vaguely recognizable. There's precious little to ground you in these images, in part because there's no ground at all. We see only clouds; the scenes might as well be abstract. But wait: Are those thunderheads we detect in some of the shots? (Look closely — they're tiny in the close-ups, even as in reality they're towering.) These "pop-up storms" give our brains *something* familiar to cling to.

While JunoCam is purely for outreach, Juno is there to do science, of course. With the spacecraft's suite of instruments, researchers seek to learn more about Jupiter's origin and evolution by investigating its core, the deeper levels of its atmosphere, and its magnetic and gravity fields (*S&T:* July 2016, p. 18).

But while Juno is busy gathering data to meet those and other key scientific objectives, JunoCam continues taking *your* snapshots. Jupiter's cloudscape is ever-changing — the "dolphin" has surely long since vanished. But through the ravishing work of astro-artisans, we can enjoy its "leap" even as we await yet more eye-popping results, both scientific and artistic.

Peter

Editor in Chief

NASA / JPL-CALTECH / SWRI / MSSS / DAVID MARRIOTT

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It's a Bird! It's a Plane!

I really enjoyed Tony Flanders's "The Wintry North" article (*S&T:* Jan. 2019, p. 62). In addition to NGC 457's nicknames of the E.T. Cluster and the Owl Cluster, I use another moniker for it: Many years ago a fellow observer and I dubbed it the Airplane Cluster.

I never forgot it and still see it as an airplane (possibly because I worked for the airlines for 35 years). The two bright stars (E.T.'s eyes) are two tail lights, E.T.'s body is the fuselage (with lighted windows), and E.T.'s arms are the swept-back wings coming off the fuselage. This also works better for me because most often E.T. and the owl are upside-down in my eyepiece, whereas the airplane is always oriented correctly, whether flying up, down, right, or left.

Bill Dellinges • Apache Junction, Arizona

▲ Owl, alien, or airplane: What do you see when you look at NGC 457?

Before the Big Bang

I've often wondered why cosmologists believe that the universe as we know it sprang from nothing. This theory always seemed a bit short-sighted to me. Although there was no one around to witness time before the Big Bang, it has long been my belief that time did exist and that the universe must have sprung from something.

Thus, I was glad to see your article "What Came Before the Big Bang?" (*S&T:* Feb. 2019, p. 16). Knowing there are some scientists giving consideration to alternate theories as to the beginning of the observable universe gives me hope that perhaps in the future we will see more interest in this area and more coverage of this line of cosmology.

Will Ouellette
Rapid City, South Dakota

While certainly there is value to identifying events, energies, and the physics in place before the Big Bang, the consequence of sorting out these facts leads to even greater questions: What happened before that? And before that? And before that (ad infinitum)? If we are part of a greater multiverse, then clearly time itself must have properties that we do not yet understand, i.e., what is time before it exists in this universe?

Clearly cosmology is still a science in a rather interesting infancy.

Richard Molitor
Bothell, Washington

According to Hoyle

British astronomer Fred Hoyle was one of the creators of the steady-state model, which held that the universe was eternal, but he never intended the term "Big Bang" to be pejorative or sarcastic when he christened the rival cosmology (*S&T:* Mar. 2019, p. 7). Hoyle had long advocated the once radical idea that the chemical elements on Earth — the oxygen we breathe, the calcium in our bones, the iron in our blood — arose in stars. So for my book *The Alchemy of the Heavens*, which describes the Milky Way and the origin of the elements, I interviewed Hoyle about his work. He said he coined "Big Bang" because he was doing a radio show on the BBC.

"On radio, you have no visual aids," Hoyle said, "so it's essential to arrest the attention of the listener and to hold his comprehension by choosing striking words. There was no way in which I coined the phrase to be derogatory; I coined it to be striking, so that people would know the difference between the steady-state model and the Big Bang model."

The term has endured ever since, and so has Hoyle's insight into the vital role that stars play in creating the chemical elements. Indeed, Hoyle's 1957 nucleosynthesis paper with E. Margaret Burbidge, Geoffrey Burbidge, and William Fowler is one of the great achievements of 20th-century science.

Ken Croswell
Berkeley, California

A Signal Accomplishment

In David Grinspoon's article "NASA Sends a Signal" (*S&T:* Jan. 2019, p. 14), he mentions NASA's Technosignatures Workshop, which took place on September 26–28, 2018.

However, he doesn't mention the workshop's report, which would be useful for those wishing to read up on the subject. Here's the link: https://arxiv.org/abs/1812.08681.

John Fairweather
Woking, United Kingdom

Problems at Home

I am in awe of the magnificence of our universe shown by our various telescopes, probes, etc. However, I'm disturbed by what I see as a waste of money on projects that have little value or relevance to Earth and its inhabitants, particularly money being approved for SETI research.

We are in crisis on this planet: Extreme weather events, pollution, drought, famine, poverty, and homelessness are increasing worldwide. Here in the "richest" country in the world much of our infrastructure is in urgent need of repair or replacement. Too many scientists have given people the idea that when we've used up this planet, we'll be able to go on and find another — nonsense. We need to spend our money on the problems that threaten this, our only planet.

Diana Guadagnino
Irvine, California

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Making a Contribution

In Shawn Dilles's letter (*S&T:* Dec. 2018, p. 6) he expressed interest in doing "some observing that can really contribute to science." He and other similarly interested readers should seek out *The Sky Is Your Laboratory: Advanced Astronomy Projects for Amateurs* by Robert K. Buchheim, which provides leads to dozens of astronomical sub-disciplines in which amateurs can make important contributions to science.

As to using video cameras, amateurs can contribute by using their equipment to measure asteroid and lunar occultations; you need only be able to make out the so-called target star, not necessarily the asteroid, and it doesn't require rural dark skies. With only amateur equipment, you can help measure bodies that would otherwise be too faint to see, and with size precision exceeded only by near-Earth radar methods.

Ted Swift
Davis, California

Fleeing the Scene

I enjoyed your article on hypervelocity stars (*S&T:* Dec. 2018, p. 30), but I'm confused about the exact process that allows these stars to break away from their companions. Does the supernova explosion provide the force needed to eject the hypervelocity stars from their orbits, or does the loss of centralized mass in the exploding star reduce its gravitational pull on its companion? Is it a combination of these processes or a different process altogether?

Jerry Cheney
Ocklawaha, Florida

Ken Croswell replies: *The article's second paragraph explains the escape mechanism; it's not the push from the explosion but the vanishing act of the exploding star, whose mass had gravitationally tethered the companion star. The companion flees fast because white dwarfs are so tiny that the companion can orbit near the white dwarf's center and thus revolve rapidly, at speeds exceeding 1,000 kilometers per second. In contrast, were the Sun to explode, the planets would sail off more slowly, because their orbital velocities are modest: 48 km/s for Mercury, 30 km/s for Earth, and 4.7 km/s for Pluto.*

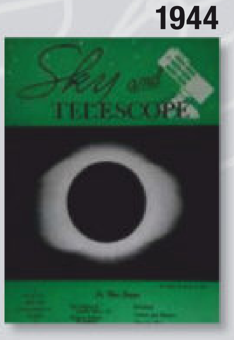
FOR THE RECORD

- The last sentence of the caption for the photo of M34 (*S&T:* Jan. 2019, p. 54) should read: "M34 lies about halfway between the stars Beta (β) Persei and Gamma (γ) Andromedae."
- The "Sunset for Dawn" News Note (*S&T:* Feb. 2019, p. 12) states that Dawn was NASA's first deep-space mission to use ion propulsion. That distinction belongs to NASA's Deep Space 1 mission, which was launched in October 1998.

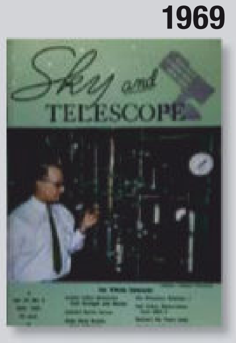
SUBMISSIONS: Write to *Sky & Telescope*, 90 Sherman St., Cambridge, MA 02140-3264, U.S.A. or email: letters@skyandtelescope.com. Please limit your comments to 250 words; letters may be edited for brevity and clarity.

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

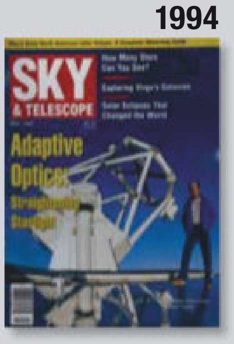
1944



1969



1994



May 1944

Cosmic Rays "Traveling with speeds a million times greater than that of a bullet from the highest power rifle known, these particles are now shooting right through your bodies at the rate of about 10 per second for each one of you. Each of them is tearing apart about a million of your personal molecules as it passes through you. . . . Do not be alarmed, however. . . . We now know that their penetrating power is [such that] a measurable number of these rays can pass through as much as 75 feet of lead."

Thus W. F. G. Swann introduced his four-part overview of cosmic rays. These high-energy particles, mostly atomic nuclei, still fascinate cosmologists, who point to supernovae and active galactic nuclei among likely sites of origin.

May 1969

Umbral Flashes "Jacques M. Beckers described a new solar phenomenon that he and Paul E. Tallant have discovered at Sacramento Peak Observatory in New Mexico. Observing in the H and K lines of ionized calcium . . . they found brief flashes of light in the dark umbras of sunspots.

"Lasting only about 50 seconds on the average, each flash undergoes rapid enhancement to maximum brightness, then declines much more slowly. In a medium-sized umbra there are an average of three to five flashes in progress at any instant. . . . The diameters of the flashing areas are very small, from the telescope's resolution limit up to about 3,000 kilometers. . . .

"At peak intensity the umbral flashes were always blue-shifted, corresponding to upward motions (toward the observer) of about six kilometers per second. . . . As each flash faded, the narrow emission line moved toward the red."

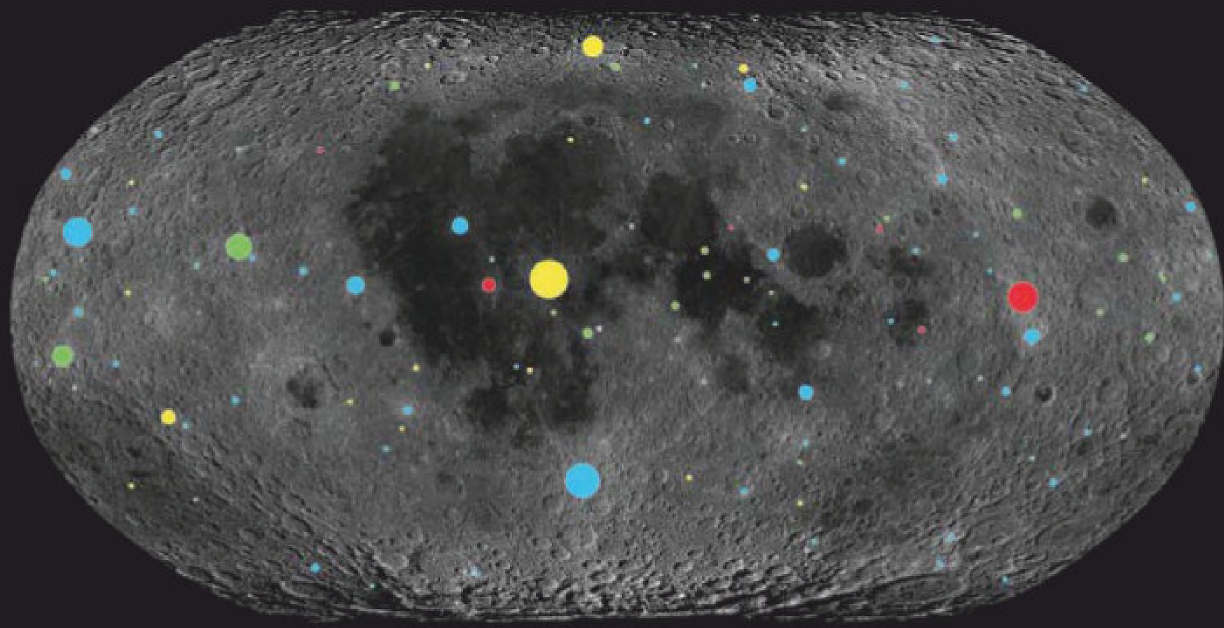
Umbral flashes and "running waves" are today studied as important clues to the magnetic field in sunspots.

May 1994

Contact Binary "The power of radar astronomy to probe solar-system objects was vividly demonstrated in *Science* for February 18th. There R. Scott Hudson (Washington State University) and Steven J. Ostro (Jet Propulsion Laboratory) show off their painstaking reconstruction of the near-Earth asteroid 4769 Castalia. Ostro and three colleagues had used the powerful radio dish at Arecibo, Puerto Rico. . . .

"The initial analysis showed that Castalia . . . has a dumbbell shape with two distinct lobes each about ¾ kilometer across. . . . Nearly four more years of work . . . reveals a striking, narrow 'waist' at its midsection [which implies] that the two lobes were once separate but came together in a relatively gentle collision."

Approximately six dozen contact binaries are now known, the most famous of these being Ultima Thule, thanks to close-up imaging this past January.



THE MOON

Lunar Craters Reveal Recent Impact History

▲ A team of scientists used NASA's Lunar Reconnaissance Orbiter to estimate the ages of 111 of the Moon's craters. The circles are scaled by size and color-coded by age (blue indicates those younger than 290 million years). Young craters dominate the lunar surface.

RESEARCHERS USING A NEW method to estimate ages of lunar craters have found that the rate of large impacts — on both the Moon and Earth — nearly tripled 290 million years ago.

In the January 18th *Science*, Sara Mazrouei (University of Toronto) and colleagues came up with a new way of dating craters, based on the fading warmth of their impact debris. Younger craters, they realized, will be surrounded by larger rocks than older craters are, because space weathering grinds down debris with time. Since larger rocks take more time to cool during lunar night, younger craters must also appear warmer.

Using the Diviner thermal radiometer onboard NASA's Lunar Reconnaissance Orbiter, the team measured the temperatures, and thus ages, of 111 craters. The researchers limited their study to craters larger than 10 kilometers across and less than a billion years old, because smaller craters wouldn't have excavated enough material from the lunar bedrock, and older craters' debris aprons would already have disintegrated under the solar wind.

The crater ages revealed a surprising trend: The rate of impacts increased 290 million years ago by a factor of 2.6. That goes against the typical assumption that the flux of impactors has been constant for the last 3 billion years, says coauthor Rebecca Ghent (also at University of Toronto). The team plans to investigate whether the change was transient or has persisted until today.

The researchers also found evidence in Earth's impact history that appears to support the trend. Scientists already knew that there is an overabundance of terrestrial craters younger than 290 million years, but they thought it was because erosion had wiped out the older craters. The team's analysis, however, suggests the uptick is real. The researchers focused on regions that have been relatively stable over the last 650 million years by looking for *kimberlite pipes*. These are extinct, carrot-shaped volcanoes that are buried several kilometers below Earth's surface and are often mined for diamonds. If a region contained preserved kimberlites, the team reasoned, then the surrounding area must be stable enough to have preserved old, large craters as well.

The search uncovered intact kimberlites over 11% of Earth's surface. In these regions, the team finds the same impact rates as observed on the Moon.

Confirmation on Earth may not even be necessary, says Peter Schultz (Brown University), who was not involved in the study. "Whatever happened on Earth, to me there are too many ways of dodging the bullet scientifically," he notes. "But there is no way to dodge that bullet on the Moon, because that is the record — it is our mirror."

■ JAVIER BARBUZANO

COSMOLOGY

Quasar "Standard Candles" Shed Light on Dark Energy

ASTRONOMERS HAVE FOUND a way to use quasars to measure the evolution of dark energy, the repulsive pressure that accelerates our universe's expansion. The results, appearing January 28th in *Nature Astronomy*, have potentially far-reaching implications for cosmology.

Cosmology is based on accurate gauges of distance, and detonating white dwarfs known as Type Ia supernovae have long been the *standard candle* of choice. Their intrinsic luminosities are known, so their distances are, too. With these objects astronomers have probed the universe at a time when dark energy began to dominate its expansion.

To see even earlier times, before dark energy took over, Guido Risaliti (University of Florence, Italy) and Elisabeta Lusso (Durham University, UK) turned to quasars, gas-guzzling supermassive black holes that are brilliant enough to be seen when the universe was less than a billion years old.

Risaliti and Lusso made use of a well-studied relation, which shows that quasars that are intrinsically brighter at visible wavelengths emit relatively fewer X-rays. The researchers argue that this relationship is based on quasar physics — an accretion disk emits visible light, while a hot, gaseous corona emits X-rays — and therefore should remain stable over cosmic time.

Previously, contaminants had muddied the relation, so for this study

SOLAR SYSTEM

Amateur Scopes Spot "Missing Link" Kuiper Belt Object

ASTRONOMERS HAVE USED amateur equipment to discover a kilometer-size object in the Kuiper Belt — a "missing link" between the belt's dwarf planets and its many, much smaller objects.

The Kuiper Belt, a sparse disk of icy rocks beyond Neptune's orbit, contains the building blocks leftover from our system's planet formation. Its most famous representatives, such as dwarf planet Pluto, span thousands of kilometers and can be seen by the sunlight they reflect. But most Kuiper Belt objects (KBOs) are too faint to be detected directly. Instead, astronomers look for *stellar occultations*, watching for one of these rocks to briefly block the light of a background star.

▼ This artist's concept shows a kilometer-size Kuiper Belt object.

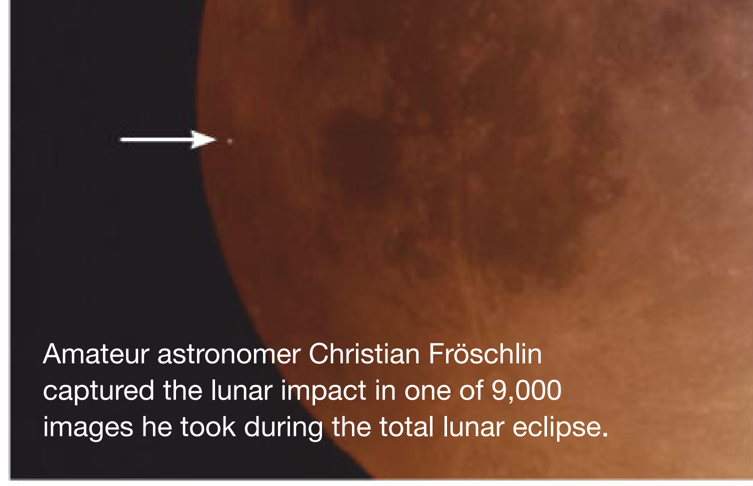
Using this method, astronomers have spotted a smattering of the hundreds of thousands of sub-kilometer-size objects expected to be in the Kuiper Belt. But until now, surveys haven't picked up the in-between, kilometer-size objects.

To extend the search toward rarer, kilometer-size KBOs, Ko Arimatsu (National Astronomical Observatory of Japan) led a team in setting up two identical observing systems, dubbed the Organized Autotelescopes for Serendipitous Event Survey (OASES), on a school rooftop. Each setup consists of off-the-shelf equipment and cost $16,000 — relatively inexpensive compared to most professional telescopes.

Arimatsu and colleagues amassed 60 hours under good weather conditions as they monitored some 2,000 stars. From these 50 terabytes of raw data, they found a single blip that indicated a candidate Kuiper Belt object with a radius between 1.2 and 2.1 kilometers. The discovery appeared January 28th in *Nature Astronomy*.

Even a single kilometer-size detection is more than the astronomers had expected based on the number of smaller Kuiper Belt objects. Its detection, they say, suggests an abundance of icy rocks of this size, perhaps indicating that this was the typical size of protoplanetary bodies reached in the primordial solar system before runaway growth occurred.

■ MONICA YOUNG



Amateur astronomer Christian Fröschlin captured the lunar impact in one of 9,000 images he took during the total lunar eclipse.

MOON

Impact Spotted During Lunar Eclipse

DURING THE JANUARY 20–21 total lunar eclipse, at least two binocular observers and more than a dozen others with cameras spotted a probable meteoroid impact on the Moon.

The flash appeared west of Mare Humorum, southwest of the crater Byrgius at 4:41:38 UT (11:41 p.m. EST), only seconds into totality. According to analysis by Jorge Zuluaga (University of Antioquia, Colombia) and colleagues, the body had a mass between 7 and 40 kilograms (15–90 pounds), a diameter of 10 to 27 cm (4–11 inches), and it probably made a crater 5 to 10 meters in size — within NASA's Lunar Reconnaissance Orbiter imaging capabilities.

Such impacts are common: NASA's Meteoroid Environment Office uses twin 14-inch telescopes equipped with video cameras to keep watch; it recorded 435 flashes between 2005 and 2018. But the circumstances of this event — a total lunar eclipse visible to millions — made this lunar impact the most widely observed and recorded.

■ BOB KING

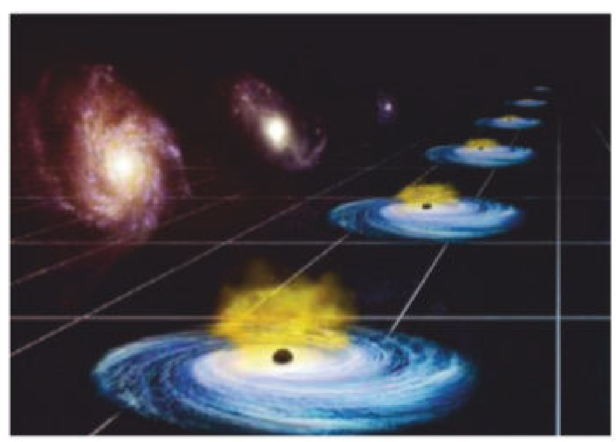
Risaliti and Lusso removed any sources where emission is obscured (by dust or gas) or contaminated (by emission from a fast-flowing black hole jet). Using data from the Sloan Digital Sky Survey and the XMM-Newton, Chandra, and Swift space telescopes, the duo then applied the relation to turn 1,600 quasars into standard candles.

The data suggest that dark energy's density has increased over cosmic time. That's a strike against the leading explanation for dark energy, known as the *cosmological constant*, which predicts a constant density over time (*S&T:* May 2018, p. 14).

But Phil Hopkins (Caltech), who wasn't involved in the study, urges caution in interpreting the results. He's unconvinced that the relation between quasars' visible and X-ray emissions remains the same over time. "[The relation] only needs to evolve a little bit to explain these observations," he notes. Nevertheless, Hopkins says the study is worth following up with bigger samples and more distant quasars.

■ MONICA YOUNG

▼ Understanding the relation between emission from accretion disks (blue-white) and X-ray-emitting coronae (yellow) can help astronomers use quasars as standard candles.



KBO: KO ARIMATSU; QUASARS: NASA / CXC / M. WEISS

SOLAR SYSTEM

Astronomers Identify Jupiter Weather Cycle

PLANETARY SCIENTISTS HAVE realized that the upper cloud layer at the gas giant's equator clears out in a predictable cycle. What's more, professionals and amateurs alike confirm that the planet is now undergoing another cloud-clearing event.

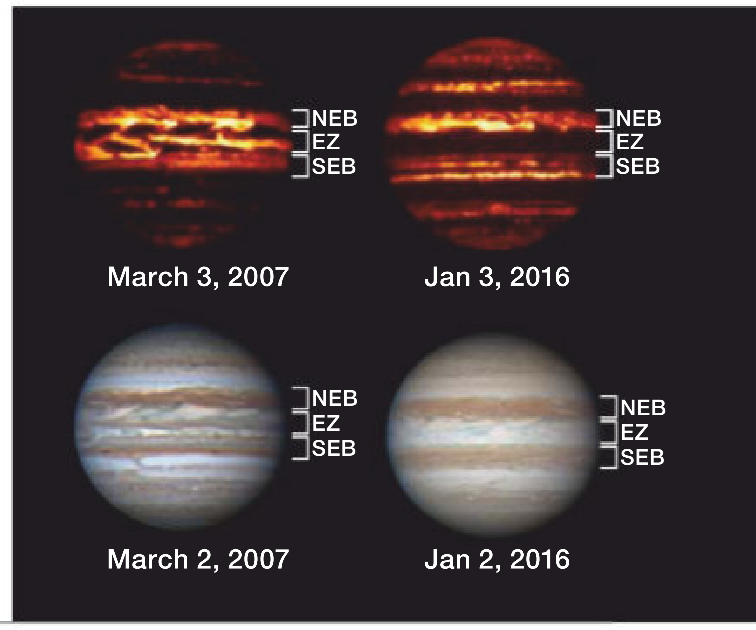
In the October 29, 2018, *Geophysical Research Letters*, a team of scientists using data from NASA's Infrared Telescope Facility published evidence of a recurring cycle: Every six or seven years the planet's Equatorial Zone, typically dark at infrared wavelengths, becomes bright. Comparing the infrared cycle to a large database spanning more than four decades of observations, the scientists found it corresponds to a visible shift in cloud cover.

"Jupiter's equator is normally completely clouded over, appearing dark in the infrared because those cold ammonia clouds appear in silhouette against Jupiter's warm internal glow," notes Arrate Antuñano (University of Leicester, UK), who led the study. "Those thick clouds make the equator look white through a visible telescope." But when the equator brightens at infrared wavelengths, the equatorial zone turns distinctly yellowish-brown. As the white ammonia clouds dissipate, they reveal darker, lower layers of atmosphere.

The scientists saw the disturbance in archival images from 1973, 1979, 1992, 1999, and 2006; each event lasted 12 to 18 months. While the team expected to see similar infrared-brightening events in 1985 and 2013, the clouds didn't clear completely at those times.

Now, the event is under way once again. Dedicated Jupiter observers, including Christopher Go, confirmed that the brown color of the equatorial zone, first spotted in late 2018, continued into January. Glenn Orton (Jet Propulsion Laboratory), a coauthor on the study, says the current event is indeed a full-blown clearing.

■ SEAN WALKER



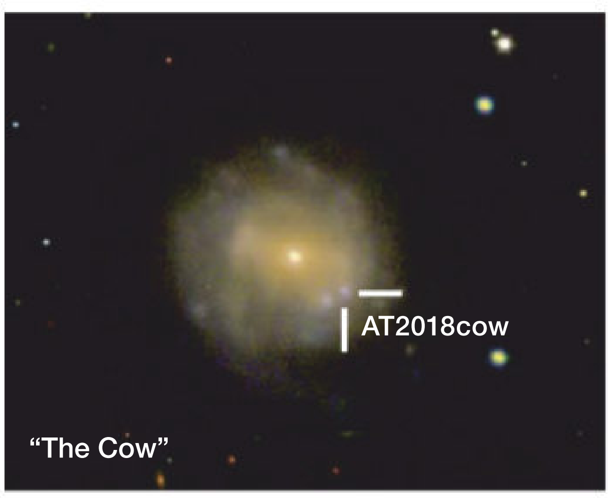
▶ Infrared *(top)* and visible-light *(bottom)* images show a 6- to 7-year cycle in the cloud cover in the North and South Equatorial Belts (NEB, SEB) and the Equatorial Zone (EZ).

TRANSIENTS

Celestial Event Dubbed "The Cow" Puzzles Astronomers

ASTRONOMERS AT THE WINTER meeting of the American Astronomical Society proposed contrasting scenarios to explain a strange celestial blast spotted last year. Did a medium-mass black hole tear a white dwarf apart, or are we seeing a new type of supernova?

The robotic Asteroid Terrestrial-impact Last Alert System (ATLAS) survey picked up the event on June 16, 2018, and automatically designated it AT2018cow, but astronomers quickly dubbed it "The Cow." The flash, which appeared in a spiral arm of a star-forming galaxy 200 million light-years away, took only two days to climb to a peak luminosity of 100 billion Suns — at least 10 times brighter than a typical supernova. Even stranger, the explosion's aftermath showed only the chemical fingerprints of hydrogen and helium, rather than the heavier elements characteristic of "ordinary" supernovae. And follow-up observations showed that the source remained hot for weeks after its discovery, rather than cooling down as supernovae typically do. These and other observations suggest that some sort of "engine" kept the explosion going for weeks.



One option is that a star came too near a black hole and was torn to shreds, said Amy Lien (University of Maryland). The Cow appeared so suddenly that the shredded star would have had to be small, such as a *helium white dwarf*, which would lack heavier elements. The black hole would have to be relatively small, too — 100,000 to 1 million times the mass of the Sun, making it a member of the elusive class of intermediate-mass black holes. However, such black holes are thought to form in globular clusters, so its location in a spiral arm would be unexpected.

Another possibility is a new kind of supernova. The event is clearly atypical of ordinary exploding stars, but Raffaella Margutti (Northwestern University) argues that, while astronomers typically see the glow of supernova ejecta, The Cow offered a clear view of the birth of a new black hole or neutron star at the blast's center.

Two lines of evidence support this picture. X-ray spectra of the blast from NASA's NuSTAR and the European Space Agency's INTEGRAL observatories show the signature of cold, dense material around the compact object. And longer-wavelength emission, seen by the Submillimeter Array on Mauna Kea, Hawai'i, could come from a shockwave that's plowing into the ejecta around the newly formed compact object.

Ongoing observations of the fading remnant may eventually tell astronomers what, if anything, remains from this mysterious explosion.

■ ELIZABETH HOWELL

JUPITER: TOP: NASA / IRTF, BOTTOM LEFT: ANTHONY WESLEY, BOTTOM RIGHT: TIZIANO OLIVETTI; GALAXY: R. MARGUTTI / W. M. KECK OBSERVATORY

SOLAR SYSTEM

Saturn Hasn't Always Had Rings

ANALYSES OF DATA from the final days of NASA's Cassini spacecraft suggest Saturn's rings are a late addition and may be related to the formation (and destruction) of its moons.

As Cassini's gas gauge sank toward empty, mission planners rerouted the orbiter to take 22 daredevil dives between the planet and its rings. Every time it passed through, the spacecraft felt the gravitational tug of both the planet and the rings.

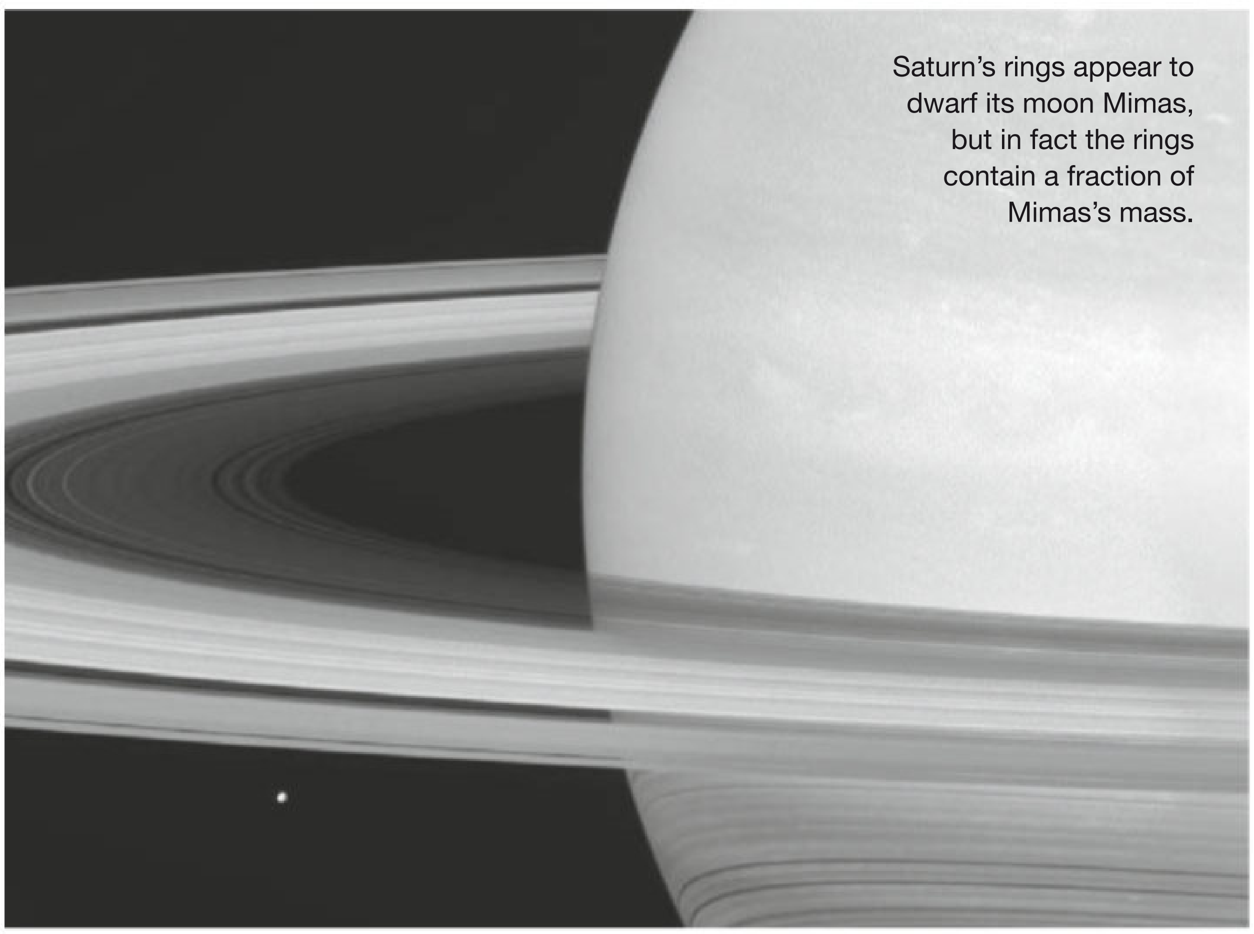
Luciano Iess (Sapienza University of Rome) and colleagues teased out the rings' contribution from the planet's, reporting January 17th in *Science* that the rings have a mass of 1.5×10^{19} kg. That's equivalent to roughly 40% of Saturn's mid-size moon Mimas.

Cassini data have also indicated that some 10 times more space dust is raining down on the rings than expected, meaning they can't be really old and still look as bright as they do. The low mass measurement, combined with information on space dust as well as simulations of the rings' evolution, suggests that the rings are young, roughly 10 million to 100 million years old.

These results jibe with work appearing in *Icarus* by James O'Donaghue (NASA Goddard) and colleagues, who re-analyzed ground-based data taken in 2011 at the Keck II Telescope on Mauna Kea, Hawai'i. They found that icy ring particles, in addition to raining down on the equator via gravity, also flow in along magnetic field lines to reshape the chemistry of the planet's outer atmosphere. Combining this analysis with Cassini data, O'Donaghue's team also pegs the rings' lifetime at less than 100 million years.

The rings' age range echoes that previously suggested for several of Saturn's mid-size icy moons (*S&T:* Aug. 2016, p. 14). Some planetary scientists think these satellites formed from the rubble of a previous generation of moons. How that event and the current ring system might be connected remains unclear, however: It's hard to understand why the detritus that makes up the rings would have migrated so close to the planet instead of clumping together into additional moons farther out, Iess's team notes in the paper. One alternate idea is that Saturn caught a passing comet or icy asteroid and tore it apart, then festooned itself in the wreckage.

■ CAMILLE M. CARLISLE & MONICA YOUNG



Saturn's rings appear to dwarf its moon Mimas, but in fact the rings contain a fraction of Mimas's mass.

NASA / JPL-CALTECH / SPACE SCIENCE INSTITUTE

IN BRIEF

A Bevy of Fast Radio Bursts Announced

A new radio array, the Canadian Hydrogen Intensity Mapping Experiment (CHIME), has spotted 13 new fast radio bursts (FRBs) — including the second one known to repeat. These mysterious flashes probably occur thousands of times a day, but they're so fleeting that astronomers miss most of them. The new FRBs were detected over a period of about three weeks last summer, when CHIME was running at only a fraction of its full capacity. The highlight of the bounty is a single burst that flared time and again. Appearing January 9th in *Nature* and announced at the winter meeting of the American Astronomical Society, the repeating burst was first detected on August 14th, and then CHIME saw it pop up five additional times. The only other known repeating FRB was first detected in 2012 (*S&T:* June 2016, p. 12) and has reappeared hundreds of times since. The two repeaters share striking similarities in their radio signals that could help astronomers understand their origins.

■ SHANNON HALL

Read more about the repeating FRB at https://is.gd/CHIMEFRB.

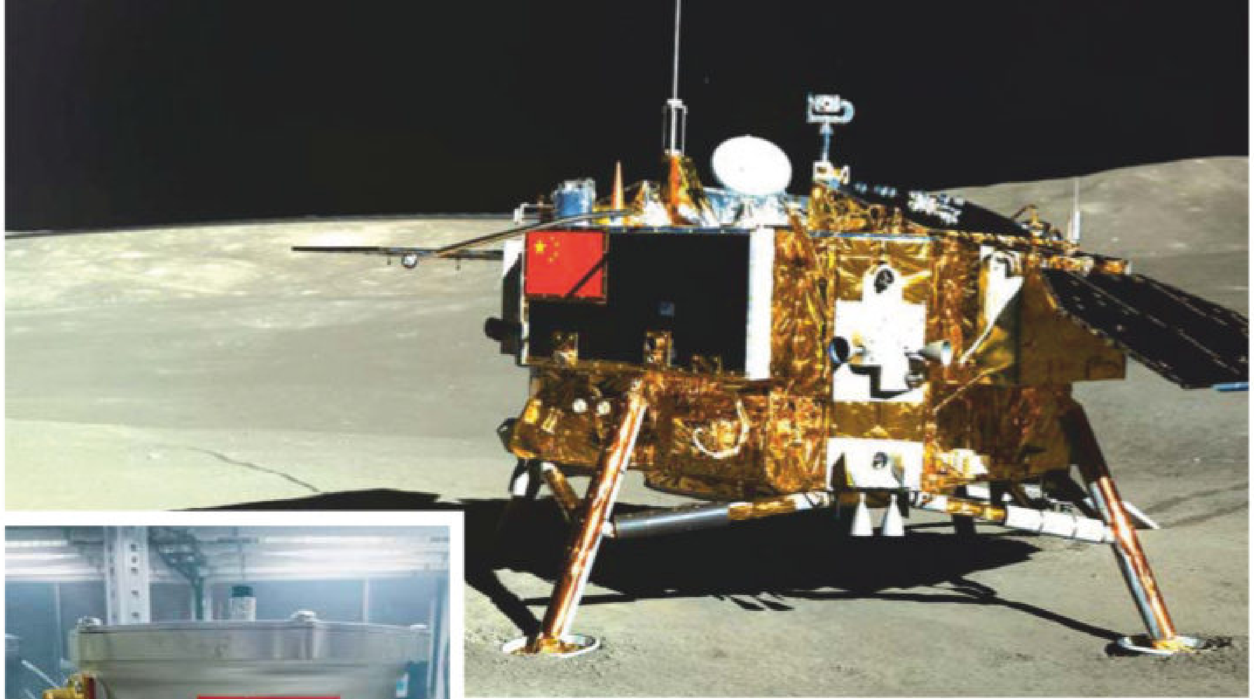
Annihilated Star Clocks Black Hole's Spin

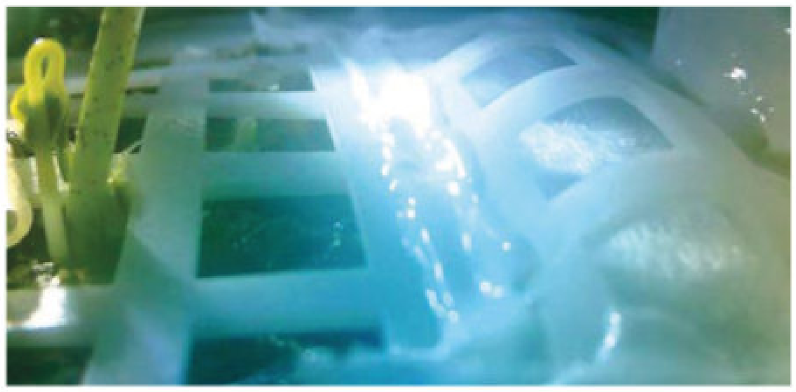
The glow of a star torn up by a supermassive black hole — a *tidal disruption event* discovered in 2014 and designated ASASSN-14li — has enabled researchers to measure how fast the black hole whirls around. Reporting January 9th at the winter meeting of the American Astronomical Society and in the February 1st *Science*, Dheeraj Pasham (MIT) and colleagues have used an innovative method to add to the list of a couple dozen supermassive black holes with measured spins. Using archival observations from NASA's Chandra and Swift space telescopes and the European Space Agency's XMM-Newton, the researchers found a bright, periodic X-ray pulse that repeated every 131 seconds. The signal lasted a surprisingly long time — at least 450 days. To endure for more than a year, the pulse is likely related to material orbiting the black hole. For the gas to come as close as the pulse's frequency implies, the black hole itself has to be spinning rapidly, dragging the gas tightly around itself. The spin is at least 70% of the black hole's theoretical maximum.

■ CAMILLE M. CARLISLE

One Small Step for Plantkind

With a germinating seed on the lunar farside, Earth's biosphere makes its first tentative foray into the cosmos.





▲ **GROWING GEAR** *Clockwise from top:* China's Change'4 lander at its touchdown spot on the lunar farside, in an image taken by the rover; the cotton sprouts during their abbreviated life on the Moon, with encroaching ice hinting at their imminent demise; and the LME experiment canister.

IN JANUARY THE CHINESE space agency achieved an impressive first, landing Chang'e 4, which also held the Jade Rabbit 2 rover, on the lunar farside. One of the most sensational image releases from this mission showed germinating cotton seeds growing inside the lander.

These aren't the first plants raised in space. Astronauts have long used the International Space Station, for example, for biological experimentation, including studies of how plants grow when subjected to low gravity and radiation. But there's symbolic potency in the first plants (that we know of) born on the surface of another world. Call it one small step for plantkind.

Yet these organisms couldn't have achieved this by themselves, so this is really another small step for humankind. It may not be a giant leap, but if humans are ever to go and live elsewhere in the solar system, not just for a visit but to remain, we'll have to take our biospheres with us and learn how to tend them there.

Among the experiments onboard Chang'e 4 is the apparatus that contained the cotton seeds — the Lunar Micro Ecosystem (LME). It also carried seeds of several other kinds of plants as well as yeast and fruit fly eggs. The plan was to keep the receptacle at Earth-like temperatures for 100 days while the plants sprouted and the flies hatched, setting up a miniature ecosystem in which the animals respired and the vegetation photosynthesized, exchanging oxygen and carbon dioxide like a mini-Gaia.

The experiment didn't go as hoped. The cotton seeds did sprout, providing an inspiring photo-op, but they didn't survive the coming of night. Unfortunately, during that first long, frozen lunar night, the LME's thermal control failed, and the young sprouts, along with the still-unhatched flies, froze to death.

While it's true that plants can't go to the Moon or Mars without us, it's also true that we can't go to Mars — at least to stay — without plants and myriad other living things. If we want to survive we'll need to learn how to keep our nonhuman companions happy.

One famous experiment attempted along these lines in the early 1990s was Biosphere 2. An enclosed habitat in the Arizona desert, Biosphere 2 bore a complement of species meant to simulate a range of terrestrial ecosystems. These microhabitats would recycle gases, water, and nutrients in order to keep the enclosure's humans and other beings alive.

The exercise failed when runaway growth of some species, die-offs of others, and dangerous changes in the O_2 and CO_2 levels meant that the human "biospherians" could not safely remain inside. Fortunately, it was easy to abandon ship, as this experiment was here and not on Mars.

Today, Biosphere 2 serves as a teaching and research facility, and studies involving enclosed people are no longer attempted there. Recently I got a tour, and it's a fascinating time capsule — a vision of the future fading into the past. But it's also a monument to both arrogance and humility, a lasting lesson in what can go wrong when we think we know more than we do. Our planet's environment maintains the complex balance of life so gracefully that it's easy to take for granted.

Like Biosphere 2, the Chinese trial is a sobering reminder that we still have an awful lot to learn about life and its mutual dependencies if we want to someday go and live beyond our home biosphere. Raising a plant on the Moon, even for a brief time, is a welcome tiptoe in that direction.

■ Astrobiologist **DAVID GRINSPOON** has tried to grow many plants on Earth, and some have even lived for a short while.

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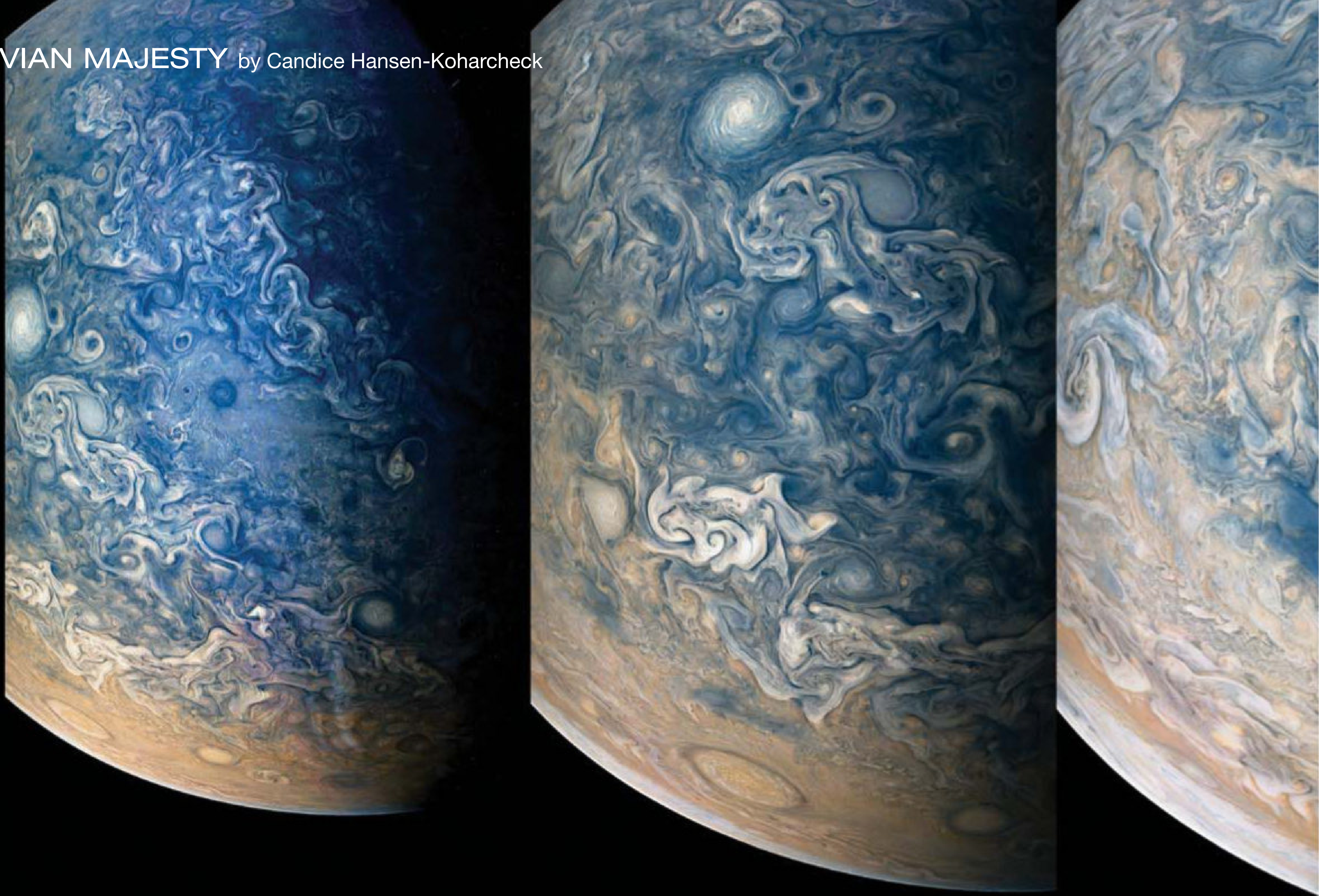


JUNOCAM AT JUPITER: Where Science Meets Art

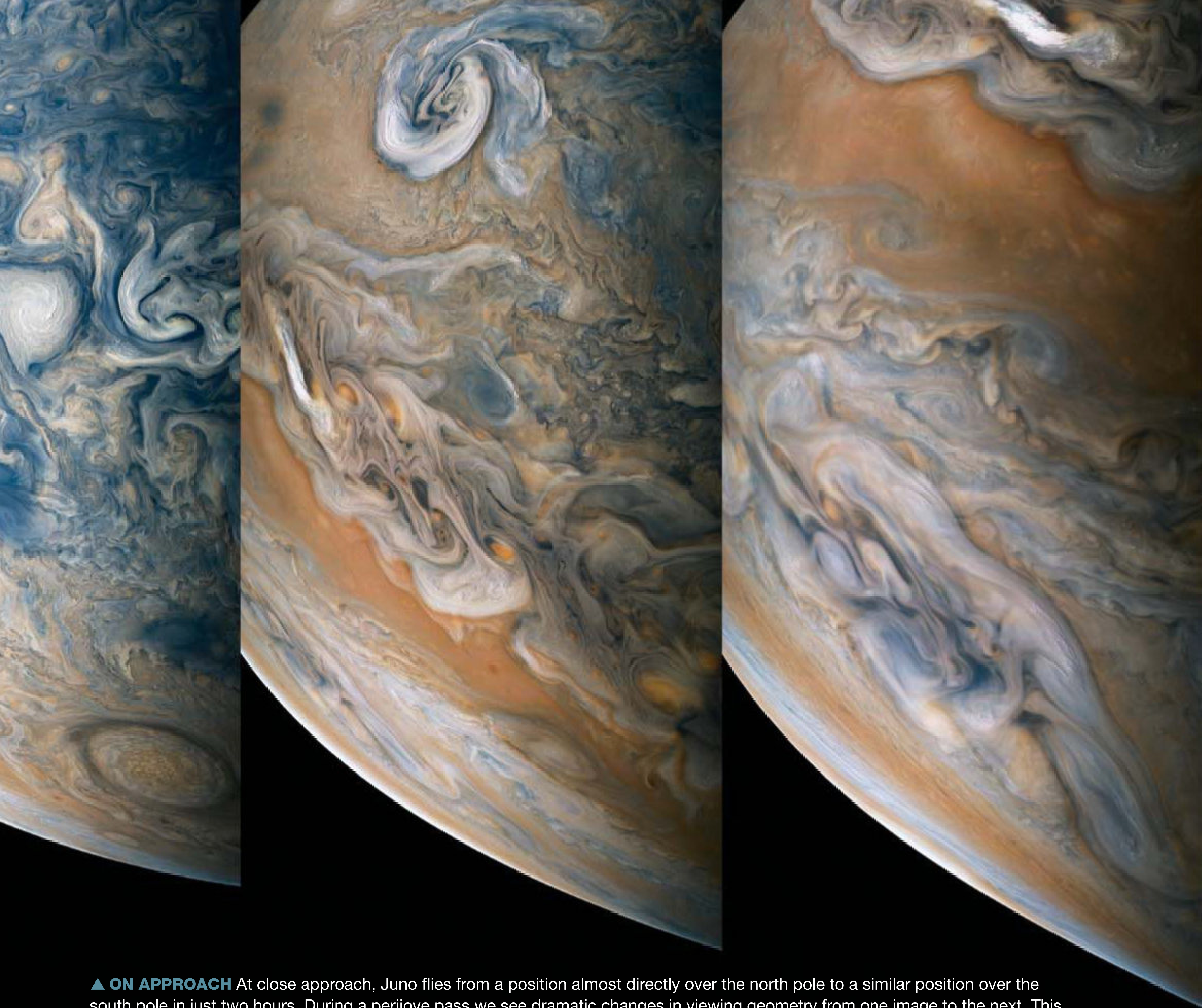
Amateur processing has revealed this fantastic world from a unique perspective.

The Juno spacecraft has been orbiting Jupiter since July 4, 2016. In addition to its eight scientific instruments, the craft carries an unusual passenger: a color camera called JunoCam. The imager has no high-level science goals, and it lacks a formal imaging science team. Instead, its role on the mission is primarily for outreach.

JunoCam engineers post both lightly processed and raw data online; then members of the public process the images. This partnership has resulted in a unique blend of science and art. Enhanced color-image processing by volunteer citizen scientists brings out subtle details in the clouds and storms that arrest the eye. Artists' contributions yield frame-worthy illustrations that help us all to appreciate the beauty of the largest planet in our solar system.

The processed images are also helping us do science. Juno's elongated polar orbit provides us with unique perspectives unavailable to Earth-based observers or previous spacecraft. The first discovery was that the familiar belt-zone structure at mid-latitudes gives way to more chaotic storms at the planet's top and bottom, with cyclones grouped around both the north and south poles (*S&T:* June 2018, p. 8). Time-lapse sequences of images have enabled scientists to measure the rotation rates and wind speeds of these circumpolar cyclones — they whirl around every 27 to 60 hours at hundreds of kilometers per hour.

In its elliptical orbit, Juno travels close to Jupiter every 53 days. During each of these *perijove passes*, the spacecraft comes in over the north pole, then sails to the south pole in just two hours. JunoCam's 1,600-pixel-wide detector has a 58°-wide field of view that allows it to capture Jupiter's entire pole in a single image about one hour before or after perijove. The spacecraft's rotation helps build the



▲ **ON APPROACH** At close approach, Juno flies from a position almost directly over the north pole to a similar position over the south pole in just two hours. During a perijove pass we see dramatic changes in viewing geometry from one image to the next. This sequence of five images of the northern hemisphere was taken at perijove pass 14. The image on the left is looking down on latitude 69°N at a distance of 25,304 km. The image on the right was taken just 17 minutes later over 36°N, at an altitude of 6,242 km.

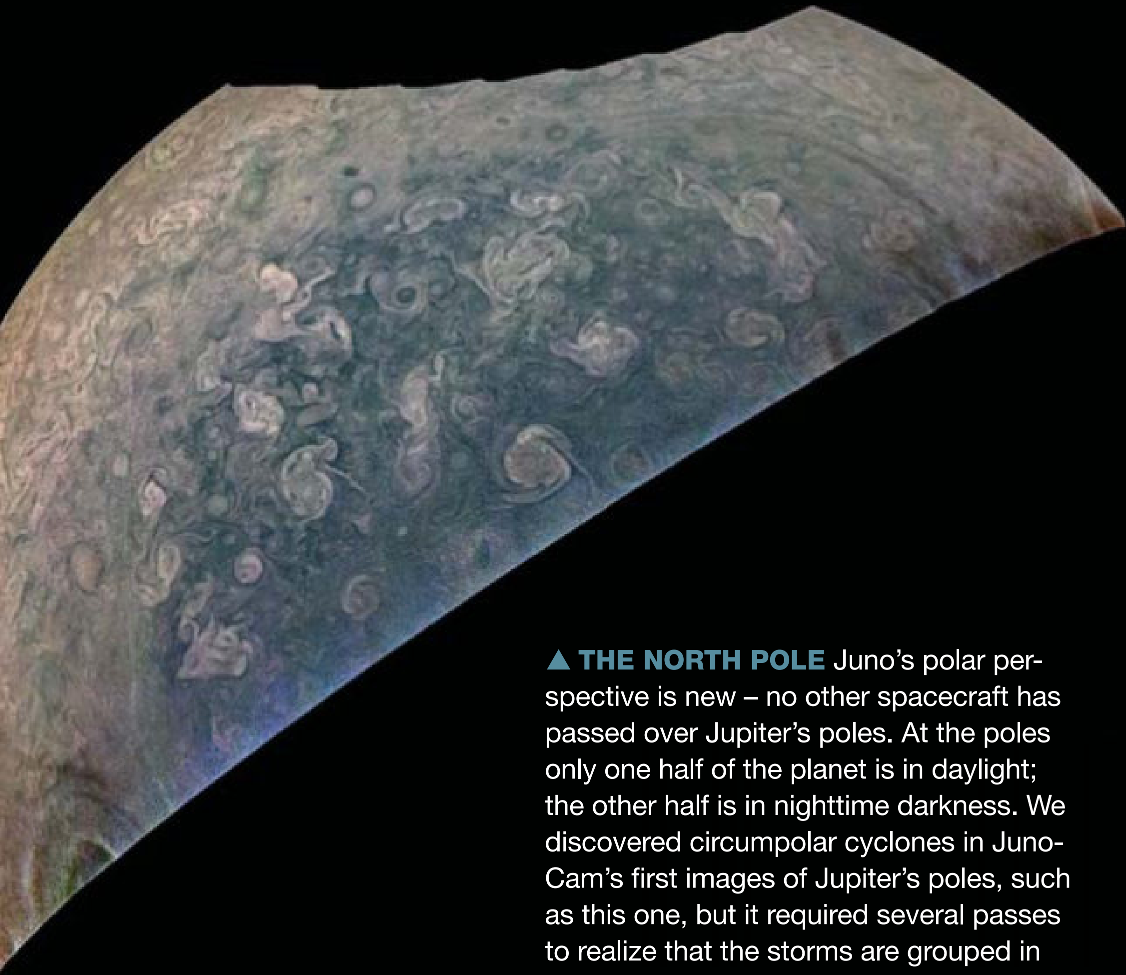
NASA / MSSS / SEÁN DORAN

second dimension of the image, up to 360°. At perijove, the images have high-resolution and are wide enough to capture entire storms, such as the Great Red Spot. JunoCam takes images through broad red, green, and blue filters, as well as a narrowband methane filter centered at 889 nm, that are mounted directly on the detector.

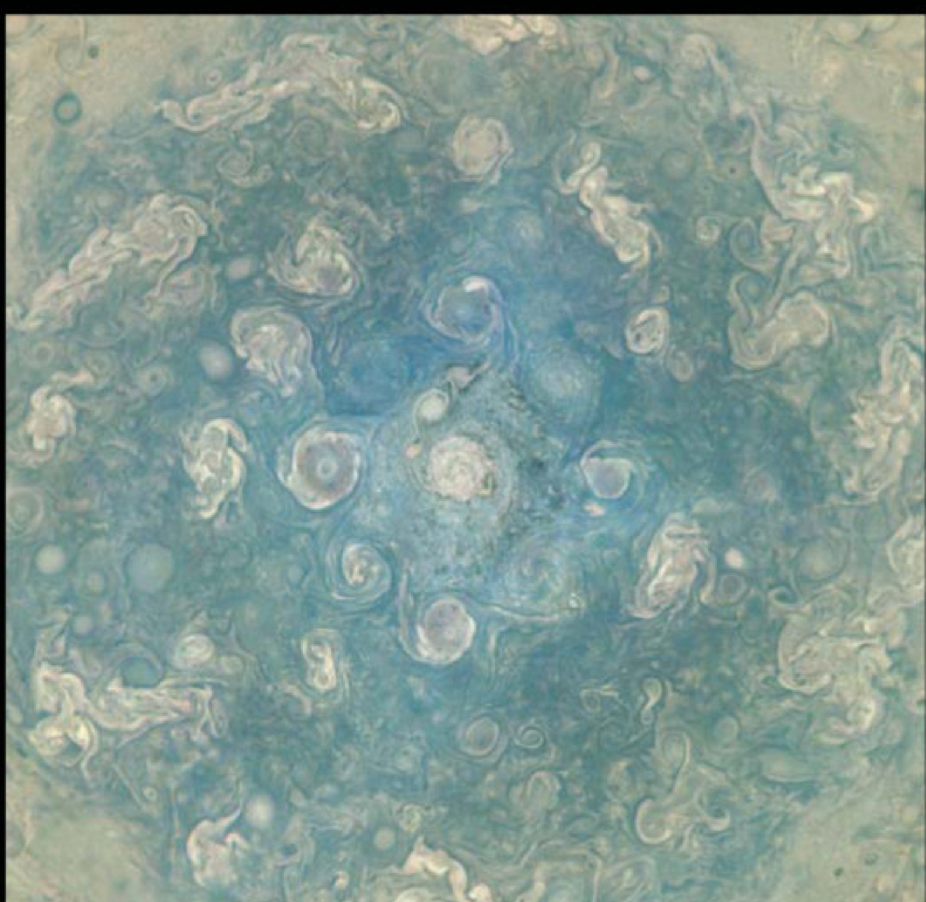
Juno's unique perspective was expected to yield discoveries of Jupiter's previously unexplored polar regions, but citizen scientists processing JunoCam images have revealed other insights. While the camera's wide field of view captures broad swaths of atmosphere, its high resolution captures fine details, showing the structure within giant storm systems. Amateur astronomers have correlated these images to known disruptions in the belts and zones, which observers have tracked for decades from Earth. Amateur-processed images have helped scientists examine clouds illuminated beyond the terminator and shadows cast by storms. And images taken through JunoCam's methane filter enabled the study of high-altitude hazes and the structure of the upper atmosphere. We've also detected new phenomena, such as the numerous, tiny high-altitude clouds dubbed "pop-up storms." We're investigating whether these are the Jovian equivalent of squall lines.

The images shown in this essay are among the favorites of JunoCam's most prolific contributors. Most have enhanced or exaggerated color processing, such that blues become bluer and reds redder. To see more examples, and participate yourself, go to https://is.gd/junocamprocessing.

■ CANDICE HANSEN-KOHARCHECK is a senior scientist at the Planetary Science Institute. She is a co-investigator on the Juno mission and leads the JunoCam team.



▲ **THE NORTH POLE** Juno's polar perspective is new – no other spacecraft has passed over Jupiter's poles. At the poles only one half of the planet is in daylight; the other half is in nighttime darkness. We discovered circumpolar cyclones in JunoCam's first images of Jupiter's poles, such as this one, but it required several passes to realize that the storms are grouped in polygons around a central cyclone located close to the pole.



▲ **NORTH POLE MONTAGE** This image combines views from Juno's first five perijove passes to show the eight circumpolar storms surrounding a central cyclone near Jupiter's north pole. This central area is in winter darkness, so the depiction of the central cyclone comes from the near-infrared instrument, JIRAM, on Juno.

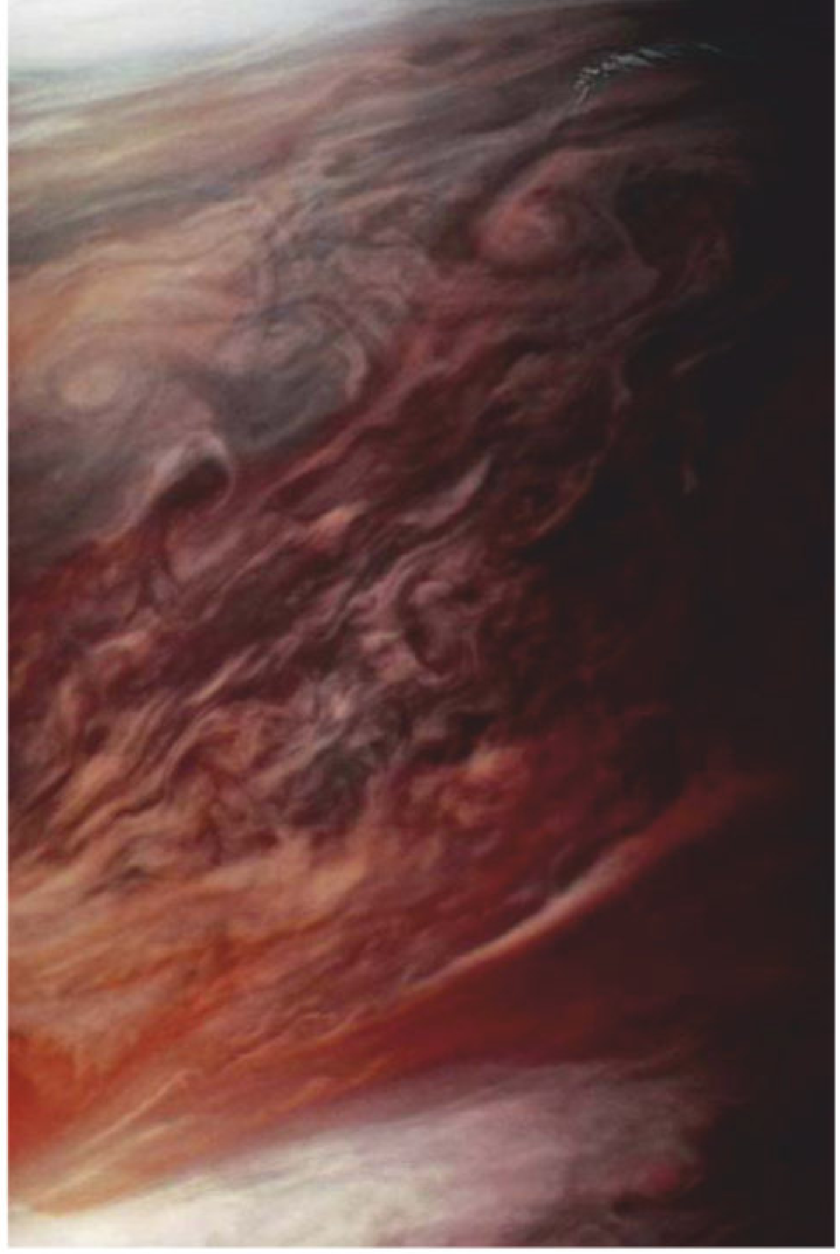
▶ **LAYERS OF CLOUDS** This image of Jupiter's North North North Temperate Belt was acquired on perijove pass 13. The enhanced color reveals the three-dimensional nature of Jupiter's cloud decks, with thin, almost-transparent hazes partially masking the storms below.

◀▶ TRUE COLOR VS ENHANCED A person looking at Jupiter through a telescope would see muted pastels like those at left. Image processing enhances color differences *(right)*, revealing detail that exists but is not obvious in the true-color version.

MORE THAN MEETS THE EYE The perspective of an artist brings us an entirely new way to see Jupiter. Amateur astrophotographer Seán Doran shares his process: "This perijove I was really getting into the groove of getting at most of the detail and color variation present in Gerald Eichstädt's source images. I was surprised to see the extent to which the images still held up aesthetically without losing too much of the subtleties to overly harsh filtering and blending. It is a fine line to walk but the reward is worth it."

NORTH POLE: NASA / MSSS / BRIAN SWIFT; MONTAGE: NASA / MSSS / BJÖRN JÓNSSON; CLOUDS: NASA / MSSS / GERALD EICHSTÄDT; TRUE VS ENHANCED COLOR: NASA / MSSS / BJÖRN JÓNSSON (2); BLUE SWIRLS: NASA / MSSS / GERALD EICHSTÄDT / SEÁN DORAN

▲ **DARK CYCLONE** Large dark storms, dubbed "brown barges," are often found in Jupiter's atmosphere. Even in this true-color version, the brown color of this barge at latitude 38°N is distinctive.



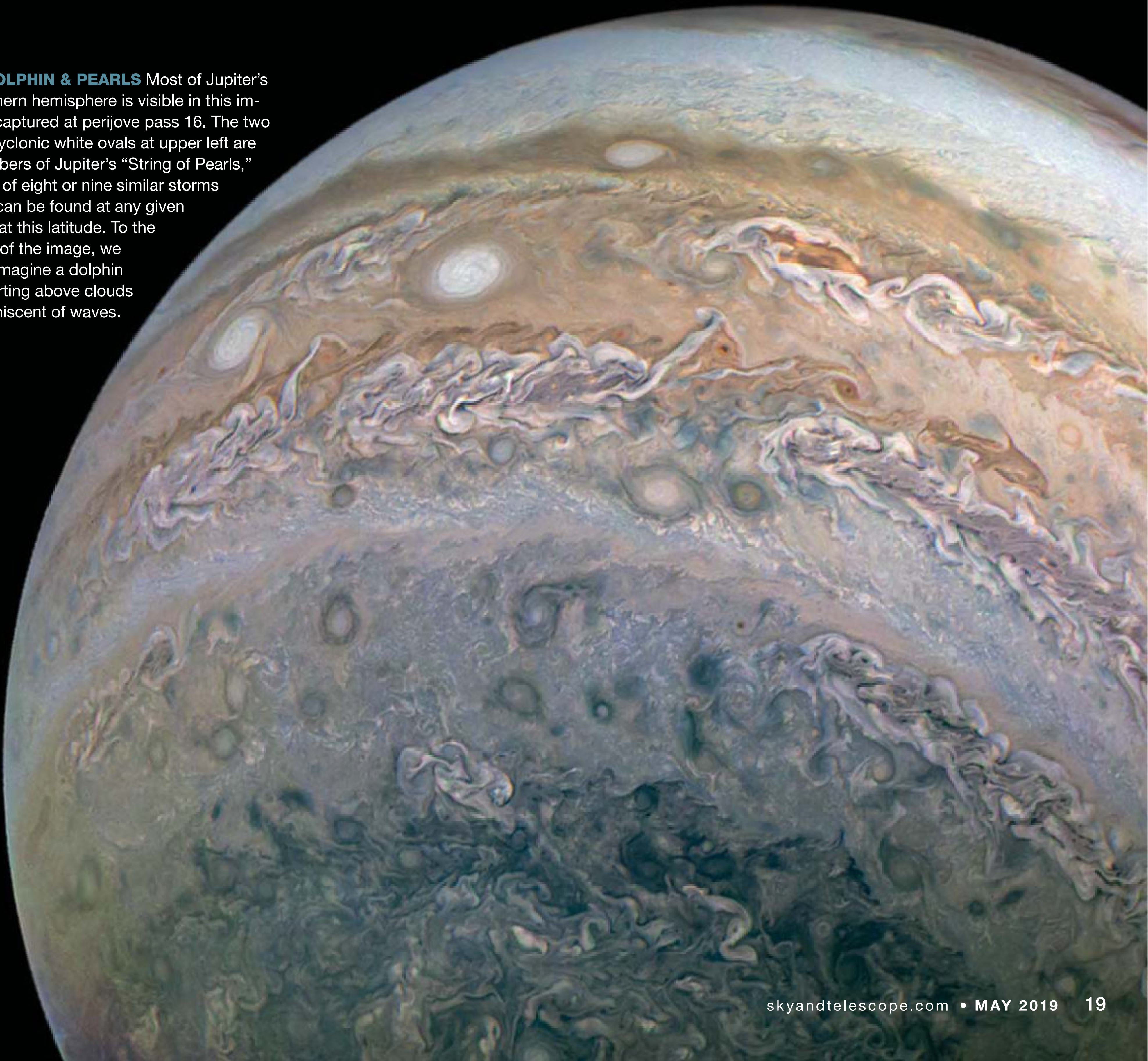
▶ **JOVIAN FLAME** This image of the Southern Equatorial Belt captures the drama of waves in Jupiter's atmosphere, as well as high-altitude hazes overlying storms. This take is one of amateur astronomer Roman Tkachenko's favorites.

▲ **TINY TO TITANIC** Storms of all sizes are captured in this image from the 12th perijove pass, ranging from a large white oval to the tiny, bright-white "pop-up storms" that appear to dot pressure ridges, as within the oval low in the center of the image.

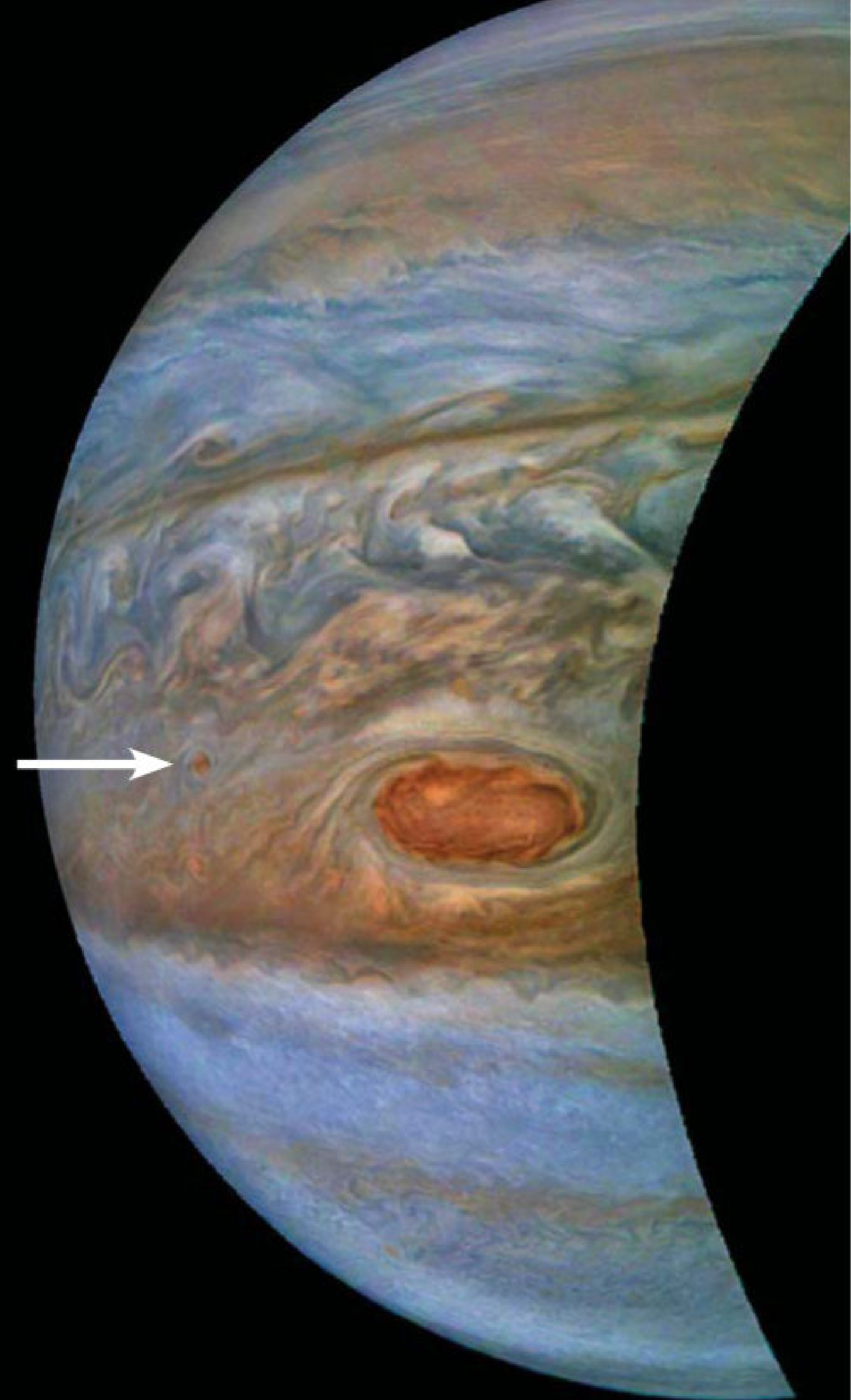
▲ **TURBULENT SEAS** We are familiar with the banded appearance of Jupiter's belts and zones in images from Earth-based telescopes. With Juno's close-up view, captured during perijove 10, we can see the turbulence roiling along the northern edge of the equatorial belt.

▲ **A MOVING VIEW** Clouds and swirling ovals almost seem to be moving along Jupiter's cloud deck within the South South South Temperate Belt. "It gives you the feeling that you're there watching Jupiter with Juno," says amateur Emma Wälimäki.

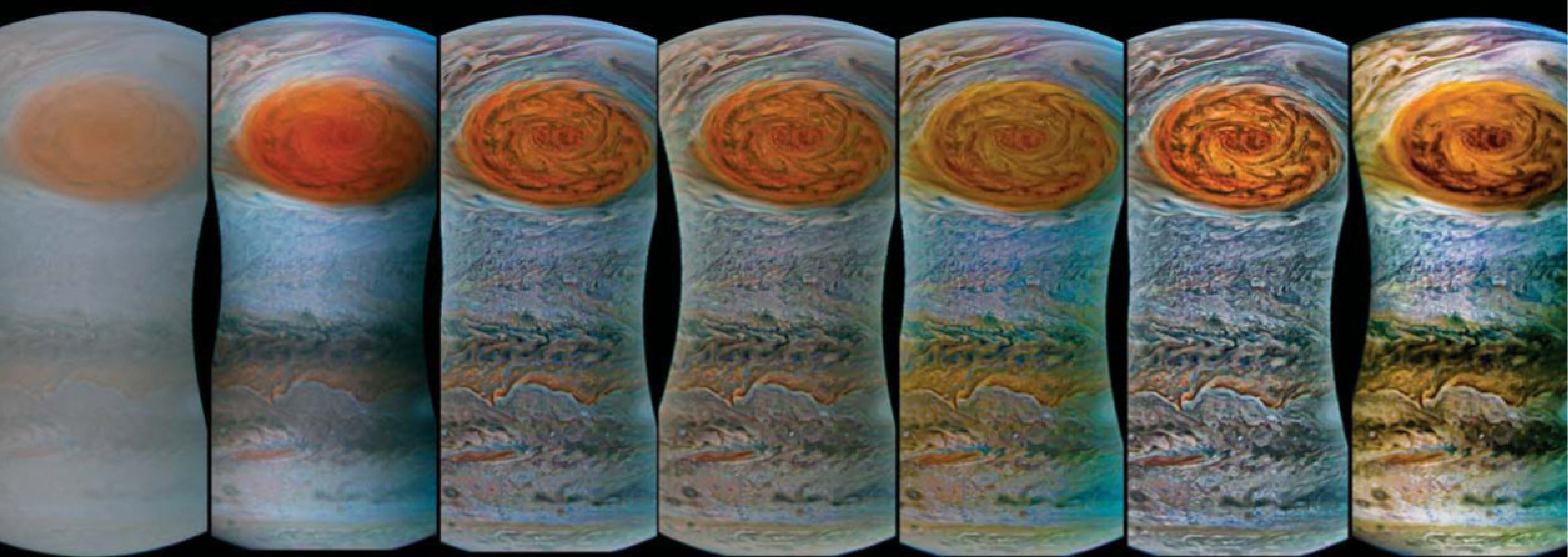
▼ **DOLPHIN & PEARLS** Most of Jupiter's southern hemisphere is visible in this image captured at perijove pass 16. The two anticyclonic white ovals at upper left are members of Jupiter's "String of Pearls," a set of eight or nine similar storms that can be found at any given time at this latitude. To the right of the image, we can imagine a dolphin cavorting above clouds reminiscent of waves.



◀ **THE GREAT RED SPOT** Earth could easily fit inside the Great Red Spot, which spans approximately 16,000 km.



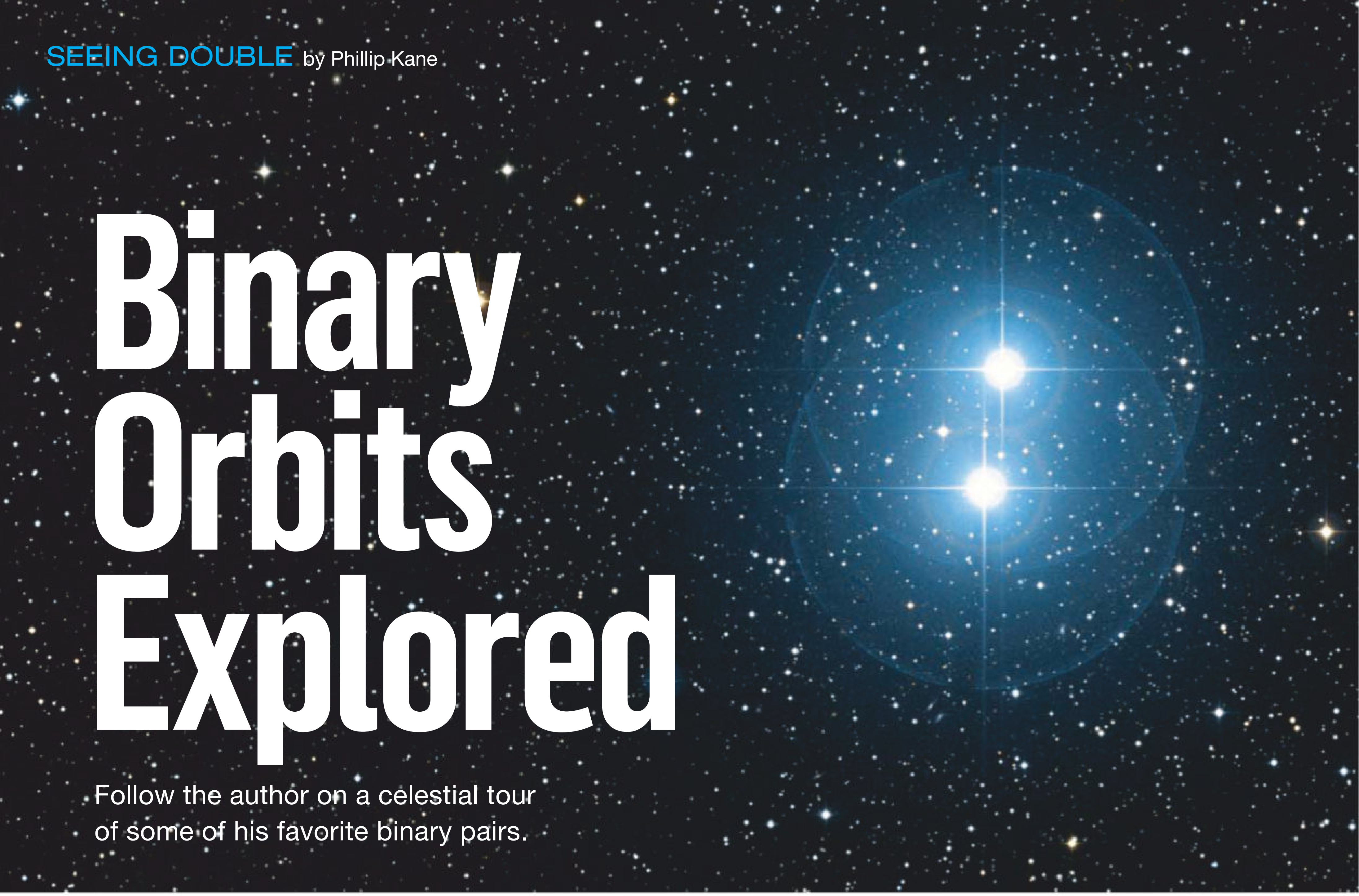
▶ **OPPOSITE WHORL** During perijove pass 14 JunoCam captured another large storm on the northern edge of the South Equatorial Belt (see arrow). It rotates in the opposite direction as the Great Red Spot.



▲ **GREATNESS ENHANCED** After the Juno spacecraft passed over Jupiter's Great Red Spot during its seventh perijove pass, several levels of processing each bring out new and different details in these images of the giant storm.

▼ **STEALING HAZE** The South Tropical Disturbance (dark region to the upper left) occasionally creates turbulence in the South Tropical Zone. In this color-enhanced image, the disturbance has just passed Jupiter's iconic Great Red Spot, drawing out strands of its orange haze.

GREAT RED SPOT: NASA / MSSS / MATTEO VACCA; HIDDEN STORM: NASA / MSSS / JOAQUIN CAMARENA; GREATNESS ENHANCED: NASA / MSSS / CARLOS GALEANO; STEALING HAZE: NASA / MSSS / KEVIN M. GILL by Phillip Kane



Binary Orbits Explored

Follow the author on a celestial tour of some of his favorite binary pairs.

▲ **DOUBLES GALORE** Epsilon Lyrae is fondly known as the Double Double since it's a binary star in which each component is a binary star in its own right. Join the author on a tour of some beloved binary pairs.

We now accept the premise that most close double stars are not random alignments but binary pairs gravitationally bound in orbit about each other. But this realization did not come easily.

Prior to about 1800, astronomers mostly regarded double stars as curiosities, the chance positioning of two stars at different distances. (One exception was John Michell who, in 1767, suggested that most doubles were physical pairs.) In 1779, the great astronomer William Herschel began a systematic study of these "accidental doubles." He saw a clever use for them — as a way of measuring stellar parallaxes (the astronomical unit was fairly well established by then). His hypothesis, a concept first considered by Galileo, was simple. If he regarded the fainter star as very distant and "fixed," he could obtain a first-approximation measure of the parallax of the brighter, closer component since the two stars would shift relative positions as the Earth made its annual orbit around the Sun. But in his 25 years of observing binary stars, Herschel didn't determine parallaxes at all. Instead, he realized his records clearly showed some pairs of stars in orbital motion.

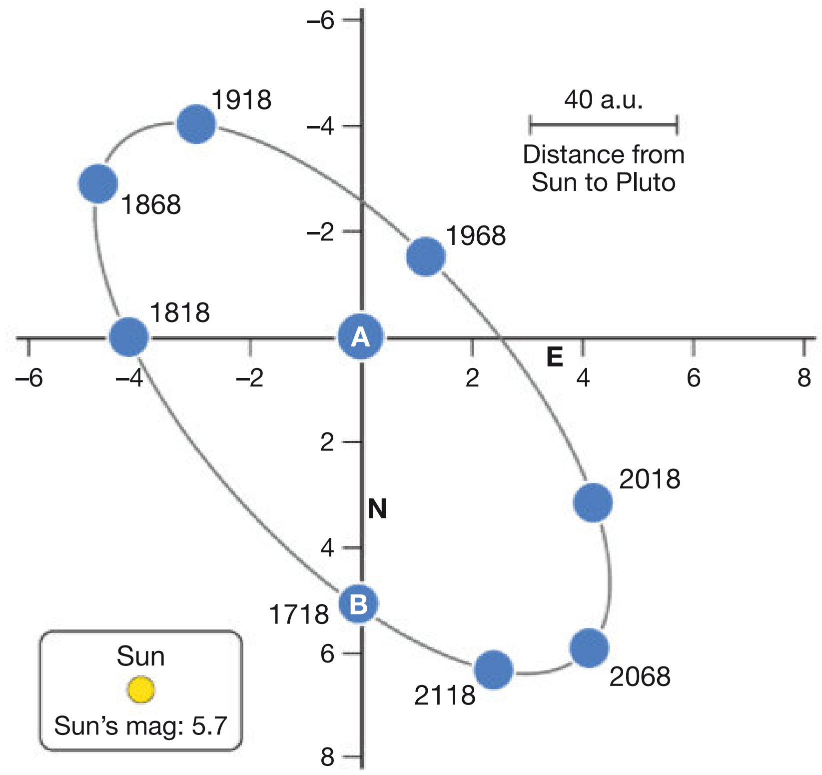
On June 9, 1803, William Herschel presented a groundbreaking paper to the Royal Society in London in which he said he would "prove that many of them are not merely double in appearance, but must be allowed to be real binary combinations of two stars, intimately held together by the bonds of mutual attraction." Robert Grant Aitken, in his classic book *The Binary Stars*, states Herschel's conclusions were "incontrovertible."

Herschel's historic paper detailing this series of observations began with the double star Castor. As Robert Burnham noted when he summed up Herschel's contribution in the second volume of his *Celestial Handbook*, "Castor . . . was the first true physical binary to be recognized, and the first object beyond our own Solar System in which the force of gravitation was shown to be operating . . . ."

All (seven) of the orbital elements necessary to calculate at least a preliminary orbit have been determined for about 2,600 double stars. A list of the elements that can be used for plotting binary orbits is available from the U.S. Naval Observatory in the Sixth Catalog of Orbits of Visual Binary Stars (**https://is.gd/wdsc6**). Several of these 2,600 confirmed binaries would probably be on any double-star enthusiast's list of favorite doubles. Here are nine of my favorites.

EPSILON LYRAE: POSS-II / CALTECH / STSCI / PALOMAR OBSERVATORY;
ALL BINARY PLOTS: PHILLIP KANE; ALL CONSTELLATION IMAGES: AKIRA FUJII

The Binary Tour



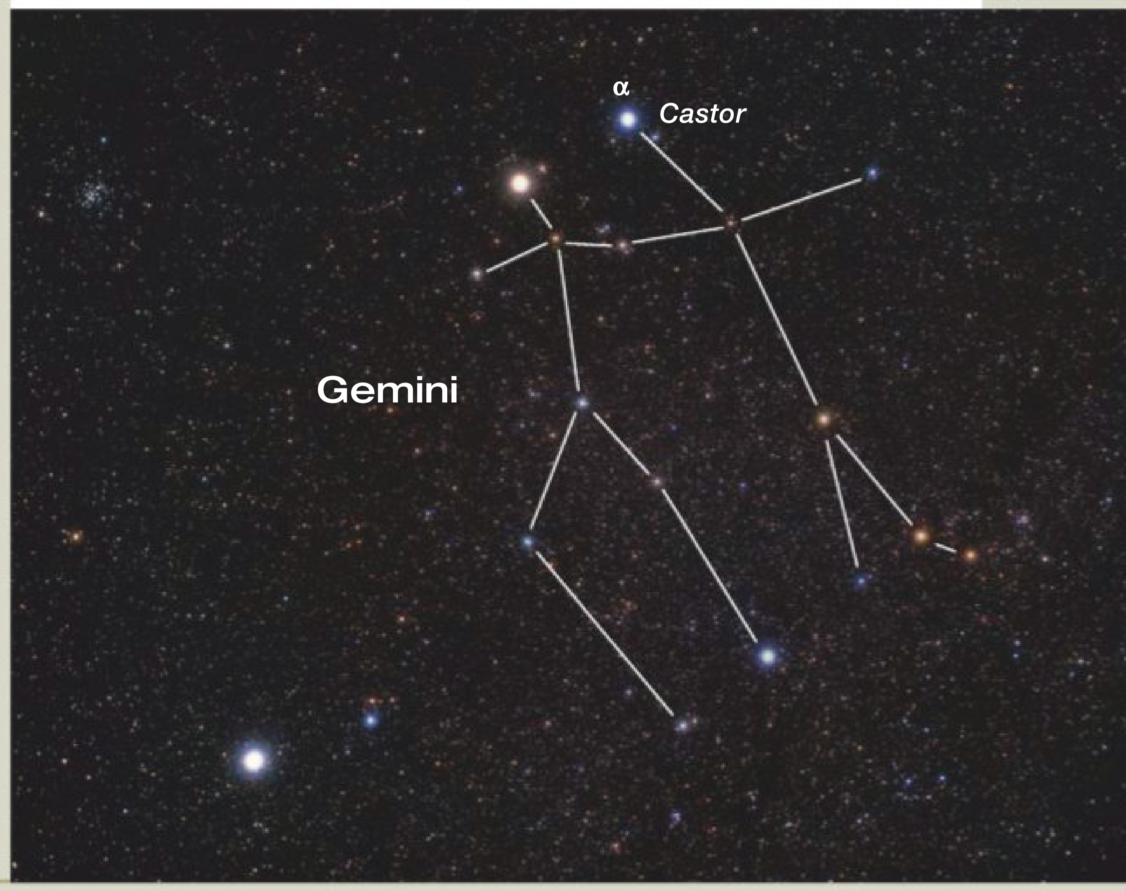
Castor

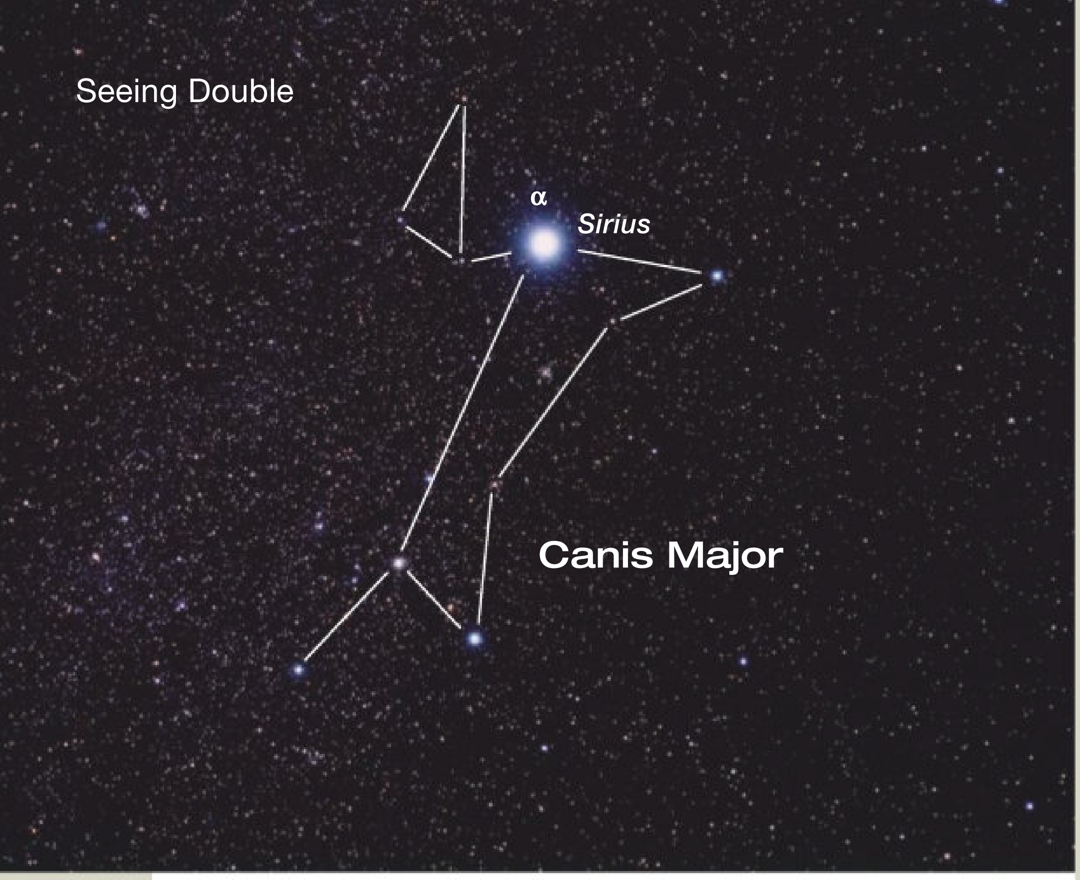
It makes historical sense to start with **Castor**, or Alpha (α) Geminorum. Except for the period from 1963 to 1973 when the components were less than 2″ apart, Castor has been (and will remain) an accessible binary for smaller telescopes. Although a spectacular and bright blue-white pair, there's much more here than what visual observers can see. Both the A and B components are *spectroscopic binaries*, making this a quadruple system. There's also a third gravitationally bound component (in its turn also a spectroscopic binary). The C companion, at 71″ and position angle (PA) 164°, is faint (magnitude 9.3) but easy to spot in its uncrowded field.

The Orbital Plots

Before we get going, let's review a few things about the orbital plots and what you might see in the sky. Don't expect the binary components to be moving as you observe! The most rapid binary pair discussed here completes its orbit in 50 years. Still, the relative positions of three binaries in this article — Sirius, Gamma Virginis, and 70 Ophiuchi — change enough in 10 years for a visual observer to confirm orbital motion. It's an exhilarating experience.

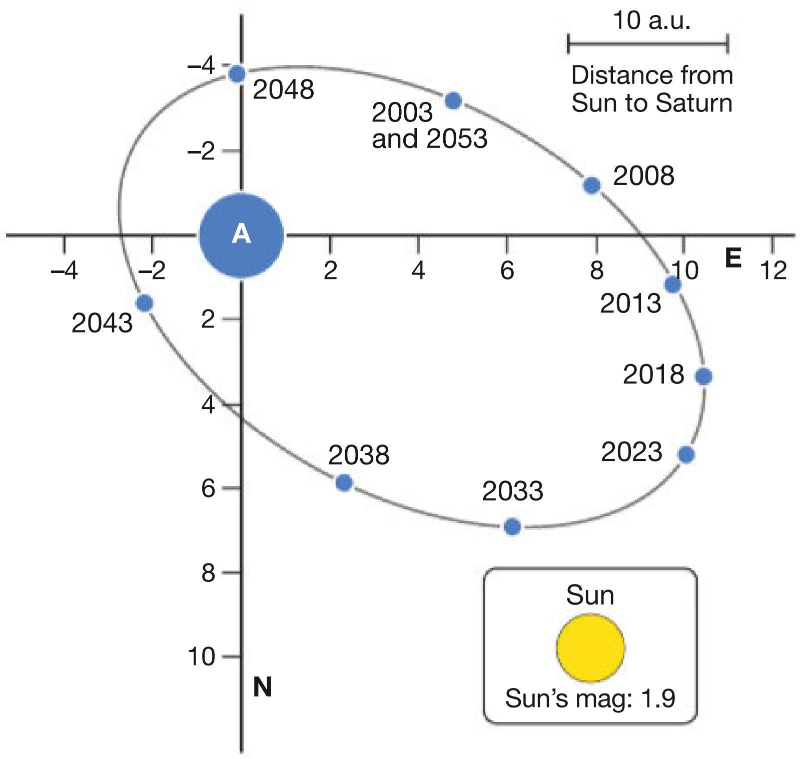
Presented here are apparent orbits where the secondary component, B, is shown revolving around a fixed primary, A (as is customary). The orbit is projected "flat" onto the celestial sphere. For the plots, I've scaled the components' magnitudes and colored them according to their spectral types. Also included is the apparent magnitude (and G2 color) of the Sun placed at the same distance as the binary pair. Lastly, a solar system scale projected onto the apparent orbit shows the distance from the Sun to either Saturn (10 a.u.) or to Pluto (40 a.u.).

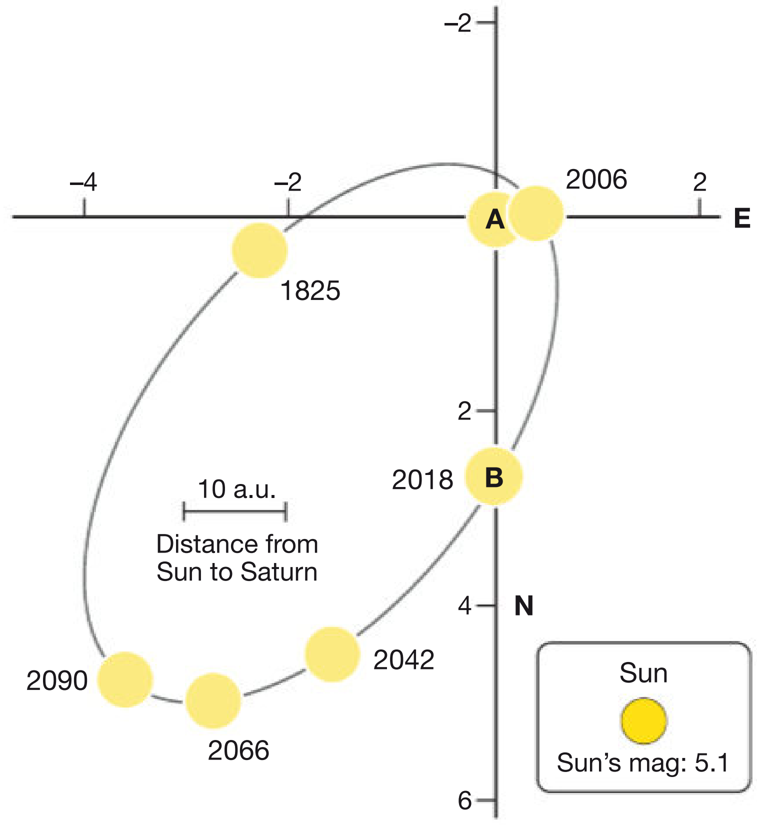




Sirius

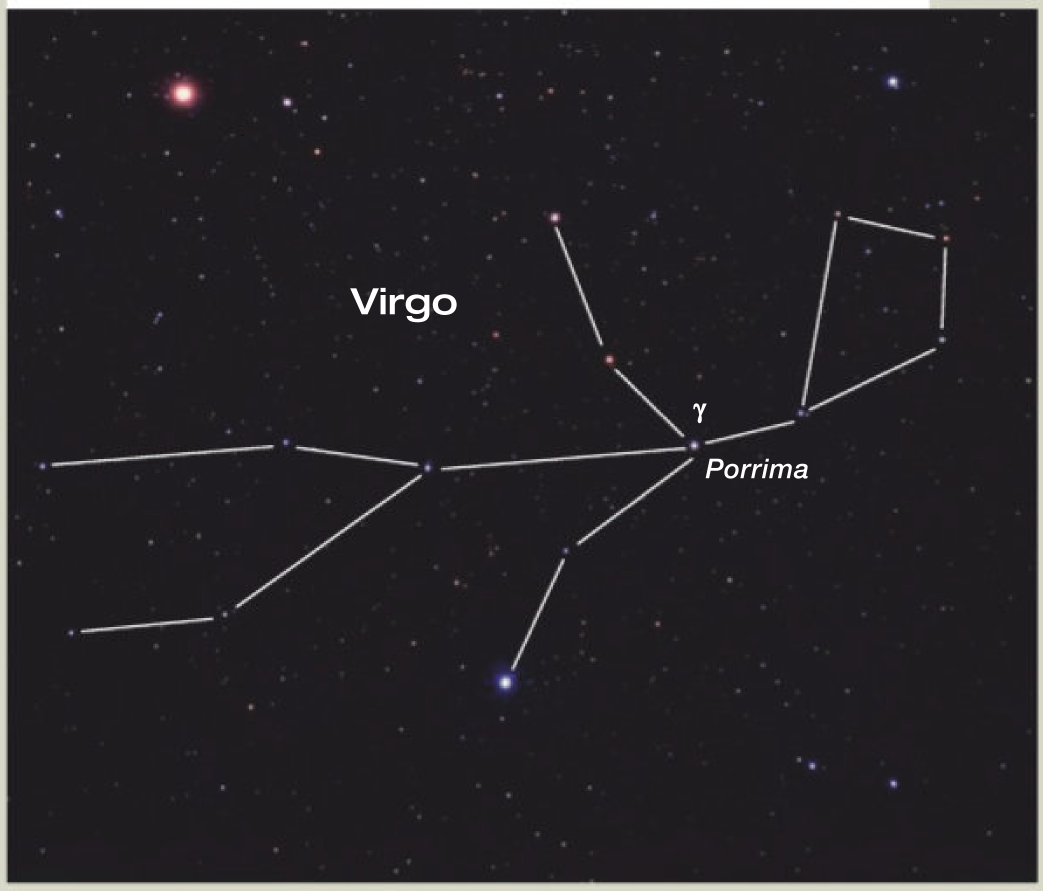
South of Gemini lies our next binary, **Sirius** (Alpha Canis Majoris). Alvan Clark first sighted Sirius B in 1862 with an 18.5-inch refractor, but heed Herschel's words: "When an object is once discovered by a superior power, an inferior one will suffice to see it afterwards." A 10-inch (250-mm) telescope is sufficient to observe B even when near *periastron*, the point at which the two components are closest, as it will be in 2044 (when the stars will be 2.7″ apart). There's a nice window from 2008 to 2036 when B is 8.0″ or more from A. During these years all of us with 6-inch (150-mm) scopes — and some of us with 4-inch (100-mm) scopes — have a good shot at glimpsing the elusive companion. Much will depend on seeing conditions, and the use of an occulting bar over Sirius A or keeping it out of the field will help, perhaps even be necessary.

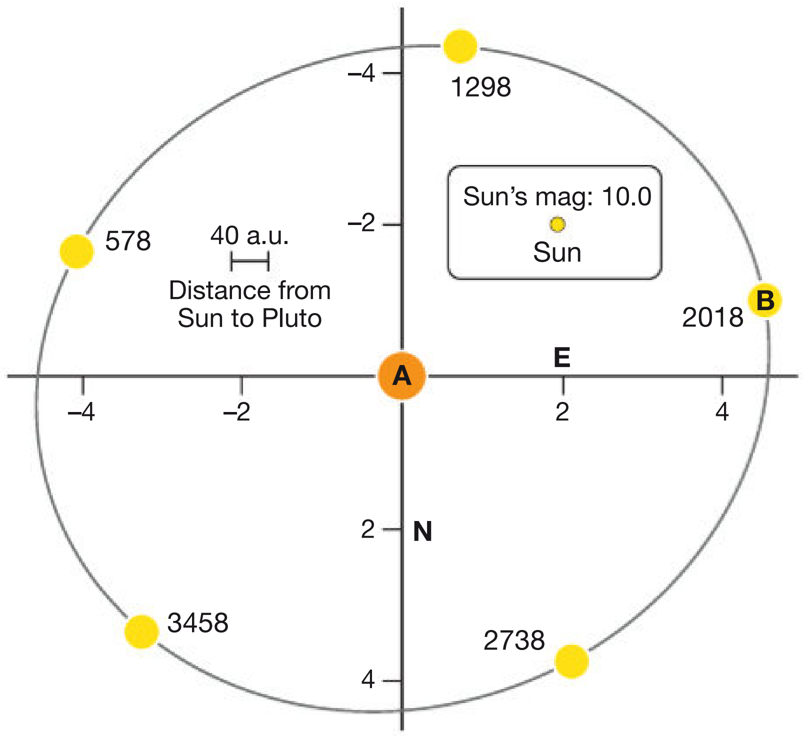




Gamma Virginis

The spectacular binary **Gamma (γ) Virginis** is next, at 6 hours of right ascension (RA) east of Sirius. Also known as Porrima, this binary is one of the most wonderful of all double stars. Its two very bright 3.5-magnitude components can be separated by up to 6.0″ (coming up in 2090) or as close as 0.41″ (as in 2006). During its last periastron passage from 2003 to 2008, a 12-inch (300-mm) telescope was required to resolve it, but things are better now. Currently (2019, at 2.8″), it's a test for a 2-inch (50-mm) scope and getting easier to resolve. Some observers describe this very bright pair as white, some as yellow. Burnham saw them as pale yellow and resembling the remote headlights of a celestial craft approaching from space.

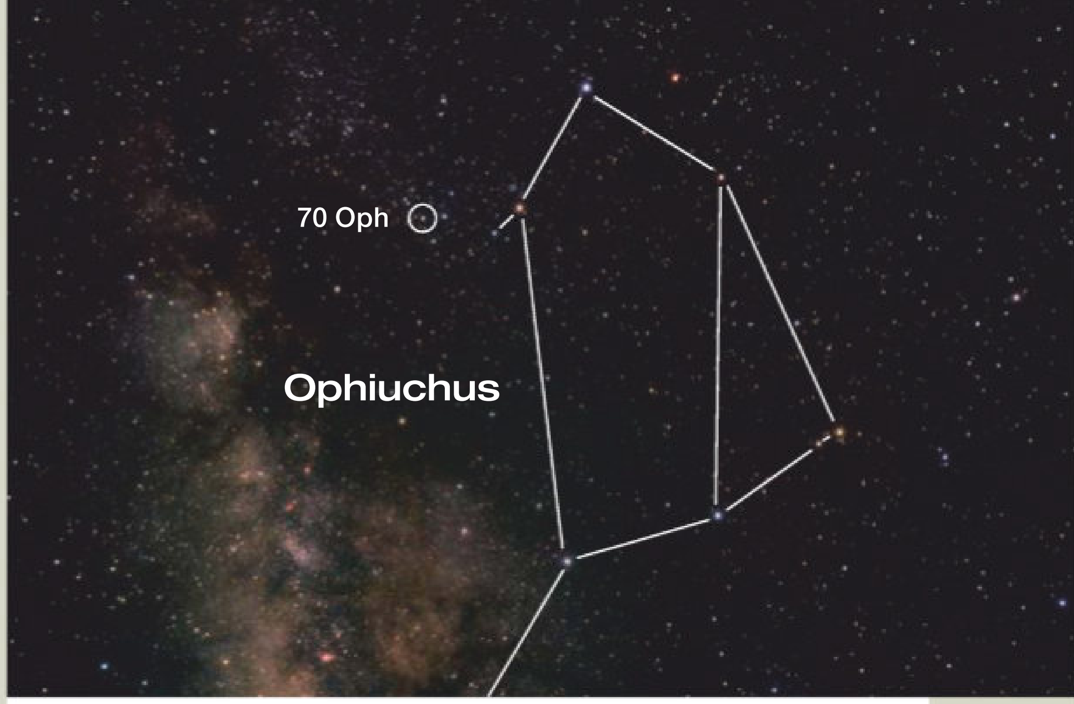




Alpha Herculis

Moving about 5 hours of RA east and some 10° north of Gamma Vir will center the view on Alpha Ophiuchi. Flanking this conspicuous 2nd-magnitude star are two impressive binaries, but impressive for different reasons. Off to the northwest is **Alpha Herculis**. Besides its strikingly orange primary star, it's the shape of Alpha Her's apparent orbit that also stands out. It plots as near circular (but not quite), because it not only happens to be oriented close to face-on from our point of view, but its orbit also has an eccentricity of zero. The secondary's distance from the primary varies from only 4.3″ to 4.7″ over a 3,600-year period of revolution! Herschel first noticed the secondary in 1779; it was identified much later to be a spectroscopic binary. The primary is a luminous red giant whose magnitude varies irregularly between 2.7 and 4.0 over a three-month period, averaging at magnitude 3.5. Herschel discovered Alpha Her's variability in 1795, 16 years after he recognized its binary nature. (Can you imagine his dedication to find this out!)

We should wish Alpha Her were closer. Of the 18 stars in the nine pairs here, Alpha Her A has the highest luminosity. Its absolute magnitude varies from –2.5 (similar to Jupiter) to –1.2 (slightly fainter than Sirius), which is what its apparent magnitude would be were it about ten times closer. It would also be a deeper orange than Betelgeuse. The B companion would be no slouch — in a telescope it would look similar to Arcturus, just 50″ from A.

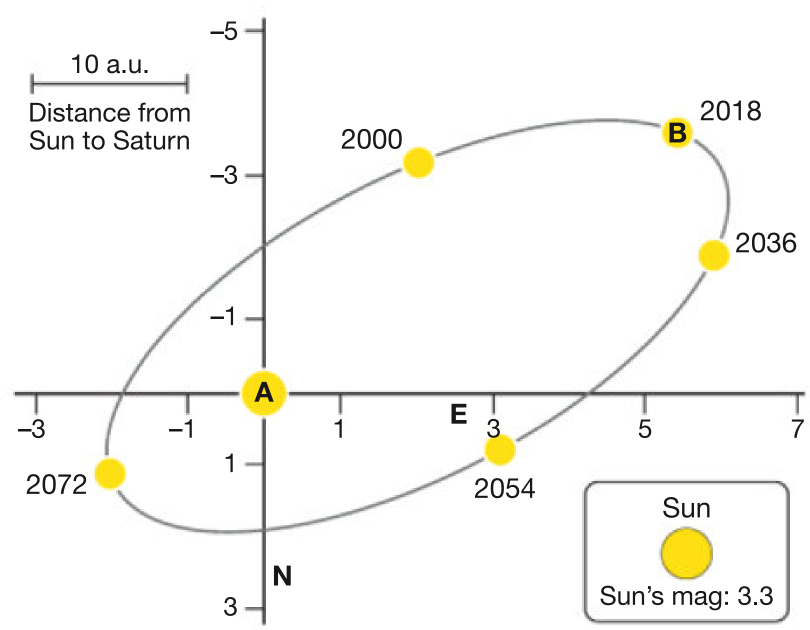


70 Ophiuchi

Southeast of Alpha Ophiuchi is one of the most studied binaries, **70 Ophiuchi**. It's only 16.6 light-years away and has a rapid 88-year revolution, having made almost three revolutions since Herschel discovered it in 1779. The pair will be widest in 2025 (7.74″) and closest just 53 years later in 2078 (1.54″). Some reading this will be alive to follow B from its widest separation from A all the way to its closest approach.

Of the nine binaries here, 70 Oph is impressive because the changing positions of its components are the easiest to follow, even by casual observers. Inspired by Burnham's 1978 plot of 70 Oph, I occasionally plotted B's position around A from 1990 to 2008. I used a red field star 30′ to the east to judge B's PA and nearby 59 Serpentis (a 3.9″ fixed double) to estimate the AB distance. My sketch shows AB widened by 4″ and changed its PA by 110°. Observing real celestial movement like this in a binary pair is ethereal!

The movements of 70 Oph's components have some odd orbital anomalies that suggest exoplanets may be present, but none have been confirmed. Irish astronomer Agnes Mary Clerke summed it up well, referring to 70 Oph as far back as 1890: "The stars have . . . persistently refused to keep to their predicted places . . ." This pair obviously needs even more study.

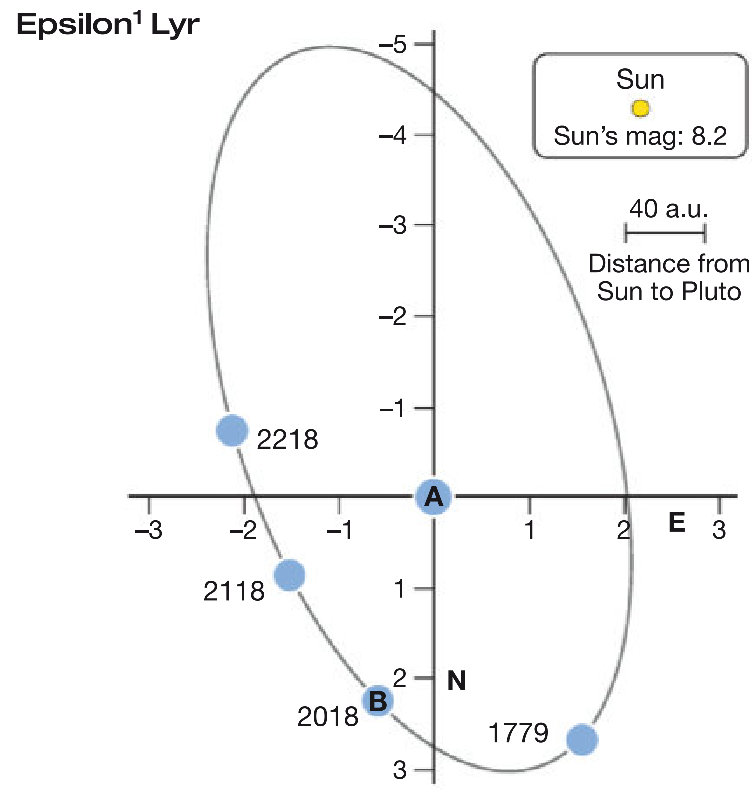


Epsilon Lyrae

About 40° north of 70 Oph lies the famous Double Double in Lyra, **Epsilon[1] (ε) Lyrae** and **Epsilon[2] Lyrae**. Nothing else matches it. Herschel first swept up this pair in 1779, noting "a very curious double double."

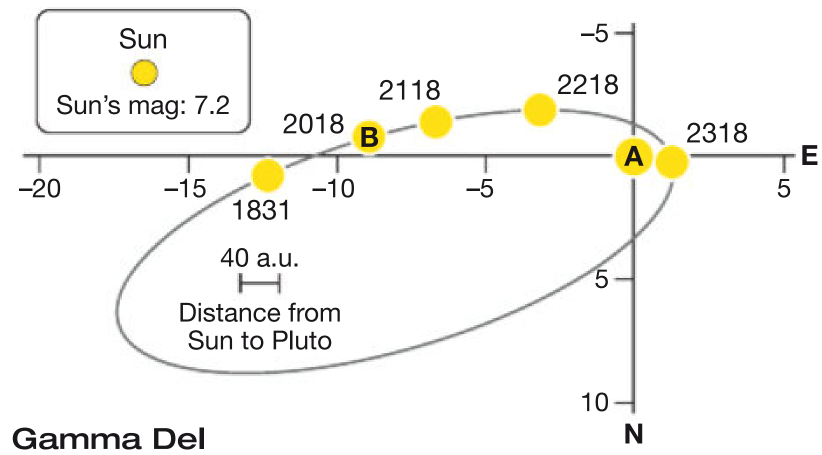
Epsilon[1] and Epsilon[2] form a wide pair 3.5′ apart that some observers can separate with the naked eye. If the two pairs were at the same distance from us, their separation would equate to just 0.2 light-years, a figure sometimes cited. But Hipparcos parallaxes indicate the Epsilon[2] pair is 6 light-years closer to us, hence 6 light-years is a more likely separation.

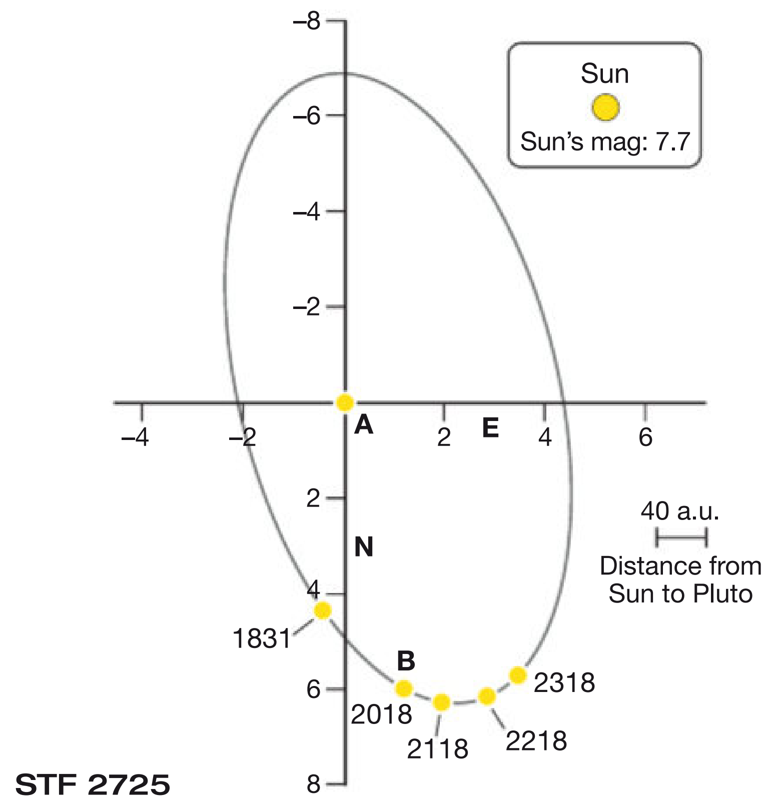
All four stars can be captured in a 150× eyepiece. Epsilon[1] gets more difficult over the next 100 years, but Epsilon[2] widens slightly. Both pairs remain resolvable in 3- to 4-inch scopes.

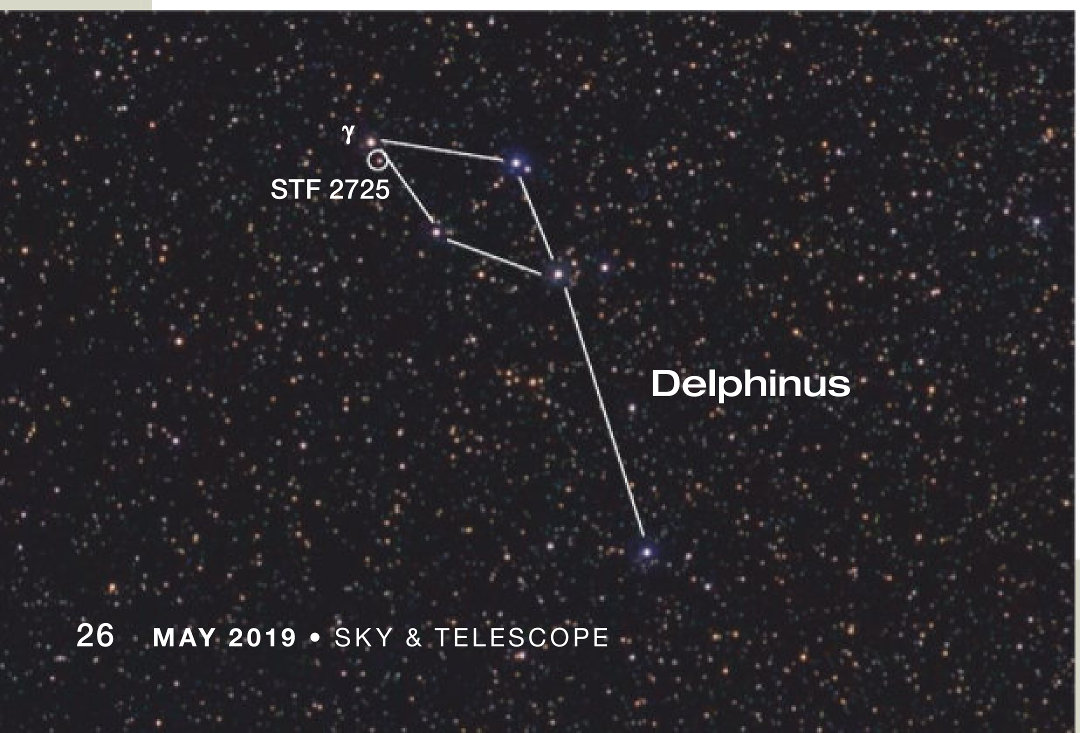


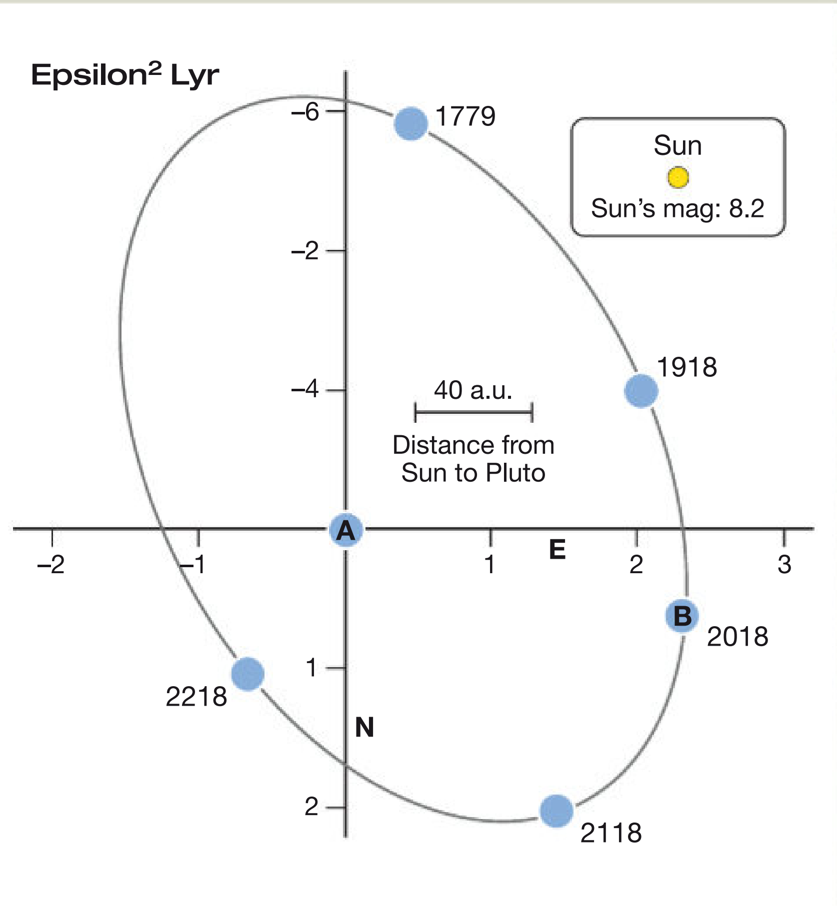
Gamma Delphini and STF 2725

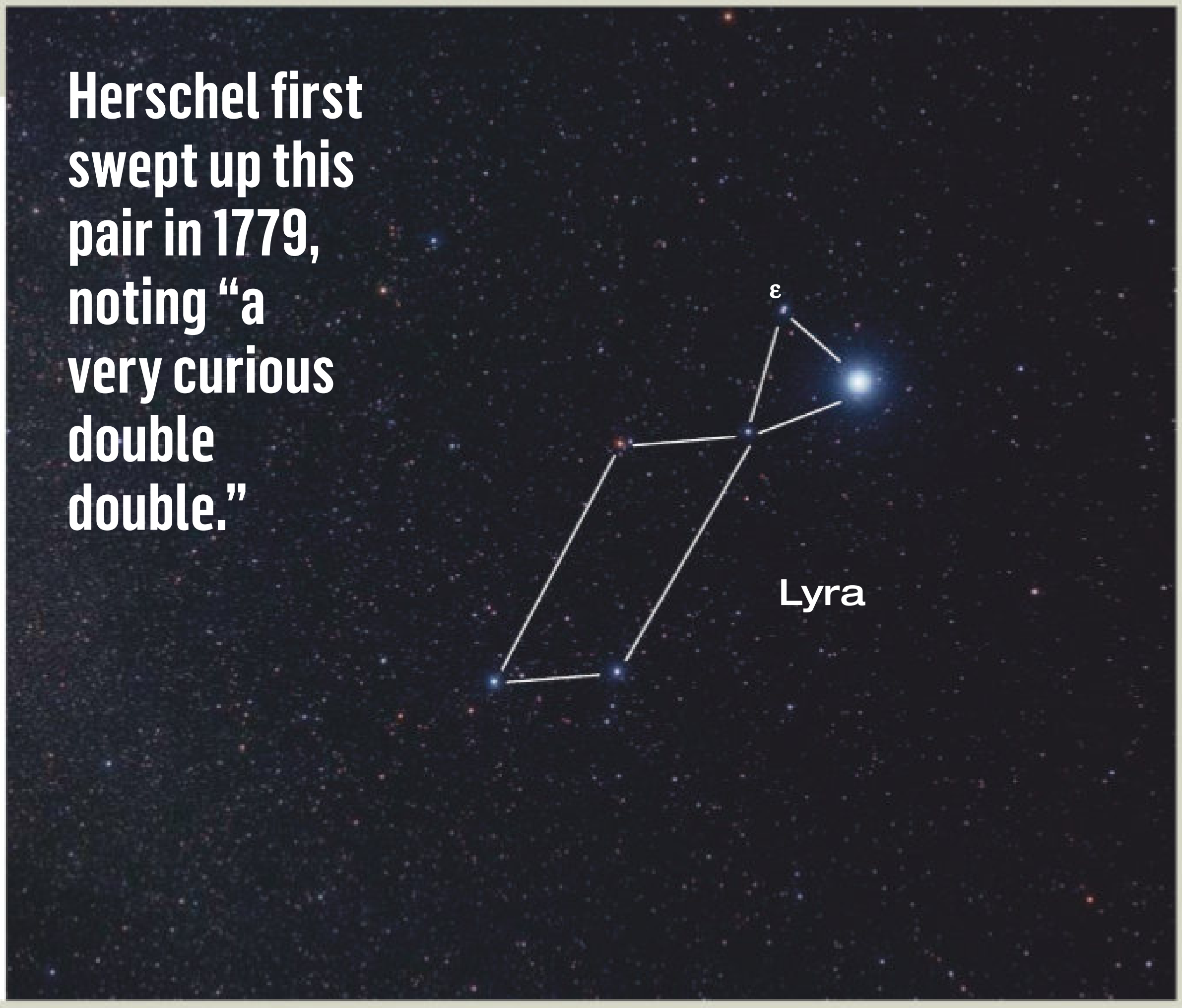
Shifting the view from Epsilon Lyr eastward to Deneb and then going south by about 30° lands one in the small but conspicuous constellation of Delphinus. The tip of the Dolphin's nose is **Gamma Delphini** and a mere ¼° to the southwest is **STF 2725** (Σ2725). These two binaries are grouped here because they can be resolved and viewed together in a 60× eyepiece field. They're a comfortable 15′ apart. In my notes I like to call them the Delphinus Double Double. This pair is certainly no Epsilon Lyrae Double Double, but it's in the same unique fraternity! The two doubles are about 20 light-years apart with different space motions and aren't physically connected. F. G. W. Struve, while observing Gamma Del in 1831, noted the separation to be 12″, but it has now closed to about 9″. It will continue to close for another 300 years (to 1.4″). STF 2725 is fainter, but both remain small-scope targets.











Touring Some Favorite Binaries

Object	RA	Dec.	Mag (A, B)	Spec (A, B)	Sep	PA	P (yrs)	Distance (l-y)
Castor	$07^h\ 34.6^m$	+31° 53′	1.9, 3.0	*A*1, *A*2	5.2″	53°	460	51
Sirius	$06^h\ 45.1^m$	–16° 43′	–1.5, 8.4	*A*1, *A*2	10.9″	72°	50.13	8.6
Gamma Vir	$12^h\ 41.7^m$	–01° 27′	3.5, 3.5	*F*0, *F*0	2.7″	0°	169	38
Alpha Her	$17^h\ 14.6^m$	+14° 23′	3.5, 5.4	*M*5, *G*8	4.6″	103°	3,600	360
70 Oph	$18^h\ 05.5^m$	+02° 30′	4.2, 6.2	*K*0, *K*4	6.5″	123°	88.4	16.6
Epsilon^1 Lyr	$18^h\ 44.3^m$	+39° 40′	5.1, 6.1	*A*3, *F*0	2.3″	345°	1,804	162
Epsilon^2 Lyr	$18^h\ 44.4^m$	+39° 37′	5.2, 5.4	*A*6, *A*7	2.4″	75°	724	156
Gamma Del	$20^h\ 46.7^m$	+16° 07′	4.4, 5.0	*K*1, *F*7	8.9″	265°	3,249	101
STF 2725	$20^h\ 46.2^m$	+15° 54′	7.5, 8.2	*K*0, *K*0	6.1″	12°	2,945	119

Position angles and separations are calculated for 2018. Right ascension and declination are for equinox 2000.0.

Epilogue

Although viewing nine objects in one observing session hardly qualifies as a marathon, there are two periods in the year when all nine binaries can be seen in one night. The most comfortable window is from mid-May to mid-June, picking up Castor as it sets and ending with Gamma Del and STF 2725 before midnight. The second window is the month of November, when Alpha Her sets soon after dusk and Gamma Vir rises at about 4 a.m.

Happy touring!

■ **PHILLIP KANE** has been reduced (by old age) to using a 4-inch refractor, because it's the only scope he has that he can still carry outside. But it's a great aperture for viewing more double stars than he can get through. He has no complaints. Phil's email address is **icycomet1944@gmail.com**.

BINARY ORBIT CALCULATOR. The author used Brian Workman's calculator along with the Sixth Catalog of Orbits of Visual Binary Stars. You can find the calculator at **https://is.gd/bincalc**.

 by Benjamin Skuse

A Relatively Important

A century ago an eclipse revealed to the world that the universe bends to Einstein's whim.

On July 2, 2019, a total solar eclipse will cut a swathe across South America, shrouding the land in darkness. As always happens during these rare events, eclipse chasers, astronomers, and interested members of the public will gather wherever they can find a good viewing spot to see our star slowly drift behind the Moon and reveal its mesmerizing corona.

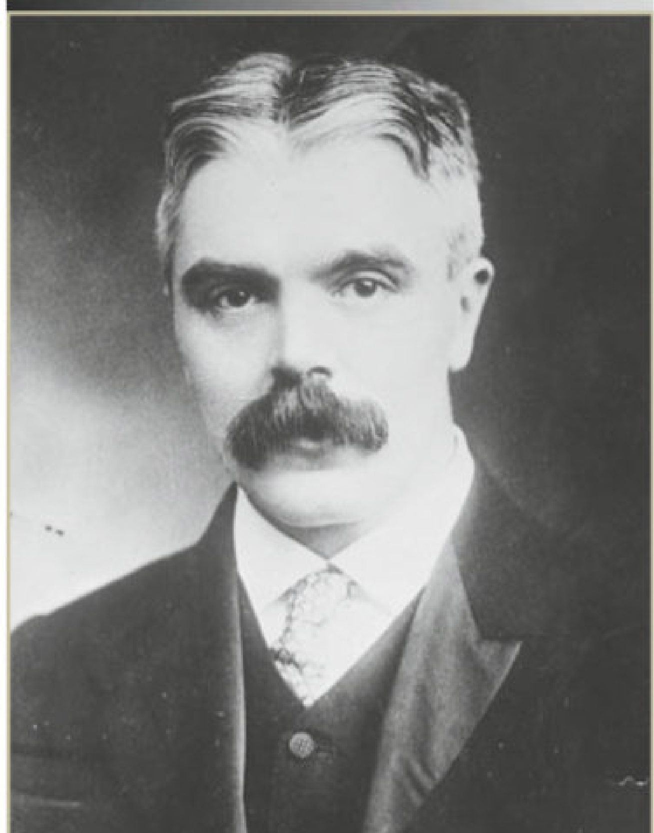
It's a total solar eclipse just like any of the 11 other ones that have occurred this past century, but for the fact that it will happen close to sunset, creating a colorful backdrop and potentially a unique U-shape in the atmosphere from the lunar shadow. Yet this isn't the reason eclipse tickets at the European Southern Observatory's La Silla Observatory sold out months in advance. The reason is that this is the "Einstein eclipse," occurring a little more than 100 years after the eclipse that helped confirm relativity and changed the world's conception of the universe forever.

No eclipse has had a greater impact on science than the one that occurred on May 29, 1919. Its studious observation helped overturn Newton's law of universal gravitation, which had stood as the generally accepted theory to explain gravity for more than 200 years. And it ushered in a new era that continues to this day, in which Albert Einstein's general theory of relativity awkwardly sits alongside quantum theory to represent our deepest understanding of the laws of nature.

Although a lone result can never prove or disprove a scientific theory, the 1919 eclipse was a watershed moment in history. It captured the imagination of both the scientific community and the public throughout the world, propelling Einstein from obscurity to international celebrity in the process. Why did it have such a big impact?

In 1915, the same year poison gas was introduced to the Western Front during World War I, Einstein published four revolutionary papers that presented general relativity to the

▶ **THE FALL GUY** Arthur Stanley Eddington was Chief Assistant at the Royal Observatory, Greenwich, from 1906 to 1913, after which date he became Plumian Professor of Astronomy and Director of the University Observatory at Cambridge. He specialized in stellar structure and was the first scientist to predict that nuclear fusion was the source of the Sun's energy. But he worked more broadly throughout his career on relativity theory, stellar motion, and the philosophy of physical science. Despite his strong reputation as an astronomer, some of his colleagues doubted the 1919 results that supported Einstein's predictions.



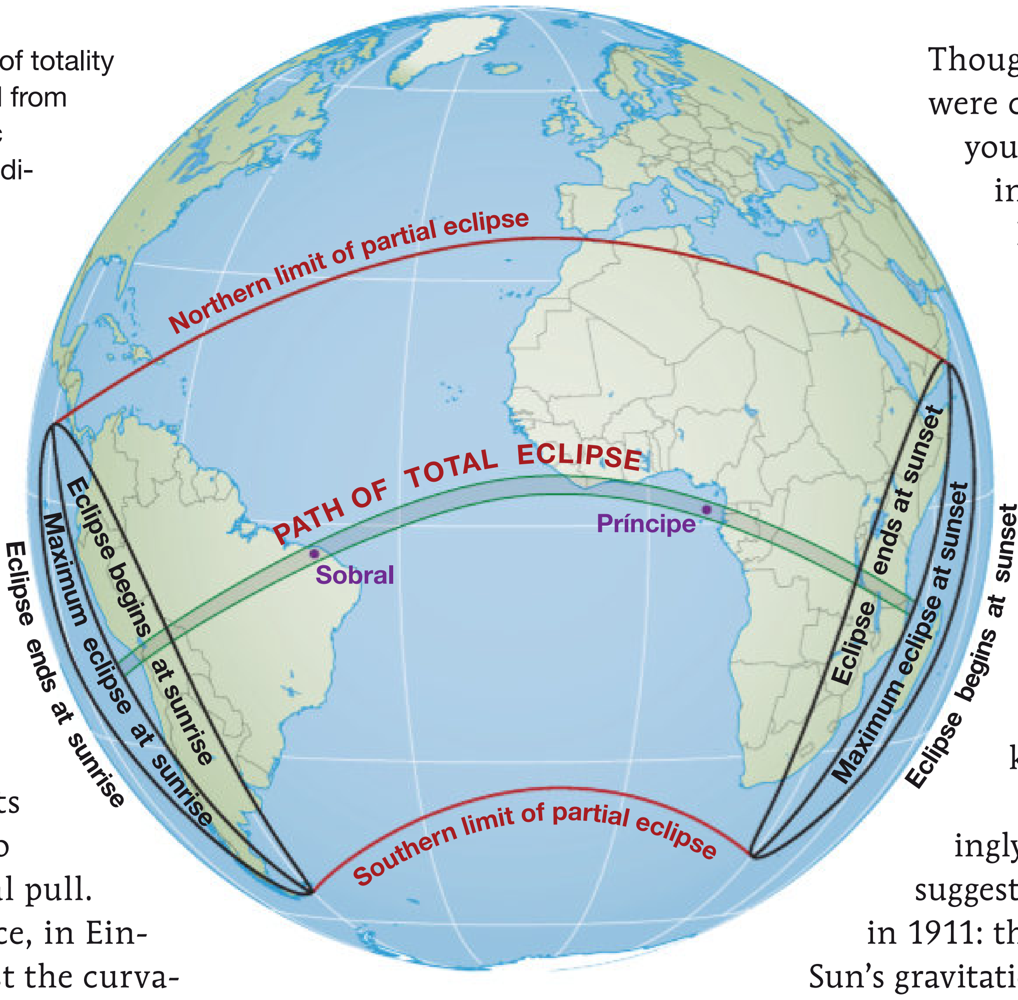
▶ **THE SKEPTIC** Frank Watson Dyson, Astronomer Royal for Scotland from 1905 to 1910 and Astronomer Royal and Director of the Royal Observatory, Greenwich, from 1910 to 1933, was a talented mathematician. He studied stellar motion throughout his career, but he is perhaps best known for his observation of total solar eclipses. He joined eclipse expeditions in 1900, 1901, and 1905, led the 1919 expeditions remotely from the UK, and also led official observations of a 1927 eclipse over Wales and northern England. Although an enthusiastic participant in planning for the 1919 eclipse, he thought the observations would prove Einstein wrong.

Eclipse

CROWNING GLORY
A Brazil-based international observing team, which included British astronomers Andrew Crommelin and Charles Davidson, used a 4-inch refractor with a focal length of 19 feet to capture this image of the Sun's corona during the total solar eclipse on May 29, 1919.

ECLIPSE: SSPL / GETTY IMAGES; EDDINGTON: LIBRARY OF CONGRESS PRINTS & PHOTOGRAPHS DIVISION / LC-DIG-GGBAIN-38064; DYSON: LIBRARY OF CONGRESS PRINTS & PHOTOGRAPHS DIVISION / LC-DIG-GGBAIN-30244

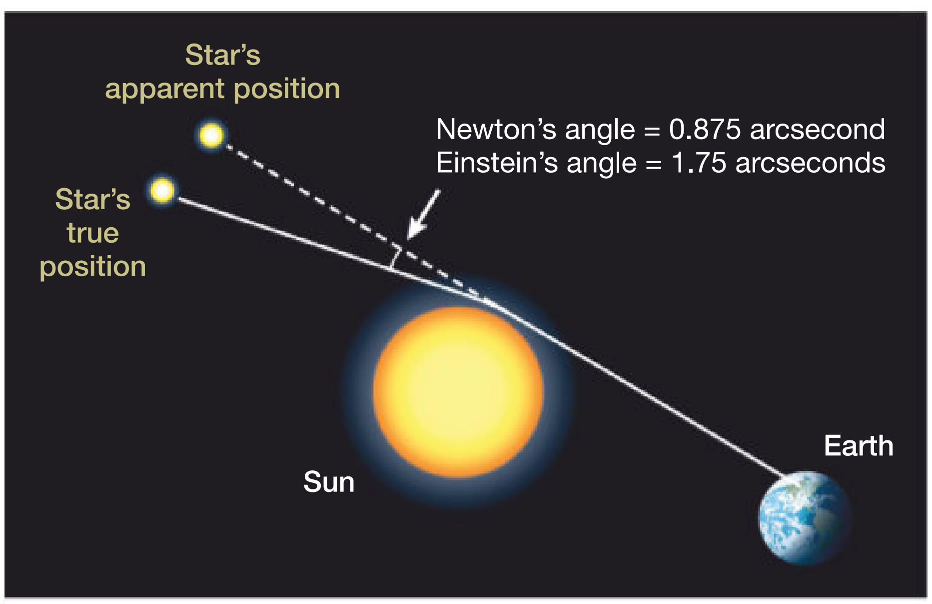
▶ **PATH TO SUCCESS** The path of totality for the 1919 solar eclipse reached from South America across the Atlantic Ocean to Africa. The eclipse expeditions organized by Dyson and Eddington traveled to determine what effect, if any, was produced by the Sun's gravity on the path of a star's light.



world. In them, he added to his special theory of relativity (which revealed how space and time are not fixed and instead part of the same thing — spacetime) by showing that spacetime is connected to matter. More massive objects bend spacetime more and so have a stronger gravitational pull. No longer a Newtonian force, in Einstein's world gravity was just the curvature of spacetime.

To put his mind-bending theory on firm footing, in one of the 1915 papers Einstein solved a mysterious flaw in Newton's perfect clockwork universe that had long puzzled astronomers. Like all planets, Mercury moves in an ellipse around the Sun, and this ellipse slowly rotates, or precesses, in space over time. Newton's theory underestimated this precession by a tiny amount, and despite numerous attempts nothing could make the observed orbit fit the theory. But when Einstein calculated Mercury's precession using general relativity, the match was perfect.

▼ **MIND-BENDING THEORY** If Einstein's theory of relativity was correct, any light grazing the Sun's disk would be bent by gravitational lensing. By comparing the positions of stars during a total eclipse — when the Sun's light would be blocked by the Moon, making background stars visible during the day — with where they would normally appear at night, Eddington and Dyson could measure how much starlight was bent as it passed the Sun, bringing them one step closer to confirming or disproving Einstein's theory.



Though an impressive result, few were convinced by it. "It was what you might call a retrodiction instead of a prediction," says Daniel Kennefick (University of Arkansas), a leading historian of 20th-century relativity and astronomy. "I think it suffered in people's minds because most people at that time didn't understand the theory very well and felt Einstein may have trimmed his calculation to fit the result because he knew the result."

A more pleasing and seemingly unbiased test was actually suggested by Einstein years before, in 1911: the deflection of light by the Sun's gravitational field. As early as 1801, German astronomer Johann Georg von Soldner worked out that light grazing the Sun's disk is bent by gravitational acceleration. The figure he arrived at was 0.84 arcsecond (a miniscule 0.00023 degree). Without knowledge of this previous calculation, Einstein did the same sums in the context of his special theory of relativity and arrived at 0.83 arcsecond. Later, more accurate calculations showed that both von Soldner and Einstein should have calculated the angle as 0.875 arcsecond. But other interpretations such as a competing relativistic theory by Finnish theoretical physicist Gunnar Nordström suggested light would not be bent by the Sun at all.

To discount these alternative theories, Einstein said that all the astronomical community needed was an opportunity to blot out the Sun to see the starlight grazing its disk: an eclipse. If light did bend, stars positioned on the sky close to the Sun would appear to be in a slightly different position to where they would normally appear, and that slight difference could be measured.

Bold attempts were made to measure light bending during eclipses in Brazil (1912) and Russia (1914). But blighted by weather and war, they were ultimately unsuccessful. And it was lucky for Einstein that they were. In 1915, while putting the finishing touches on general relativity, he realized that his calculation of light bending neglected the effect of the Sun distorting spacetime itself. Rerunning the numbers, he found the deflection would be double his first estimate — 1.75 arcseconds. Had any of these early expeditions been successful and shown a large bending effect before general relativity had been formulated, Einstein's position in the annals of history might have been very different.

There was now a clear difference between Einstein's and Newton's light-bending predictions, making the eclipse test the best chance of settling the issue at the time. But with

ECLIPSE PATH: GREGG DINDERMAN / *S&T*; LIGHT BENDING: LEAH TISCIONE / *S&T*

the planet busy fighting World War I, eclipse viewing opportunities in 1916 and 1918 came and went. As a result, when British astronomers, including the already renowned Arthur Stanley Eddington, set out from Liverpool in March 1919 to chase an eclipse — just four months after the armistice was signed between the Allies and Germany — there was everything to play for.

Eddington, then Director of the Cambridge Observatory, had probably heard of the eclipse light-bending experiment, and maybe even Einstein's work on special relativity, as early as 1912. He was attempting to study the solar corona during the eclipse in Brazil at the same time an Argentinian team was scrambling and ultimately failing to measure light bending, and tongues likely wagged. However, his first proper introduction to relativity came through a friendship with a Dutch astronomer. In 1915, Willem de Sitter sent Eddington the only copies of Einstein's papers to reach Britain during the war.

Though a shy and reserved man, Eddington was a persuasive writer and orator, and he soon became a powerful champion of Einstein's theory. But he faced a wall of opposition from the scientific establishment in Britain. "Astronomers were used to the fact that there had been many challengers to Newton's theory," says Kennefick. "There had been other moments when it looked like Newton's theory might have something wrong with it or might fail on experimental tests, but it had never worked out that way for over 200 years."

His enthusiasm did, however, persuade friend and Astronomer Royal Sir Frank Watson Dyson to propose the 1919 expedition at the height of conflict with Germany in 1917. Dyson argued that the 1919 eclipse was a unique opportunity to test relativity, given the Sun would be close in the sky to the bright Hyades star cluster. At least that was the official story, because Dyson also saw the expedition as a gilt-edged opportunity for his friend and staunch pacifist Eddington to avoid the labor camps for conscientious objectors to the war.

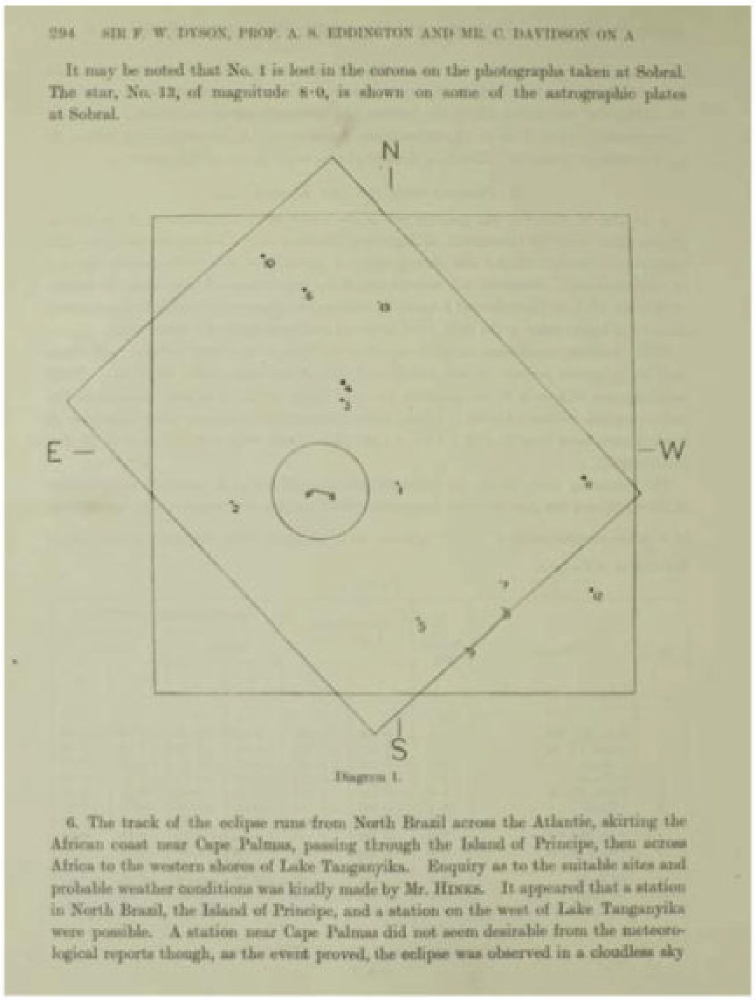
As the dust finally settled on the battlefields of Europe in November 1918, Dyson and Eddington had just enough time to prepare the eclipse expeditions. They hastily gathered instruments and equipment, and cobbled together a small team. Dyson arranged for Andrew Crommelin and Charles Davidson, an assistant and computer at the Royal Observatory, Greenwich, respectively, to head to Sobral, about 50 miles inland from the Brazilian coast. Meanwhile, Edwin Cottingham, an experienced instrumentalist, would accompany Eddington to Príncipe, an island off the coast of West Africa.

Crommelin and Davidson's sea voyage to Brazil with 14 crates of heavy equipment in tow took two weeks. After landing in Pará in northern Brazil, they had a month's delay before they could travel to Sobral, during which they saw "1000 miles of the luxuriant forests of the Amazon, with their denizens of gorgeous plumage." When they then arrived in Sobral, they started setting up the equipment on a racecourse in the town ready for the eclipse. Meanwhile, Eddington and Cottingham's journey was a brutal six and a half weeks by steamship, held up by returning troops from the war, and only made tolerable by the copious amounts of bananas — a highly

▼ **TREMENDOUS TEAMWORK** Researchers from Brazil, the UK, and the U.S. came together in Sobral, Brazil, to observe the 1919 total solar eclipse. Here, members of the Eclipse Commission are shown posing beside Sobral's Patrocínio Church. From left to right are Luiz Rodrigues (National Observatory, Brazil), Theophilo H. Lee (Geological and Mineralogical Service of Brazil), Daniel Wise (Carnegie Institution of Washington), Henrique Morize (Director, National Observatory, Brazil), Charles Davidson (Royal Observatory, Greenwich), Andrew Crommelin (Royal Observatory, Greenwich), Allyrio de Mattos (National Observatory, Brazil), Andrew Thomson (Carnegie Institution of Washington), Domingos Costa (National Observatory, Brazil), Lélio Gama (National Observatory, Brazil), Antônio C. Lima (National Observatory, Brazil), and Primo Flores (National Observatory, Brazil).

COURTESY OF THE OBSERVATÓRIO NACIONAL, RIO DE JANEIRO, BRAZIL

▶ **STELLAR CHOICES** Dyson and Eddington calculated that 12 stars, with photographic magnitudes ranging from 4.5 to 8.0, would be detectable during the eclipse. One of the target stars was lost to the Sun's corona at Sobral, but an additional star, labeled "13" on this diagram, was captured on several of the exposed plates.


294 SIR F. W. DYSON, PROF. A. S. EDDINGTON AND MR. C. DAVIDSON ON A

It may be noted that No. 1 is lost in the corona on the photographs taken at Sobral. The star, No. 13, of magnitude 8·0, is shown on some of the astrographic plates at Sobral.

Diagram 1.

6. The track of the eclipse runs from North Brazil across the Atlantic, skirting the African coast near Cape Palmas, passing through the Island of Principe, then across Africa to the western shores of Lake Tanganyika. Enquiry as to the suitable sites and probable weather conditions was kindly made by Mr. Hinks. It appeared that a station in North Brazil, the Island of Principe, and a station on the west of Lake Tanganyika were possible. A station near Cape Palmas did not seem desirable from the meteorological reports though, as the event proved, the eclipse was observed in a cloudless sky

exotic delicacy to a ration-weary Englishman at the time. Given Eddington's Quaker beliefs — the Quakers started the campaign to abolish slavery in Britain in the 18th century — the two scientists surprisingly chose Roça Sundy, a former Portuguese slave plantation that may have still been using forced labor, as the spot for their observations.

After a month tinkering with their equipment in blistering heat, the day of the eclipse finally came. In the morning, the tension was palpable as weather threatened to ruin both experiments. The Brazil team was fortunate, with the clouds eventually shifting to leave clear skies throughout the six minutes of totality. But in Príncipe Eddington was not so lucky. A menacing morning storm only dissipated enough during the last stages of the eclipse for any stars to be visible at all. Not that Eddington noticed, as he was too busy to even look up: "We have no time to snatch a glance at it," he recalled. "We are conscious only of the weird half-light of the landscape and the hush of nature, broken by the calls of the observers, and the beat of the metronome ticking out the 302 seconds of totality."

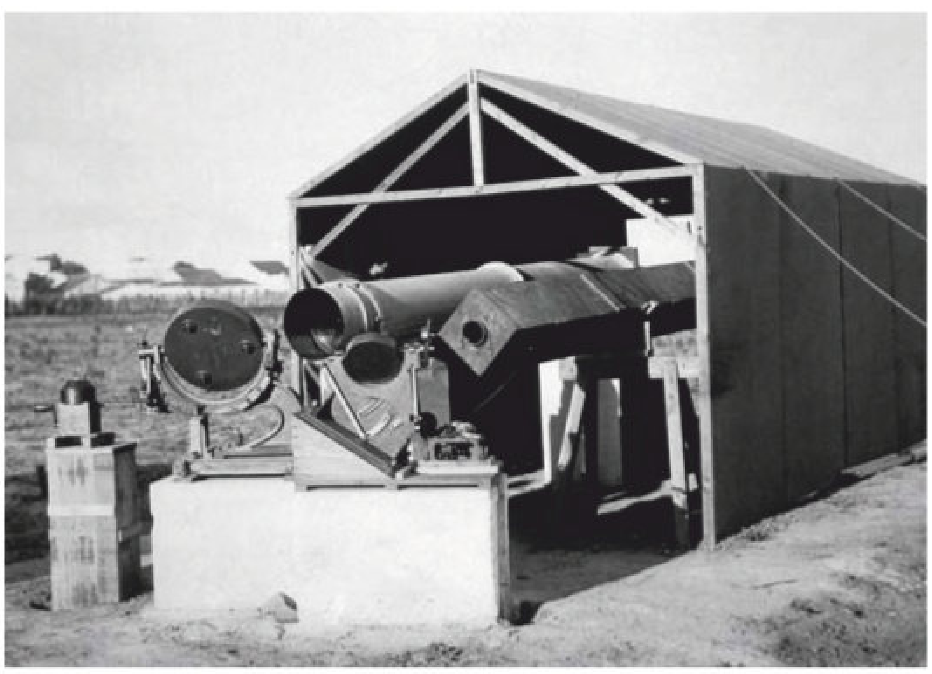
The Príncipe and Sobral teams arrived back in England in July and August and then, alongside Dyson, painstakingly analyzed the photographs from the twin expeditions. In November 1919, Dyson, Crommelin, and Eddington presented the results to the British astronomical community and dropped a bombshell: The eclipse revealed that light was bent just as Einstein's theory predicted.

Far from the whooping-and-hollering reaction you might expect for such Earth-shattering results, the news was met with ambivalence by the crowded room of experts. The likes of J. J. Thomson — the discoverer of the electron — were convinced by Dyson's presentation, declaring that "this is the most important result obtained in connection with the theory of gravitation since Newton's day." But various views swirled around the room, with some struggling to understand the theory, others highlighting evidence from other experiments that contradicted the results, and many calling for further tests.

Nevertheless, the press immediately latched on to the story. The next day's triple-stacked headline in *The Times of London* read: "Revolution in Science; New Theory of the Universe; Newtonian Ideas Overthrown." Similar headlines emblazoned the front pages of the world's newspapers in the days that followed. To borrow a quote from astronomer W. J. S. Lockyer in the *New York Times* front-page story, that the theory did "not personally concern ordinary human beings" didn't matter. The audacity of the experiment, the clear evidence it produced, the scientific revolution relativity promised, and the yearning for a positive story after four years of brutal war were more than enough — Einstein's iconic status was sealed.

Over the next century, scientists undertook a raft of further tests of general relativity. Every time it passed with flying colors. Einstein's theory is now part of the scientific furniture, our basis for understanding space, time, and gravity. Yet still today, the 1919 eclipse results — the catalyst for all this success — are often brought into question.

Philosophers John Earman (University of Pittsburgh) and Clark Glymour (Carnegie Mellon University) produced a detailed analysis of the 1919 eclipse expeditions in 1980. Though they presented a balanced view, their work brought



◀ **EQUIPMENT ASSEMBLED** The eclipse team set up two heliostats with moveable mirrors (at left and center of image) on the racecourse of the Sobral Jockey Club. The 16-inch heliostat directed images of the eclipsed Sun into a horizontal astrographic telescope stopped down to 8 inches, while the 8-inch heliostat was paired with a 4-inch lens mounted in a square wooden tube, 19 feet in length, that held 10 x 8-inch photographic plates. No photos of the Príncipe expedition exist, but the team used a 16-inch heliostat and telescope identical to the one in Sobral.

DIAGRAM: *PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY OF LONDON. SERIES A, CONTAINING PAPERS OF A MATHEMATICAL OR PHYSICAL CHARACTER* (1920); EQUIPMENT: SSPL / GETTY IMAGES up a number of doubts about Eddington's interpretation of the eclipse results that had been whispered through physics departments for decades.

The whispers suggested that Eddington fudged the results in favor of Einstein's predictions by discarding contradictory measurements from one of the Sobral telescopes. He did this for two reasons: He was an obstinate believer in relativity, and he wanted scientists in Britain and Germany to reconcile after the hostility of war. The former led to confirmation bias, while the latter predisposed him to forcing a British proof on a German theory.

Since Earman and Glymour's paper, these rumors have taken on a life of their own, painting Eddington as a master manipulator, everywhere from online forums to popular science books. But Kennefick, who published an exhaustive study of the data-fudging allegations in 2012, is adamant that Eddington didn't "cook the books." He assessed the reasoning behind the eclipse team's rejection of data from one of the two telescopes in Brazil, finding their arguments "very convincing." He also re-examined an obscure paper from the Greenwich Observatory in the 1970s in which a team remeasured the 1919 photographic plates and confirmed Dyson and Eddington's conclusions. But one of his most persuasive arguments is also his simplest: "Eddington didn't make those data analysis decisions," he says. "Dyson did, and he was skeptical about the theory and thought it was probably going to be wrong." Why would a skeptic fudge results in favor of relativity?

Arguments about Eddington's status as the hero or villain of the 1919 eclipse story will no doubt rumble on. But what is clear is that the 1919 eclipse was one of those rare occasions in science where something big happened at one decisive moment. Though it didn't truly confirm relativity — no single experiment could — it brought Einstein and his ideas to the attention of the world, and for that we should all celebrate the centenary of the eclipse that opened our eyes to how the universe truly works.

■ **BENJAMIN SKUSE** is a science writer based in Somerset, UK, just a few miles down the road from Weston-super-Mare, Eddington's childhood hometown.

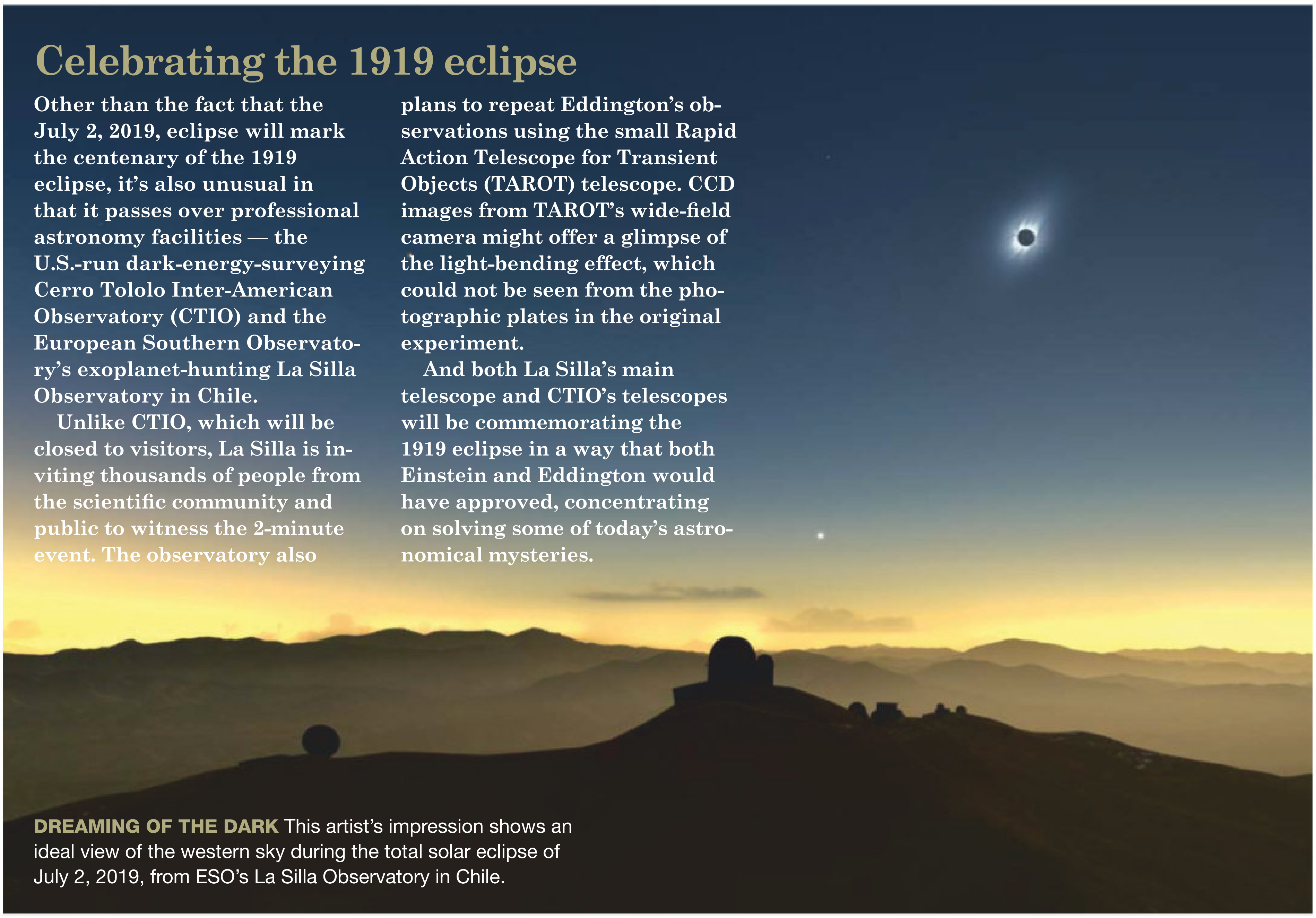
FURTHER READING: To learn more about the 1919 eclipse expeditions and their enormous impact in greater detail, read *No Shadow of a Doubt: The 1919 Eclipse that Confirmed Einstein's Theory of Relativity*, by Daniel Kennefick (Princeton University Press, 2019).

Celebrating the 1919 eclipse

Other than the fact that the July 2, 2019, eclipse will mark the centenary of the 1919 eclipse, it's also unusual in that it passes over professional astronomy facilities — the U.S.-run dark-energy-surveying Cerro Tololo Inter-American Observatory (CTIO) and the European Southern Observatory's exoplanet-hunting La Silla Observatory in Chile.

Unlike CTIO, which will be closed to visitors, La Silla is inviting thousands of people from the scientific community and public to witness the 2-minute event. The observatory also plans to repeat Eddington's observations using the small Rapid Action Telescope for Transient Objects (TAROT) telescope. CCD images from TAROT's wide-field camera might offer a glimpse of the light-bending effect, which could not be seen from the photographic plates in the original experiment.

And both La Silla's main telescope and CTIO's telescopes will be commemorating the 1919 eclipse in a way that both Einstein and Eddington would have approved, concentrating on solving some of today's astronomical mysteries.



DREAMING OF THE DARK This artist's impression shows an ideal view of the western sky during the total solar eclipse of July 2, 2019, from ESO's La Silla Observatory in Chile.

M. DRUCKMÜLLER / P. ANIOL / K. DELCOURTE / P. HORÁLEK / L. CALÇADA / ESO by Peter Tyson

The Allure of Betelgeu

LIKE A SORE THUMB Betelgeuse (upper right) stands out boldly from its blue-white Orion neighbors, including the three Belt stars (middle) and Rigel (lower left). Blazing its own path, the pulsating red supergiant seems to taunt us about when it will go supernova.

Astronomers are itching to know when this red supergiant will go supernova, but a clear answer eludes them.

Betelgeuse, that orange beacon shining from the shoulder of Orion, the Hunter, is one of the best-studied stars out there. Yet despite all we've learned, virtually everything we know — or think we know — about this aged, highly volatile red supergiant remains uncertain. This includes everything from its distance and mass to the question that astronomers can't reliably answer without getting a better handle on those and other basic stellar parameters: When will this amber-glowing behemoth go supernova?

The suspicion is, it could explode anytime. Increasingly frustrated by the uncertainties, astronomers are trying every tool in their toolkits to improve their understanding of this nearby supernova progenitor.

What We Know

Betelgeuse — Alpha (α) Orionis — was born roughly 10 million years ago, condensing out of a molecular cloud probably in the area of Orion's Belt. It's thought to be a runaway star from that region, possibly forced out by a supernova. Today Alpha Ori is hurtling away from the Belt at a speed of 30 kilometers per second (67,000 mph).

> "There's a real scientific issue here: We really *are* ignorant of when it's going to blow up. What can we possibly do about that?"

Betelgeuse is a star of superlatives. It's the ninth-brightest star in the night sky, but if we could perceive all the wavelengths of radiation it emits, it would be the brightest star of all. With an average angular diameter of about 44 milliarcseconds — equivalent to a lunar crater 80 meters wide as seen from Earth — Alpha Ori is also one of the largest stars in our sky. It's so near to us that we can actually resolve its surface like we can that of our own Sun. With sophisticated enough scopes, the red supergiant appears as a disk rather than a point, and like a planet it doesn't twinkle. It's not just close but *big*. If Betelgeuse were placed at the center of our solar system, it would extend out beyond the asteroid belt, engulfing Mercury, Venus, Earth, Mars, and possibly even Jupiter.

The star is most likely burning helium in its core, with a surrounding shell that's consuming hydrogen. Beyond that shell and all the way to its distant surface lies an envelope of churning convective cells constituting a hugely extended atmosphere. At some point, Betelgeuse will have burned up all the helium in its core and will begin fusing heavier elements: carbon, oxygen, silicon, and so on. When only iron remains in its core, the star's explosive demise will be imminent (see sidebar on page 39).

When Alpha Ori eventually does go supernova, it will be as bright as the quarter or even full Moon, perhaps for weeks on end. We'd be able to read outdoors at night by its light. Not all astronomers would likely welcome that. "It will ruin nighttime astronomy for a few months when it happens," says Edward Guinan (Villanova University).

Distance

When studying a star, almost the first thing astronomers want to know is: How far away is it? Distance provides the key to unlocking luminosity and, beyond that, other critical factors such as radius, age, and mass. Without such basic elements nailed down, guessing when a supergiant like Betelgeuse will go supernova is a shot in the dark.

To gauge the distance of a star, astronomers often rely on *parallax*. As Earth orbits the Sun, the angle of our view of a nearby star changes slightly. The star appears to shift its position by a fraction of an arcsecond against the backdrop of more distant stars. Astronomers can use that, along with the baseline of Earth's orbit, to measure a star's distance.

Parallax works only for relatively nearby objects. While Alpha Ori is close by astronomical standards, getting a precise parallax for it is challenging, because that measurement is small compared to the supergiant's angular diameter. In other words, Betelgeuse is just too darn big to make this method useful. Also, the star might not even have a symmetrical shape, and the bright spots on its photosphere come and go in various positions, making it hard to locate its center.

Other common tactics for assessing distance also offer no help. Astronomers often use a companion star to aid in estimating distance, as was done with Polaris (*S&T:* March 2019, p. 14). But Alpha Ori has no known companions. The star is also too bright for Gaia, the European Space Agency satellite that is successfully fixing the distance to a billion stars and other celestial objects (*S&T:* March 2019, p. 26).

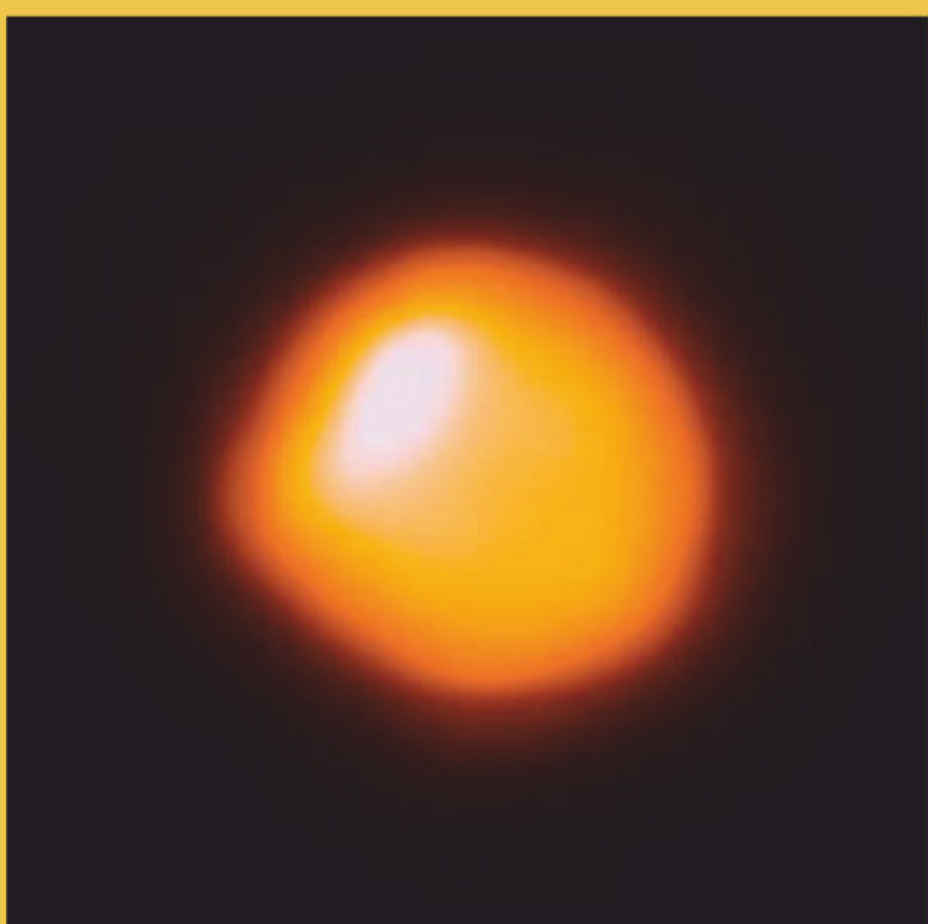
In 2017, Graham Harper (University of Colorado) and colleagues published one of the most thoroughly calculated distance estimates. The team combined data from four different instruments: the Hipparcos satellite, the European Southern Observatory's Very Large Telescope, and two arrays of radio telescopes, e-MERLIN and ALMA. Their study put the distance at about 222 parsecs, or 717 light-years. Yet Harper and his coauthors admit they could be off by 20%. "It is frustrating that its parallax is currently so poorly constrained, which severely limits what can be gleaned from all the research effort into this system," they lament in the 2017 paper.

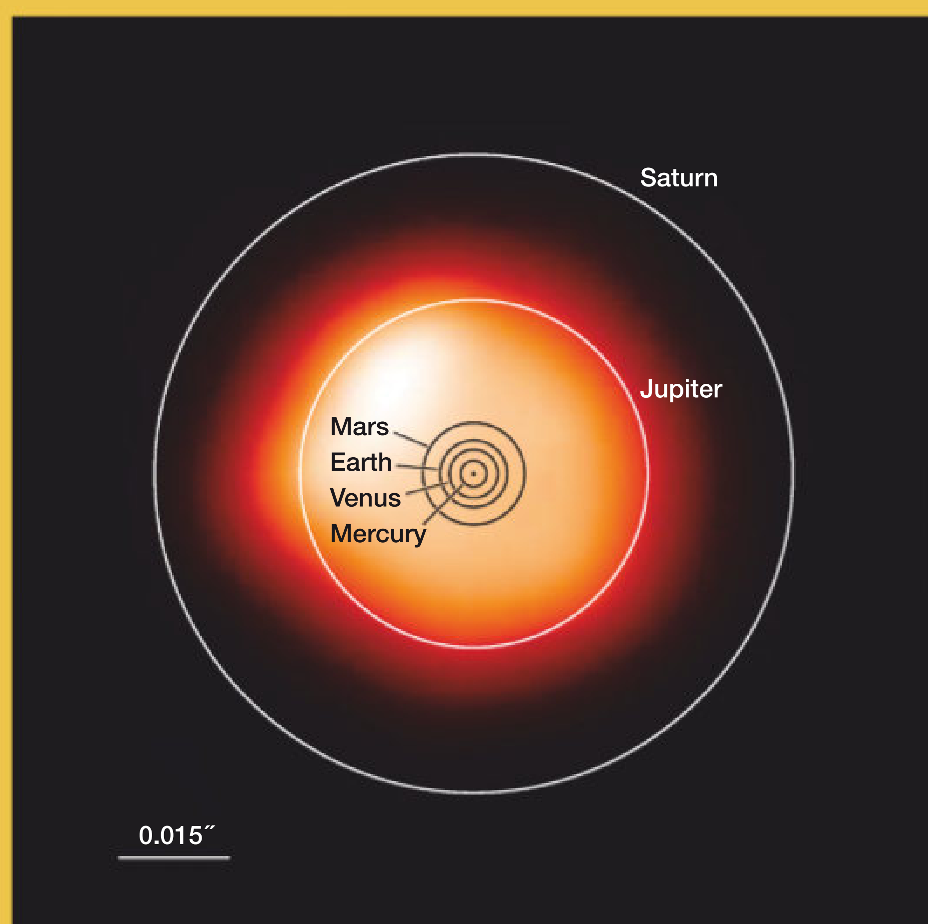
Radius

Diameter scales with distance linearly, so our grip on Alpha Ori's radius has that same 20% uncertainty. Plus, Betelgeuse has shells of gas and dust that its strong stellar wind continuously blows out. These make it difficult to define the star's visible surface.

But that Betelgeuse is mind-bendingly huge is not in question. Estimates of radius over the years have ranged between 3 and 5 astronomical units or more. (One a.u. is the mean Earth-Sun average distance, or about 150 million kilometers.) A recent estimate put the radius — with the expected large

▼ **SUPERGIGANTIC** Taken by ALMA in 2015, this picture *(left)* of hot gas in the star's lower chromosphere is the highest-resolution image of Betelgeuse currently available. The overlay of planet orbits *(right)* shows how far the star would reach into our solar system if it stood in place of the Sun.





ALMA (ESO / NAOJ / NRAO) / E. O'GORMAN / P. KERVELLA (2) error factor — at 955 times that of the Sun. (This is slightly larger than the 2016 estimate we use at right.) That gives us a star that might be 1.3 *billion kilometers* across.

Brightness and Mass

That 20% uncertainty in distance doubles with how much light the star puts out. "That's a 40% uncertainty in the luminosity, and that gets to be big enough you can drive a model truck through it," says theoretician Craig Wheeler (University of Texas, Austin).

Accurately determining luminosity is knotty even if astronomers are confident about the distance. "It's *really* hard to figure out exactly how luminous a star is," says Emily Levesque (University of Washington). Beyond knowing how far away it is, researchers need a solid fix on a star's temperature. We have that for Betelgeuse, which is known to be relatively cool, with a surface temperature of about 3500K (5800°F) versus the Sun's 5778K (10,000°F). But they also need a grip on how the temperature affects the light they get in bluer versus redder wavelengths (hotter stars look bluer). Plus they need to understand how much dust encircles the star, because dust can block and redden some of the light.

Intrinsic brightness offers insight into stellar mass, which itself helps reveal a star's evolutionary history and expected lifetime. As it stands, Betelgeuse's absolute magnitude is thought to be about –6. That implies a minimum mass of at least 5 or 10 times that of the Sun, and current estimates put the star's mass at roughly 10 to 20 solar masses. Having luminosity and mass only ballparked further limits our chances of guessing when Betelgeuse will rip itself apart.

Rotation

Another complicating factor concerns the speed of Alpha Ori's rotation. In 1995, Andrea Dupree (Harvard-Smithsonian Center for Astrophysics, or CfA) and Ronald Gilliland (then Space Telescope Science Institute) used the Hubble Space Telescope's Faint Object Camera to take an ultraviolet picture of Betelgeuse. It was the first direct image of a stellar surface other than the Sun's. In that study and a later one with Han Uitenbroek (then CfA), the pair determined that Betelgeuse's rotational velocity was about 15 km/s. That's extraordinarily high, even close to break-up speed, Wheeler says. Yet recent observations with ALMA, the Atacama Large Millimeter/submillimeter Array, appear to confirm that rotational speed.

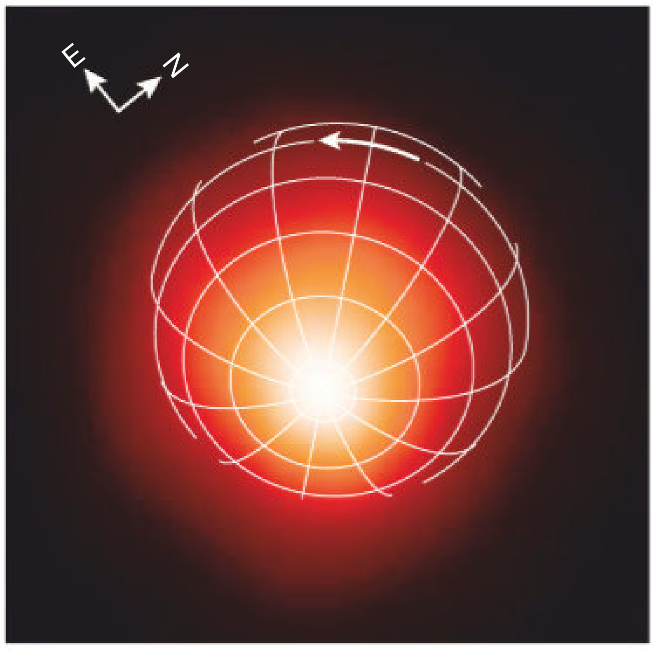
Wheeler tried to match that velocity in models he created with a group of his Texas undergraduates. But he and his students could compute a velocity only 1⁄50 of what Dupree's team had found. The only way they could get to 15 km/s in their models was by "inventing" a companion star that Betelgeuse swallowed earlier in its lifetime. If the companion was about one solar mass, being gobbled would pro-

"Most likely it's in helium core-burning and we still have, I'm sorry to say, 100,000 years to go."

▶ **OUR STELLAR CAST** In our three-part series we discuss Polaris, the Alpha Centauri system, and Betelgeuse. These stars span a range of sizes, shown to scale. Listed diameters ("D") are approximate and given as multiples of the Sun's diameter. We've included the Sun here for visual reference.

TERRI DUBÉ / S&T

▶ **SPINNING STAR** In this ultraviolet image of Betelgeuse, researchers have added a wire frame to give a sense of proposed rotation. They think the bright spot possibly coincides with the star's pole of rotation, though both the pole's position and the speed of rotation remain unconfirmed.



vide just the right amount of angular momentum, the team discovered, to spin up the star to 15 km/s.

But whether Betelgeuse ate a star is speculative, and those giant eddies regularly welling to the surface further muddy the picture. Spectra reveal those *supergranules*, as astronomers call such massive convection cells, have their own velocity associated with them. "You can see a blueshift in the upwelling stuff and a redshift in the downwelling stuff," Wheeler says, indicating movement towards or away from us, respectively. He wonders whether what Dupree and colleagues detected was the turbulent overturn of these eddies rather than the rotational velocity of the star itself.

Dupree wonders the same thing, and she plans to have another look. Last year, she began assembling an international team of researchers interested in Alpha Ori. She calls it "the MOB," for Months of Betelgeuse, denoting the timespan over which she and about 20 colleagues around the world hope to observe the star. Recently, she and the MOB were awarded a three-year program to use Hubble four times a year to obtain spatially resolved ultraviolet spectra across Betelgeuse's extended atmosphere. The spectra will enable the team to detect the star's atmospheric motions and possibly clarify the rotational uncertainty. That is, if she and the MOB come up with the same 15 km/s figure, it would bolster the possibility that it is indeed the star's speed of rotation. If the number differs significantly, it might be arising from the upwellings, which astrophysicists would expect to vary over time.

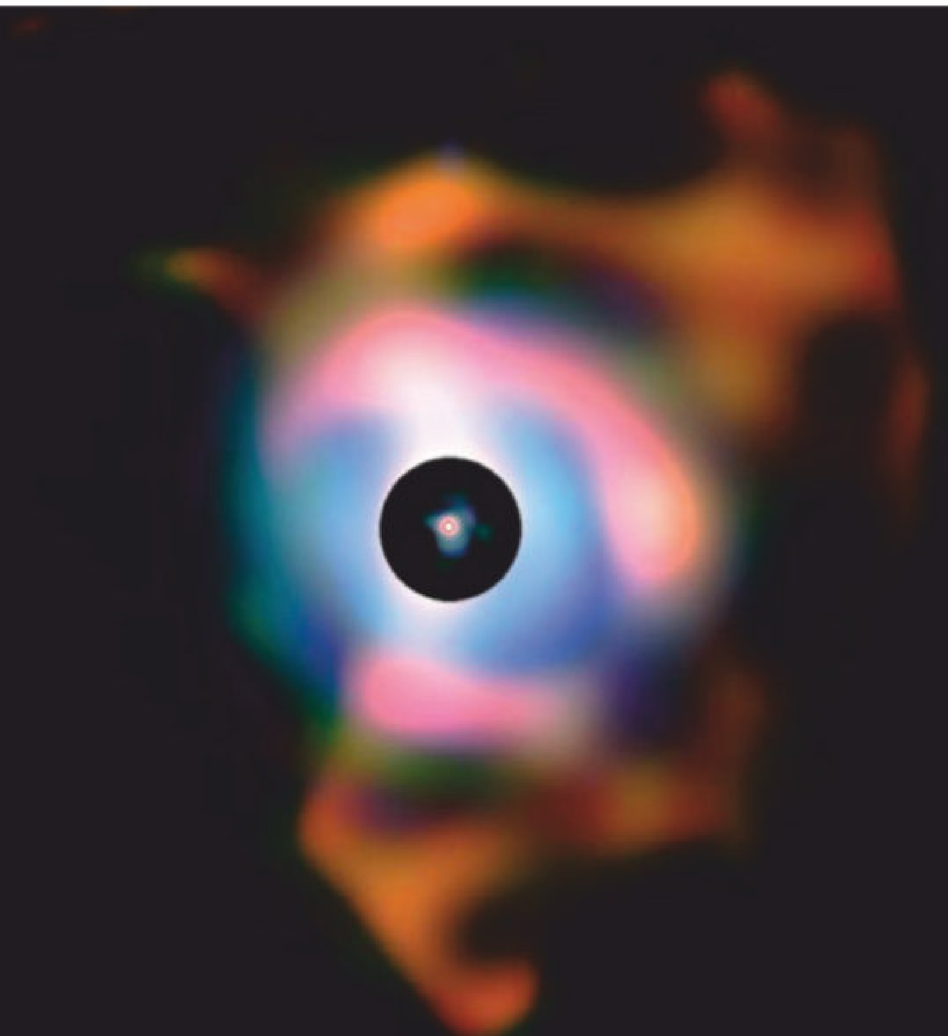
The MOB has other questions: Where exactly is the star's pole? What mix of hot and cold material does its atmosphere possess, and is the hot material coming from the supergranules? Does the mass the star loses on a continual basis shoot out from the poles or via the convection cells? How does that mass outflow relate to the circumstellar material?

"It's just amazing when you think about it how many techniques and technologies and instruments and everything have been pursuing this star," Dupree says. "We're trying to pull it all together."

Variability

Over a season, Betelgeuse typically varies by three-to-five-tenths of a magnitude, but its variability itself varies. This makes it challenging and often confusing to compare observations secured at different epochs. Guinan has done continuous photometry on the supergiant since 1980, working with former student Scott Wacker in the 1980s and ever

"Because it's so close, we can ask questions about Betelgeuse that we can't ask about other stars."



FLAMETHROWER This infrared image taken by the ESO's Very Large Telescope shows the nebula that surrounds Betelgeuse, created by gaseous material the star continuously sheds. The tiny red circle in the center represents the star's visible surface at about 4.5 times Earth's orbit. The black disk corresponds to a mask used to reveal the smaller nebula seen right around the star in an earlier observation.

ULTRAVIOLET IMAGERY: A.K. DUPREE & R.P. STEFANIK / *EAS PUBLICATIONS SERIES* 2013; NEBULA: ESO / P. KERVELLA since with Villanova colleague Rick Wasatonic. Over the years they've noted many random changes. The star once ceased varying altogether for several months, and Guinan wondered whether it might be getting ready to blow. The star's pulsation period, which normally lies between about 370 and 425 days, also varies.

Guinan and Wasatonic recently conducted a study of the supergiant's period going back to the 1800s to see if it has been increasing as the star gets bigger and redder. Rigel, Betelgeuse's blue-white Orion mate, usually outshines it, but between 1837 and 1840, Betelgeuse was the brighter of the two (hence its alpha designation). It might have experienced an outburst at that time, Guinan says, perhaps one that created the gaseous *bow shock* identified about 7 arcminutes from Alpha Ori in the direction the star is heading.

Evolutionary State

Most central to figuring how close to the end Betelgeuse might be is knowing where exactly it lies in its lifetime. But astronomers don't have tight constraints on that either. For years Wheeler, with a twinkle in his eye, has told his students that Betelgeuse could go anytime and that they should keep a watch on it and let him know if it starts to get bright. "After doing it for awhile, I realized, wait a minute, there's a real scientific issue here: We really *are* ignorant of when it's going to blow up. What can we possibly do about that?"

That realization led him, again with his University of Texas students, to explore whether *asteroseismology* could help astronomers probe the interior state of Alpha Ori (and, by extension, other red supergiants) and thereby give clues to its evolutionary state. Asteroseismology involves analyzing the resonant frequencies of *acoustic waves* that arise deep within stars. In theory, such studies can provide insight about stellar interiors in the same way that seismic studies reveal details of Earth's subsurface (*S&T:* Jan. 2018, p. 22).

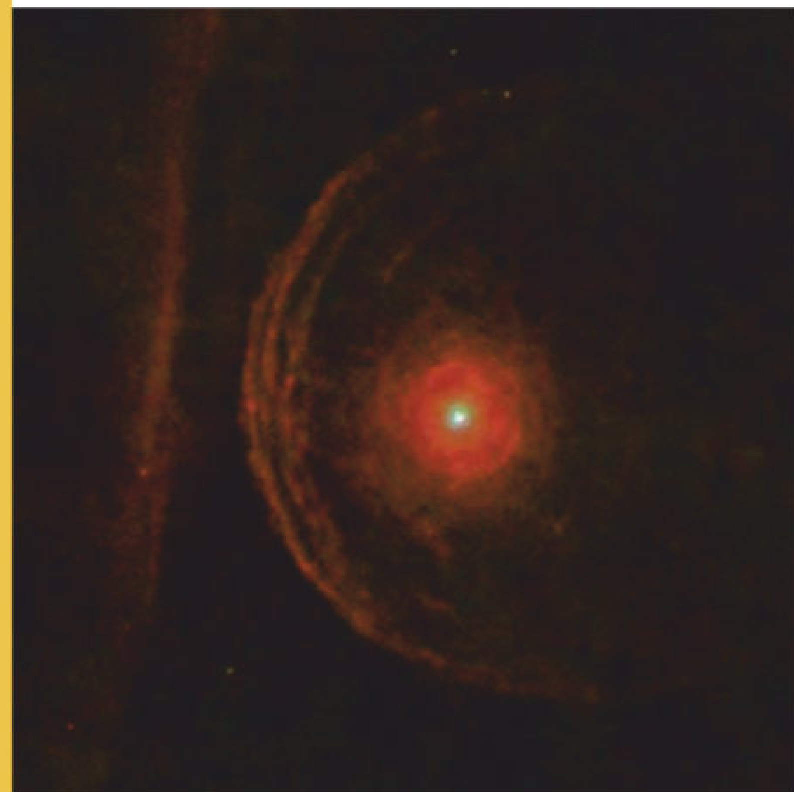
Wheeler wondered whether any signal from such waves in a red supergiant like Betelgeuse would propagate to the surface and be observable as short-period oscillations in the star's light. Using the stellar evolution code *MESA* (Modules for Experiments in Stellar Astrophysics), the team found that such waves would likely dissipate before they reached the far-off surface, especially the closer the star got to going supernova. "I'm still trying to maintain a little optimism that some kind of seismological signal will reach the surface," Wheeler says. But at the moment, he adds with a sigh, "it's not looking real good."

WHY AN IRON CORE MEANS THE END IS NEAR

Throughout its life, a star keeps an extraordinary balance between energy pushing out from its core and gravity pulling in. As long as the star burns elements lighter than iron at its center, this *hydrostatic equilibrium* will hold steady. But once only iron remains in the core, its demise is imminent.

Until this moment, the star could generate the energy needed to hold gravity at bay by fusing elements lighter than iron. Energy can also be produced by fissioning, or splitting, elements heavier than iron. But to transform iron into something else, you need an input of energy. Without that, a star that has wound up with an iron heart keeps it together for only a fraction of a second.

Suddenly, the long-restrained gravity becomes unleashed and the star implodes, collapsing at near the speed of light into an ultra-dense neutron-star core. Iron nuclei break up, and neutrons form, but only for an instant. When the density of nuclear matter is reached, the core cannot stand more pressure, and the imploding material rebounds. Bursting back out at thousands of kilometers per second, it creates a blindingly bright supernova, spews heavy elements into the interstellar medium, and leaves the core exposed as a neutron star — or, if the star is massive enough, collapsed as a black hole.



▲ **PLOWING AHEAD** Seen here in a far-infrared image taken by the European Space Agency's Herschel Space Telescope, Betelgeuse appears to be pushing crescent-shaped waves of gas and dust ahead of it in the direction it's heading, like a ship pushes waves before its bow. Astronomers think this "bow shock" comprises material that the star has released. The origin and nature of the straight bar at left is unknown.

ESA / HERSCHEL / PACS / L. DECIN ET AL.

When Will It Blow?

Naturally, the timing of Betelgeuse's annihilation is the uncertainty most nagging to everyone, from researchers to weekend astronomers. Everyone is *dying* to know when it will detonate. Guinan, who admits Alpha Ori is a pet star of his, even has a cap with pinholes ready to place over his telescope.

"That's for when Betelgeuse is –11," he laughs. "I don't know how scientifically valid it is, but it impresses our students."

Levesque, for her part, likes to imagine how the world would react if the star exploded today: "It would get a hashtag. It would get photographed everywhere. People would get *really* excited about it."

We know it's a fast-evolving star that, in astronomical terms, is approaching the end of its life, and that it will likely blast apart as a Type IIP supernova. (The "P" refers to a plateau seen in the light curve of this type of supernova.) But we have no idea just when it might do so. "It's difficult to know, really," says Guinan. "People have guessed that it's within a million years. There's a paper that claims half a million years. There's no way of knowing exactly. It could be, like, tonight." Dupree, too, throws up her hands. "Maybe it's already exploded," she chuckles. (At the distance reported by Harper and colleagues in 2017, Betelgeuse's light would take more than 700 years to reach us.)

▲ **BLAZING BEACON** When Betelgeuse goes supernova, it will shine in the heavens as brightly as the quarter Moon, or perhaps even brighter. Above is one artist's concept of how the Orion constellation might appear in the northern night sky when that long-awaited eventuality happens.

Before it goes supernova, the star might even loop back across the *Hertzsprung-Russell diagram*, the standard plot of star types, and become a blue supergiant like Rigel or even a superhot *Wolf-Rayet star*. It might burst as one of those, or re-loop back to erupt as a red supergiant. While astronomers hope beyond hope that they'll get to witness Betelgeuse go supernova in their lifetime, most think that's wishful thinking. "Most likely it's in helium core-burning and we still have, I'm sorry to say, 100,000 years to go," says Wheeler.

Would we see any hints just before it explodes? "This is a really active and interesting question for people studying red supergiants right now," Levesque says. Some kinds of stars give off what you might consider death throes, she says. *Luminous blue variables*, for instance, can produce a visible outburst before they die. "We haven't seen red supergiants do this, but that doesn't mean they don't," she says. "It just means we have a limited sample."

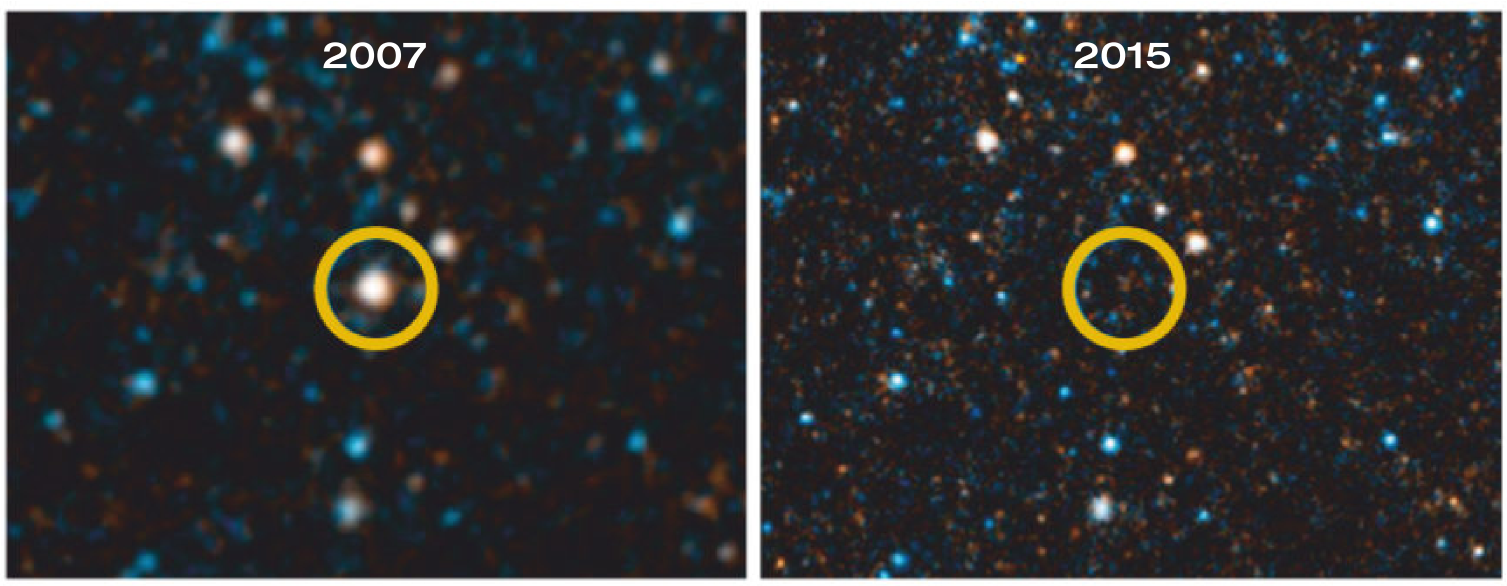
Aftermath

Whenever it does blow itself to pieces, Betelgeuse will pose no threat to Earth. Even at the closest distance estimates, it's too far away for its X-rays, UV radiation, or debris to affect us here. "It will be really intensely bright — and just a *point,* of course — but not dangerous," Wheeler says. "A supernova would have to be like 30 light-years away for it to be really dangerous."

But it will be a tremendous learning opportunity. "We haven't had a visible galactic supernova in hundreds of years, so it'll be exciting and answer a lot of questions when that does eventually happen," says Levesque. One of those questions concerns the flux of neutrinos released. After Supernova 1987A in the Large Magellanic Cloud, which lies about 165,000 light-years away, detectors on Earth picked up just a handful of neutrinos. But Betelgeuse is over 200 times closer than the LMC, so the dose of neutrinos that we receive, while still not enough to harm us, would be much greater, providing unprecedented insight into Alpha Ori's apocalypse, Wheeler says. "We'd learn an immense amount about the explosion through the neutrino flux that we didn't learn from '87A because it was so far away."

In the meantime, Alpha Ori continues to serve as a fantastic laboratory for studying red supergiants. "Because it's so close, we can ask questions about Betelgeuse that we can't ask about other stars," Levesque says. These include questions about how its surface is behaving, what its core is doing, and how it's losing mass. "If we can figure out exactly what stage *this* star is in, we can study those stages in just amazing detail and then generalize to other red supergiants."

■ Editor in Chief **PETER TYSON** hopes Betelgeuse goes supernova right after this issue hits the newsstand.



▶ **THERE AND GONE** Post-supernova, Betelgeuse will end up as a neutron star or, less likely, a black hole. In this image, a giant star known as N6946-BH1 is shown before and after it vanished from the sky. The left image shows the star, thought to be about 25 times the mass of the Sun, in 2007. The right image, from 2015, reveals the spot where the star collapsed into a black hole.

2 **DAWN:** Look toward the east just before sunup to see Venus rise; paralleling the Morning Star's path some 5° to the lower right you might glimpse the very thin crescent Moon.

6 **MORNING:** The Eta Aquariid meteor shower is best for viewers at southern latitudes and peaks before dawn; see page 50.

6–7 **DUSK:** The thin waxing lunar crescent is in Taurus the next two evenings. Catch it on the 6th when it's 2–3° upper right of Aldebaran. The next evening the Moon is less than ½° from Zeta Tauri, with Mars some 4° upper right of the pair.

10 **EVENING:** The Moon, one day shy of first quarter, is in the Beehive Cluster (M44) in Cancer.

11–12 **EVENING:** The fattening Moon is almost equidistant from Regulus these two evenings, first appearing to the star's right and then on its left.

15 **DUSK:** The waxing gibbous Moon, in Virgo, is a little more than 8° above Spica.

19–20 **ALL NIGHT:** The Moon, a day past full, forms a wide triangle with Jupiter and Antares in the southeast. Follow the trio as it glides across the sky through the night.

20–23 **MORNING:** Look toward the south-southwest well before sunrise to see the Moon some 5° right of Jupiter. Watch over the next three mornings as the thinning Moon approaches and then overtakes Saturn, ending up about 5° left of the ringed planet.

28 **ALL NIGHT:** Asteroid 1 Ceres is at opposition. Binoculars will help you spot the dwarf planet as it straddles the border between Scorpius and Ophiuchus. See page 48 for more on this interesting target.

— DIANA HANNIKAINEN

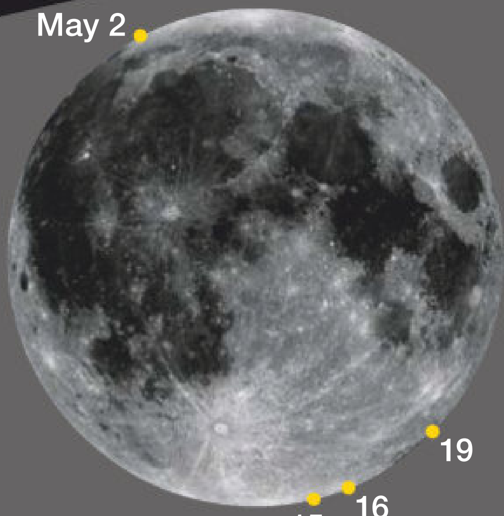
▲ Ceres, the first asteroid identified as such, was discovered by Giuseppe Piazzi in 1801. NASA's Dawn spacecraft entered into orbit around Ceres in 2015 and — until it ran out of fuel in 2018 — sent back the highest-resolution images thus far of the dwarf planet. This image is taken from a distance of 13,600 kilometers (8,400 miles).

NASA / JPL / CALTECH / UCLA / MPS / DLR / IDA

MAY 2019 OBSERVING

Lunar Almanac

Northern Hemisphere Sky Chart



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

NASA / LRO

MOON PHASES

SUN	MON	TUE	WED	THU	FRI	SAT
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30	31	

NEW MOON
May 4
22:46 UT

FIRST QUARTER
May 12
01:12 UT

FULL MOON
May 18
21:11 UT

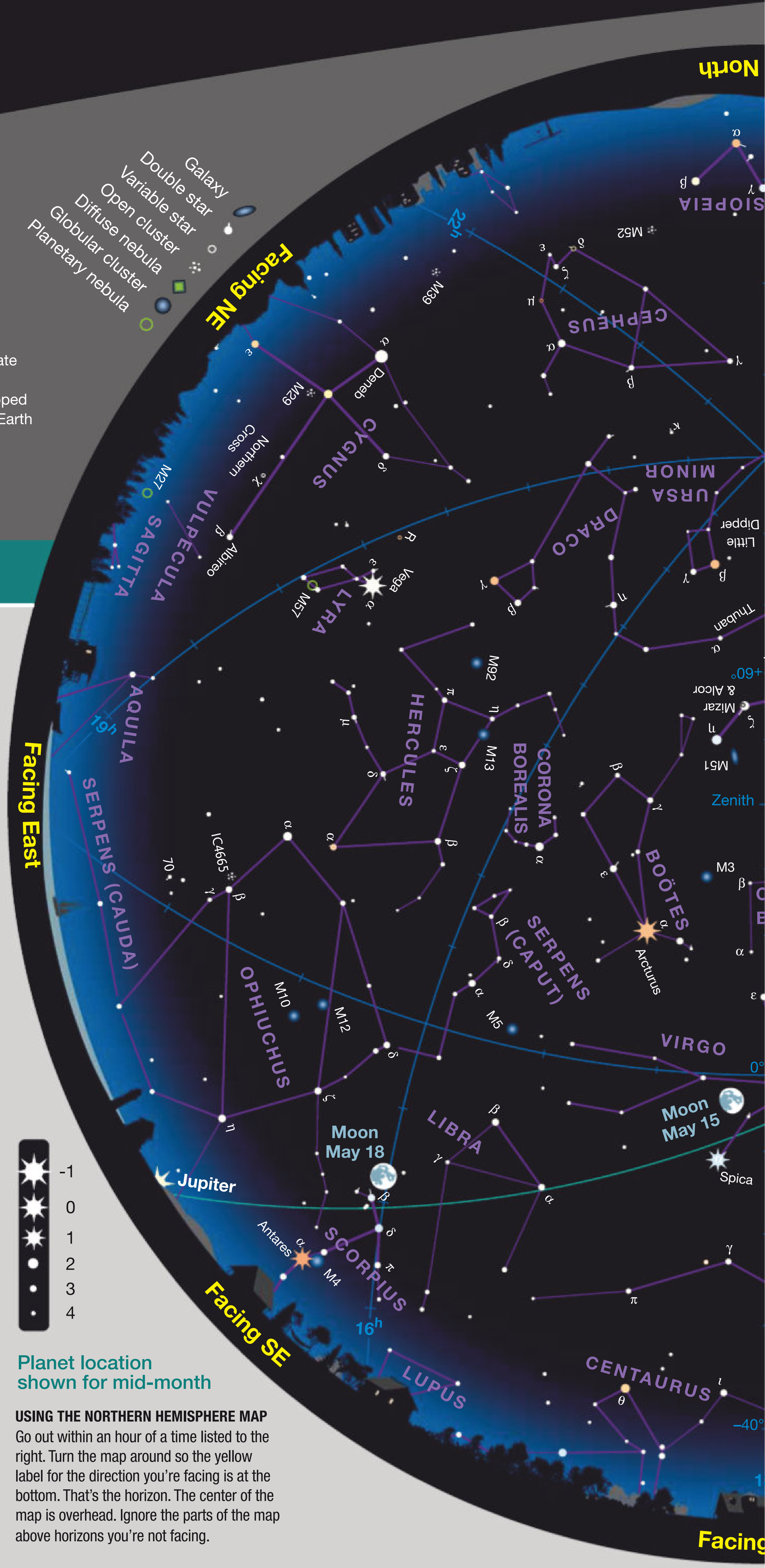
LAST QUARTER
May 26
16:34 UT

DISTANCES

Perigee	May 13, 22^h UT
369,009 km	Diameter 32′ 23″
Apogee	May 26, 13^h UT
404,137 km	Diameter 29′ 34″

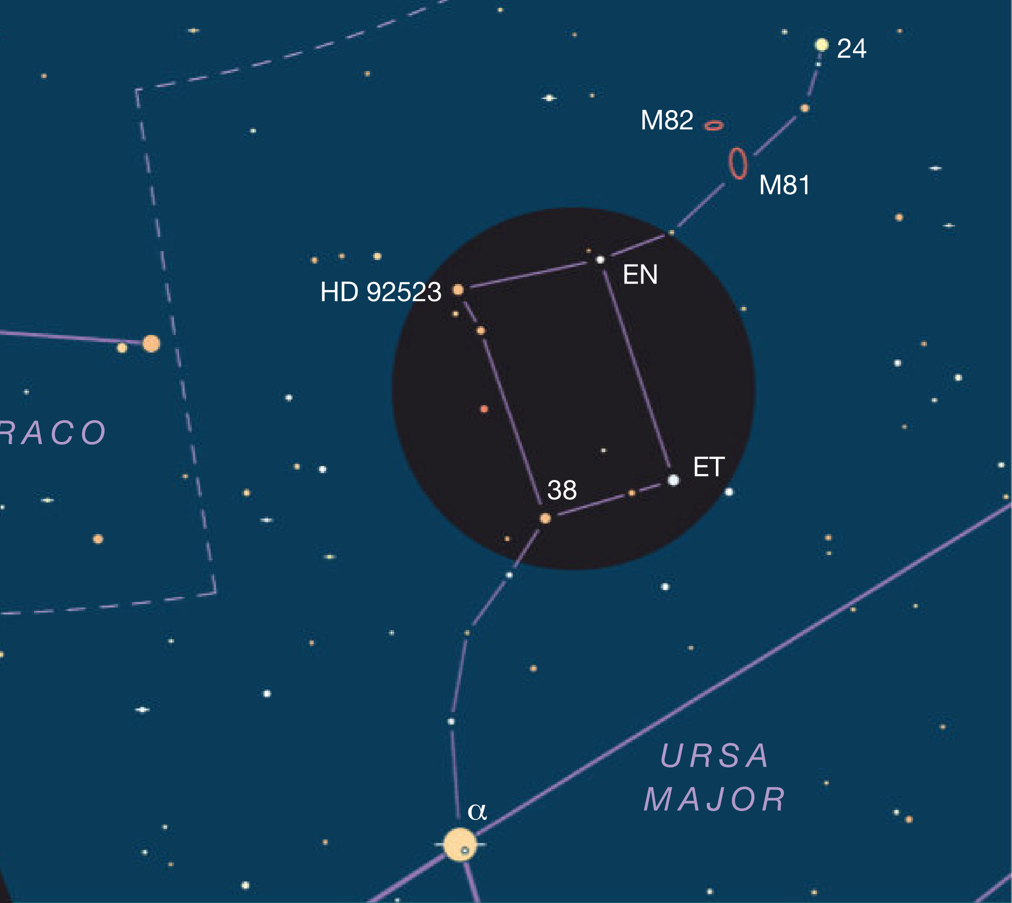
FAVORABLE LIBRATIONS

• Xenophanes Crater	May 2
• Boguslawsky Crater	May 15
• Wexler Crater	May 16
• Mare Australe	May 19



Planet location shown for mid-month

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



Binocular Highlight by Mathew Wedel

Mini-Dipper Points the Way

At this time of year, the galaxies M81 and M82 — also known as Bode's Nebulae — are crossing the zenith in the early evening. These interacting galaxies, some 12 million light-years away, are popular targets for binocular and telescopic observers alike. This column isn't about the galaxies per se, but rather about an asterism that will help you quickly and easily locate these celestial gems.

The very fast, very rough way to Bode's Nebulae is to aim from Phecda, or Gamma (γ) Ursae Majoris, northwest to Dubhe, Alpha (α) Ursae Majoris, and farther on about the same distance and direction. That's a pretty gross approximation, and it can be tough to pull off since it spans several binocular fields.

Another, more precise way to find M81 and M82 is to start at Dubhe and follow the chain of 6th- and 7th-magnitude stars that arcs north and then west. This will take you to 38 Ursae Majoris, the southeast corner of an almost perfect rectangle of stars 2° wide (east-west) and 3° degrees tall (north-south). The other corners of the rectangle are HD 92523 and the variable stars ET Ursae Majoris and EN Ursae Majoris on the west side. From EN Ursae Majoris, another chain of stars curves west and then north to the bright outpost of 24 Ursae Majoris. M81 lies on this arc, about halfway between EN and 24 Ursae Majoris, and M82 lies just ½° north-northeast of M81.

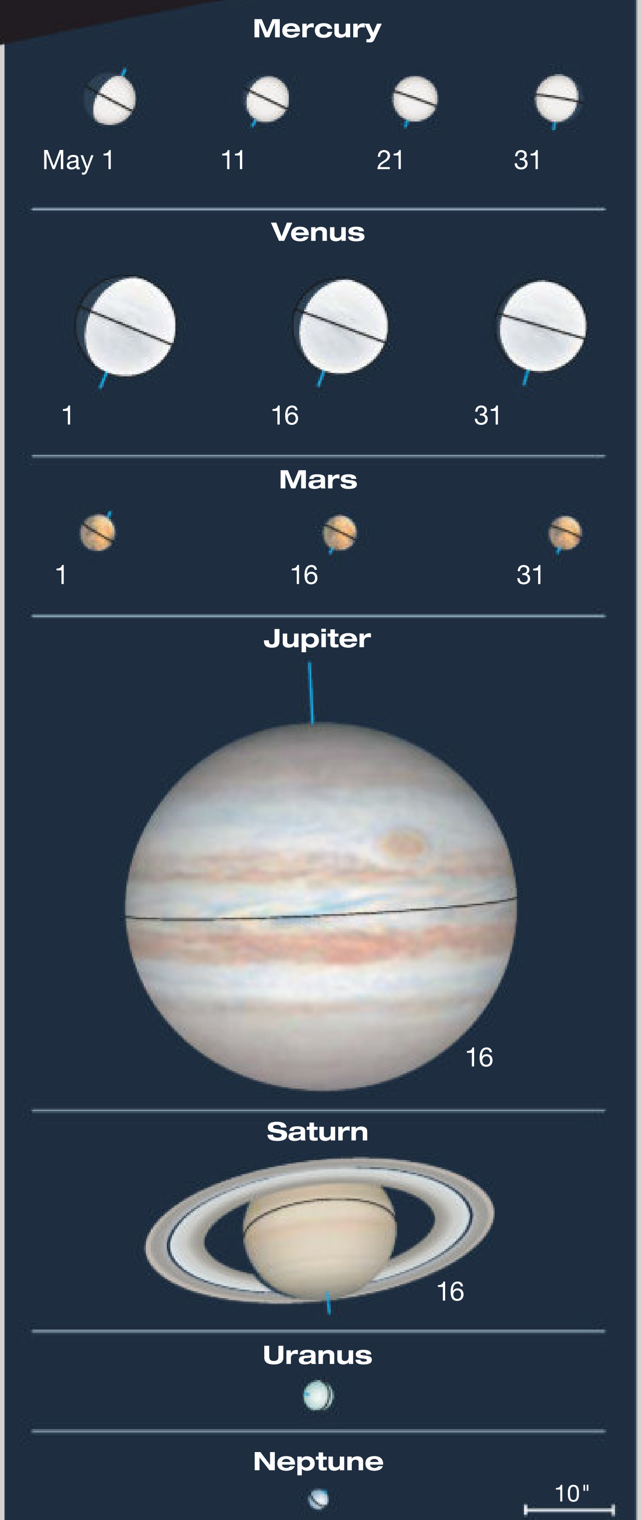
My favorite thing about this star-hop is that the first chain of stars and the rectangle form a miniature dipper shape. It's easy to remember: Go to the rim of the Big Dipper, follow the mini-dipper, and you're home free. So take a dip and scoop up a couple of galaxies.

■ **MATT WEDEL** always feels like he's getting away with something when he observes galaxies (galaxies!) with handheld binoculars.

WHEN TO USE THE MAP

Late March	2 a.m.*
Early April	1 a.m.*
Late April	Midnight*
Early May	11 p.m.*
Late May	Nightfall

*Daylight-saving time



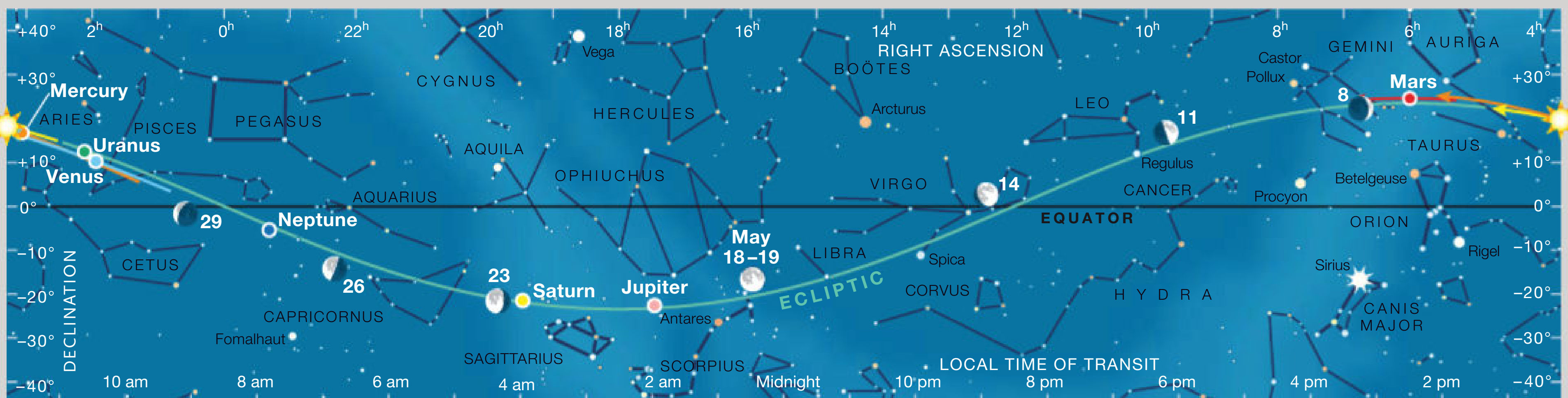
PLANET DISKS have south up, to match the view in many telescopes. Blue ticks indicate the pole currently tilted toward Earth.

PLANET VISIBILITY **Mercury:** visible at dusk after the 29th • **Venus:** visible at dawn all month • **Mars:** visible at dusk, sets mid-evening • **Jupiter:** rises before midnight, visible until dawn • **Saturn:** rises near midnight, visible until dawn

May Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	2^h 30.7^m	+14° 50′	—	–26.8	31′ 45″	—	1.007
	31	4^h 29.3^m	+21° 48′	—	–26.8	31′ 33″	—	1.014
Mercury	1	1^h 16.3^m	+5° 22′	21° Mo	–0.4	5.8″	75%	1.149
	11	2^h 23.6^m	+12° 45′	12° Mo	–1.0	5.3″	90%	1.271
	21	3^h 45.8^m	+20° 07′	1° Mo	–2.4	5.1″	100%	1.323
	31	5^h 17.1^m	+24° 46′	11° Ev	–1.2	5.4″	89%	1.245
Venus	1	0^h 47.7^m	+3° 19′	28° Mo	–3.8	11.5″	88%	1.445
	11	1^h 32.8^m	+7° 55′	25° Mo	–3.8	11.2″	90%	1.496
	21	2^h 18.9^m	+12° 15′	23° Mo	–3.8	10.8″	92%	1.542
	31	3^h 06.4^m	+16° 08′	20° Mo	–3.8	10.5″	94%	1.584
Mars	1	5^h 15.8^m	+24° 07′	40° Ev	+1.6	4.2″	96%	2.239
	16	5^h 58.5^m	+24° 34′	35° Ev	+1.7	4.0″	97%	2.336
	31	6^h 40.9^m	+24° 16′	30° Ev	+1.8	3.9″	97%	2.422
Jupiter	1	17^h 31.6^m	–22° 39′	137° Mo	–2.5	43.5″	100%	4.535
	31	17^h 19.0^m	–22° 30′	168° Mo	–2.6	45.8″	100%	4.306
Saturn	1	19^h 27.4^m	–21° 31′	110° Mo	+0.5	17.2″	100%	9.668
	31	19^h 24.2^m	–21° 39′	140° Mo	+0.3	17.9″	100%	9.260
Uranus	16	2^h 06.0^m	+12° 15′	21° Mo	+5.9	3.4″	100%	20.787
Neptune	16	23^h 17.8^m	–5° 37′	67° Mo	+7.9	2.3″	100%	30.325

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



The Sun and planets are positioned for mid-May; the colored arrows show the motion of each during the month. The Moon is plotted for evening dates in the Americas when it's waxing (right side illuminated) or full, and for morning dates when it's waning (left side). "Local time of transit" tells when (in Local Mean Time) objects cross the meridian — that is, when they appear due south and at their highest — at mid-month. Transits occur an hour later on the 1st, and an hour earlier at month's end.

Meadow in the Sky

During the month of May, take a moment to marvel at open clusters, globular clusters, and sparkling stars.

Carl Sagan once wrote of the Earth surrounded by space as "a meadow in the middle of the sky." I've written in this column previously about a different "meadow in the middle of the sky."

The meadow in question is the section of heavens bounded by the main patterns of the Big Dipper, Boötes, Virgo, and the hindquarters of Leo. It hangs overhead on May evenings for observers at mid-northern latitudes. It contains the constellations Coma Berenices and Canes Venatici and the central region of the Virgo Galaxy Cluster. It's bounded by mostly rather bright stars but is itself sparse of naked-eye stars — and superbly rich with fuzzy, intricate, relatively bright galaxies for amateur telescopes.

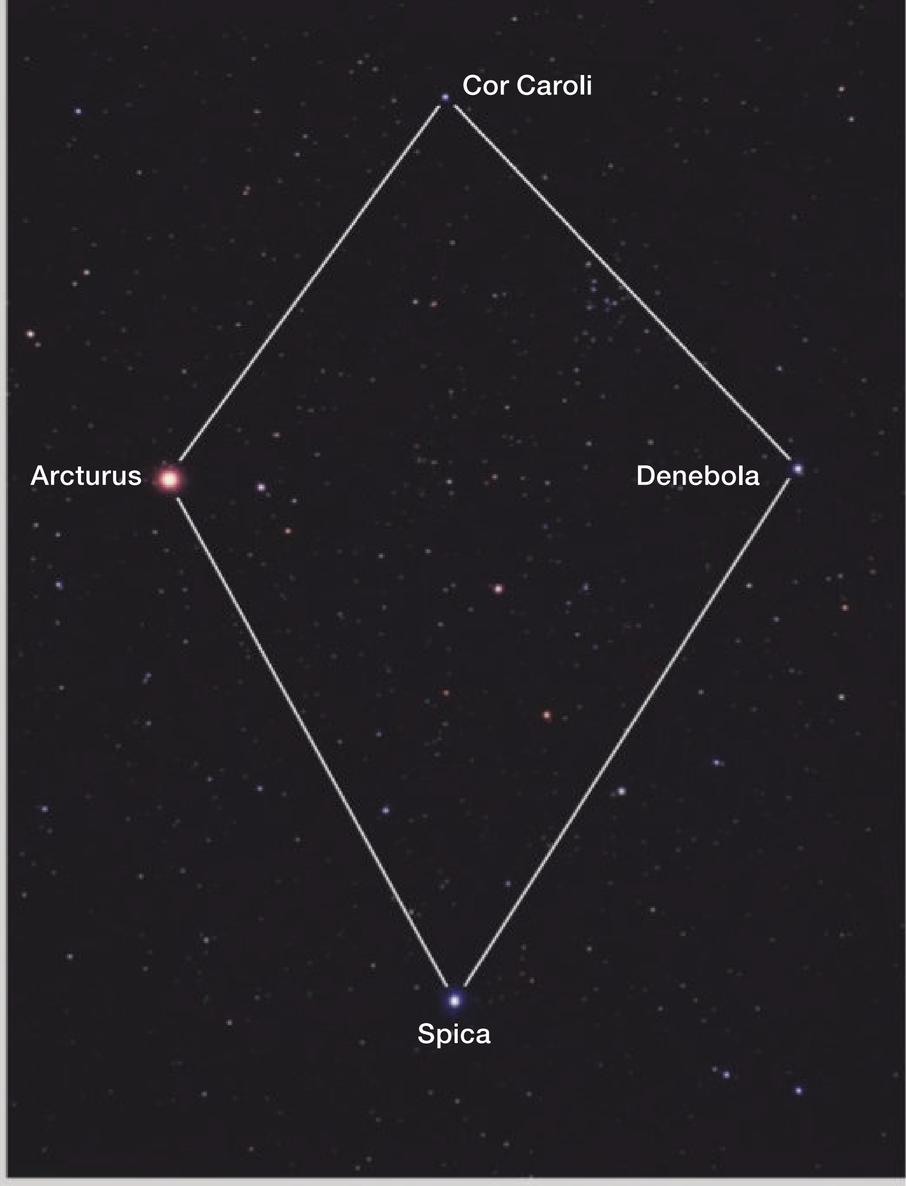
Revisiting the meadow in the sky. In May, when Earth's fields (or at least those at temperate latitudes) are abloom with countless wildflowers, the meadow overhead is similarly blossoming with dozens, hundreds, thousands of galaxies. But let's first consider a closer resident of the meadow: the Coma Star Cluster, technically known as Melotte 111.

The name of the constellation Coma Berenices means "Berenice's Hair," referring to the locks of the historic Queen Berenice. It's based on the naked-eye appearance of the Coma Star Cluster — in a dark sky, an irregular scattering of stars that looks like beautifully disheveled hair. The cluster more anciently marked the tuft at the end of Leo the Lion's tail. The cluster consists of a few dozen stars, at least five of them brighter than magnitude 5.5 and about a dozen brighter than 6.5. It spills over more than 5° of sky, so you need a pair of binoculars with a reasonably wide field of view to include the entire cluster (see *S&T:* Apr. 2019, p. 43). The Coma Star Cluster is, at about 280 light-years distant, the second-closest cluster to Earth, less than twice as far away as the Hyades. The magnitude-4.4 star Gamma Comae Berenices, though appearing near the northern edge of the Coma Star Cluster, isn't a member. The brightest true member is the magnitude-4.8 star 12 Comae Berenices.

Gamma Comae Berenices is useful for finding the Coma Star Cluster in a light-polluted sky, for it lies about ⅔ of the way between 2nd-magnitude Denebola (Beta Leonis) and the 3rd-magnitude beautiful double star Cor Caroli (Alpha Canum Venaticorum). Cor Caroli is essentially right at the zenith at the time of our all-sky map on the preceding pages.

The diamond in the meadow. The line connecting Denebola and Cor Caroli is one of four that forms an asterism that just about fills the meadow in the sky. This asterism is one that's rarely heard of in recent decades: the Diamond of Virgo. I first learned about it in childhood in a beloved little yellow book, the 1954 edition of William Tyler Olcott's *Field Book of the Skies*.

The other stars of the Diamond are the brilliant Arcturus and Spica. And this diamond is extremely valuable for locating a variety of deep-sky objects. In addition to Gamma Comae Berenices and the Coma Star Cluster, we can find virtually all the Virgo Galaxy Cluster wedged within the western angle of the Diamond (not far west of Epsilon Virginis, also known as Vindemiatrix). About halfway between Arcturus and Cor Caroli is the isolated but great globular cluster M3. In addition, about two-thirds of the way along the line from Denebola to Arcturus — a line which bisects the Diamond of Virgo — there shines the magnitude-4.3 star Alpha Comae Berenices and, about 1° northeast of it, the 7.7-magnitude globular cluster M53.



AKIRA FUJII

▲ **GEM IN THE SKY** The Diamond of Virgo is an asterism that straddles five constellations: Virgo, Boötes, Canes Venatici, and Leo, which contain the anchor stars, with Coma Berenices in the middle.

Top of the galaxy to you. Within half a degree of 31 Comae Berenices is the North Galactic Pole. This is the direction perpendicular to the equatorial plane of the Milky Way. When the galactic pole is virtually overhead, the band of the Milky Way is hidden along the horizon. But at least very bright stars bedeck the sky near the horizon in different cardinal directions at this hour: Capella in the northeast, Procyon in the west, Antares in the southeast, and Deneb in the northeast.

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

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

The Planets Perform

A dwarf planet reaches opposition in May, while the two gas giants march towards their own oppositions later on.

There are some distinctive solar system highlights to catch this month. Every year, Jupiter and Saturn enter the evening sky and get brighter and bigger as they get close to opposition. But this year, for the first time in almost two decades, these two gas giants march towards their climactic showings of the year just one constellation apart, approaching next year's quasi-conjunction in May and historically close conjunction in December.

Other special solar system sights of May include the opposition of Ceres and a close encounter of Mars with the bright open cluster M35.

At nightfall, Mars is an extra 2nd-magnitude light, first in Taurus and then in Gemini. As the month progresses, brightening Jupiter is rising earlier and earlier in evening twilight. Brightening Saturn appears above the horizon about two hours after Jupiter. Meanwhile at dawn, Venus languishes low in morning twilight.

DUSK AND EVENING

Mars starts the month several degrees from Beta (β) Tauri (El Nath) and at about the same brightness as the star, around magnitude 1.6. By late May the magnitude of Mars has faded to a meager 1.8. This slightly ruddy world sets more than 3 hours after the Sun as May begins but less than 2½ hours as the month ends. Mars shrinks to less than 4″ wide in telescopes this month, but binoculars and telescopes show the fine sight of Mars passing near the big open cluster M35 at the feet of Gemini a few days after mid-month. Mars shines on the northeast edge of the cluster after sunset on May 19th.

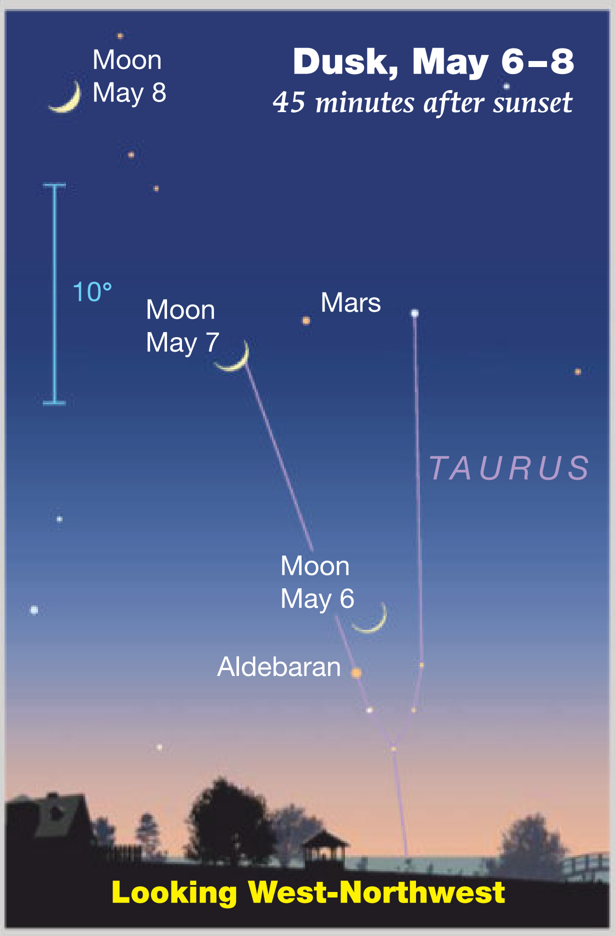
Mercury may be glimpsed low in the west-northwest in the Sun's afterglow, far to the lower right of Mars, on the last few days of the month. Visibility starts after Mercury passes through superior conjunction with the Sun on May 21st.

ALL NIGHT

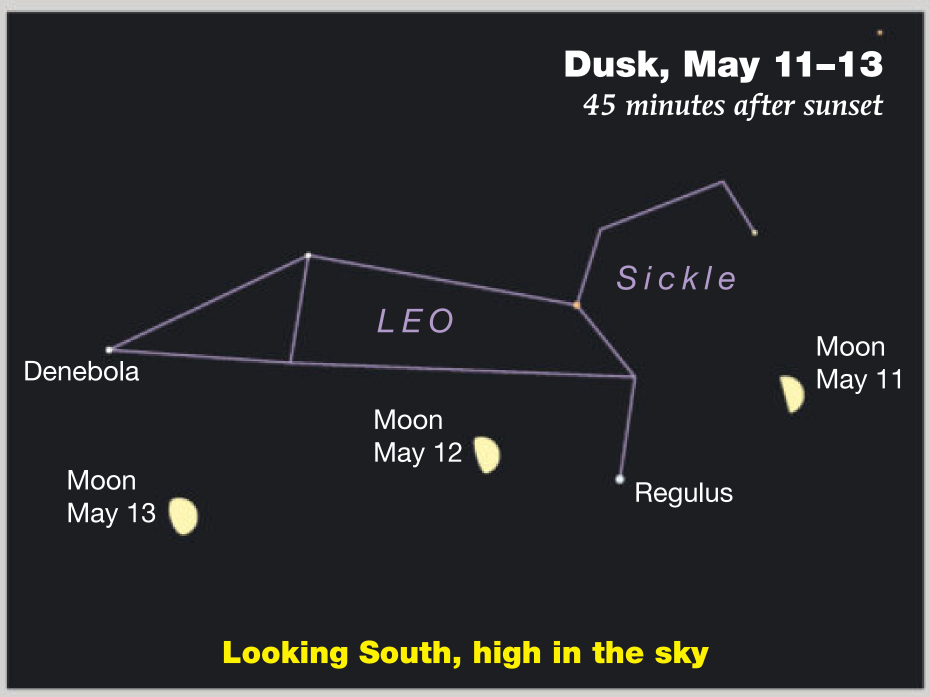
Ceres, the largest asteroid and the only one to also be classified as a dwarf planet, reaches opposition on May 28th. It's then on the border of Ophiuchus and Scorpius, retrograding into the claws of Scorpius. See page 48 for more.

EARLY EVENING TO DAWN

Jupiter makes a grand entrance onto the sky's evening stage a little earlier each night in May. The mighty planet brightens from magnitude –2.5 to –2.6 as it nears its opposition, which occurs on June 10th, and telescopes show its majestic, intricately patterned disk grow from 43″ to almost 46″ in equatorial diameter. Jupiter-rise occurs more than 3 hours after sunset as May starts but roughly 40 minutes after sunset as



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



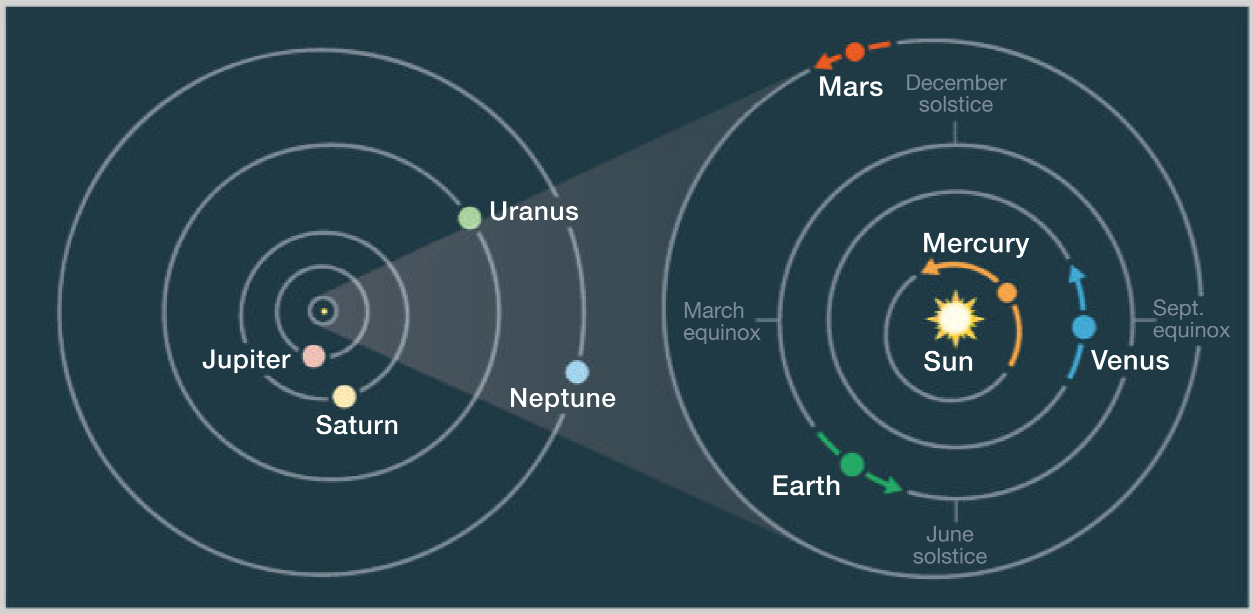
May ends. The time of Jupiter's culmination (when it's highest in the south and best seen in telescopes) backtracks from about 4 a.m. to well before 2 a.m. in May. The banded giant continues to retrograde among the stars of southern Ophiuchus, its distance from Antares in Scorpius decreasing from more than 14½° to about 12° during the month.

MIDDLE NIGHT TO DAWN

Saturn rises in the middle of the night throughout May and starts reaching the meridian around the first glimmers of morning twilight by the end of the month. Saturn brightens noticeably, from magnitude +0.5 to +0.3 in May, while its equatorial diameter swells to just short of 18″ wide. The span of the golden planet's rings grows to more than 40″, and their tilt starts to increase from a temporary minimum of 23.5° from horizontal. Saturn retrogrades back in eastern Sagittarius, slowly gaining on the Teaspoon asterism. The separation of Saturn from Jupiter increases to around 29° by the close of May.

DAWN

Venus rises about an hour before the Sun in May but is particularly low for observers at mid-northern latitudes. The always-brilliant planet shines at its minimum magnitude of –3.8 now. Venus's disk is about 11″ wide and about 91% illuminated on May 18th. That's the day that a telescope might reveal 6th-magnitude **Uranus** 1.4° north of Venus.

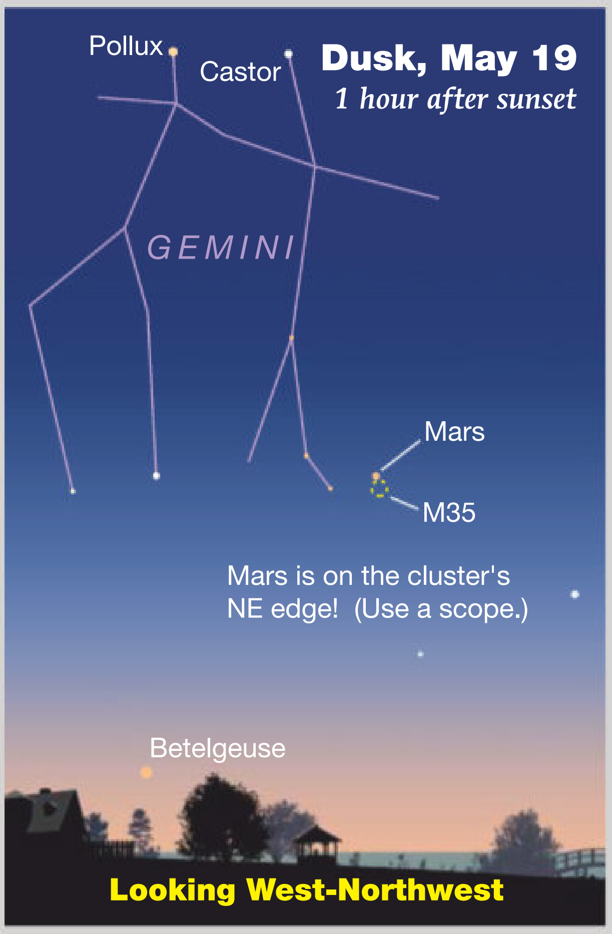


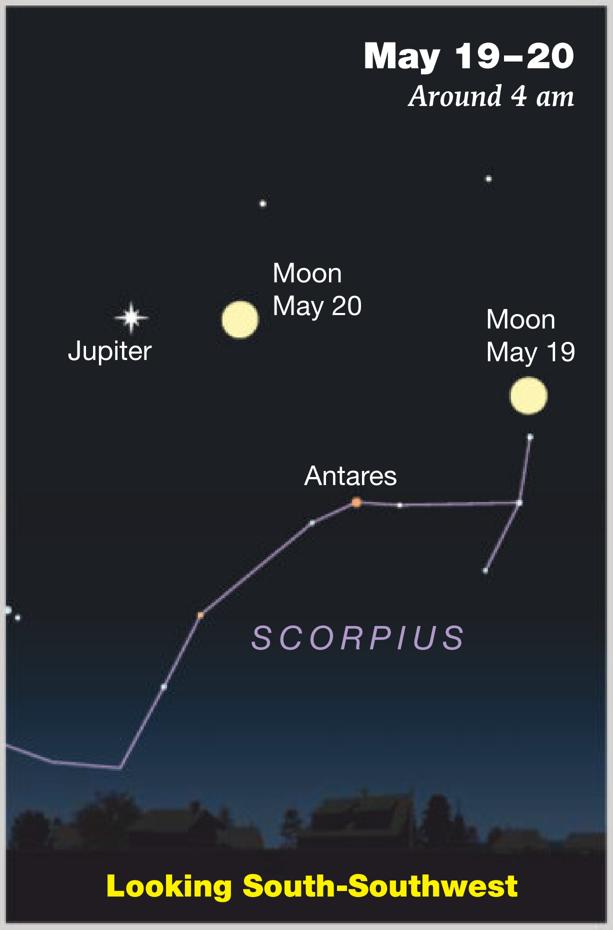
ORBITS OF THE PLANETS
The curved arrows show each planet's movement during May. The outer planets don't change position enough in a month to notice at this scale.

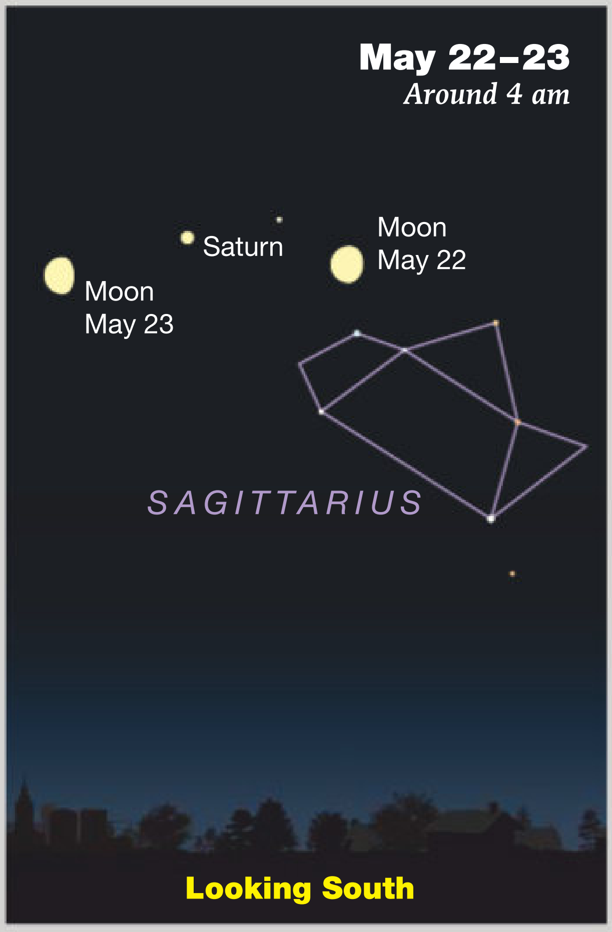
MOON PASSAGES

The Moon is a slender crescent hanging 3° upper right of Aldebaran in the dusk on May 6th. The next night, the waxing lunar crescent is less than ½° left of Zeta (ζ) Tauri and forms a compact line with Mars some 3° to 4° to its right or upper right and similarly bright Beta Tauri even farther right. The first-quarter Moon is 8° to 9° right or upper right of Regulus on the evening of May 11th, while the waxing gibbous Moon is closer to the left of Regulus the next evening. The waning gibbous Moon is around 4° degrees to the right of bright Jupiter on the morning of May 20th. The thinning gibbous Moon floats some 7° to the right of Saturn on the morning of May 22nd, and closer to the lower left of Saturn the next morning.

■ Contributing Editor **FRED SCHAAF** has been writing about the skies above us for more than 40 years.

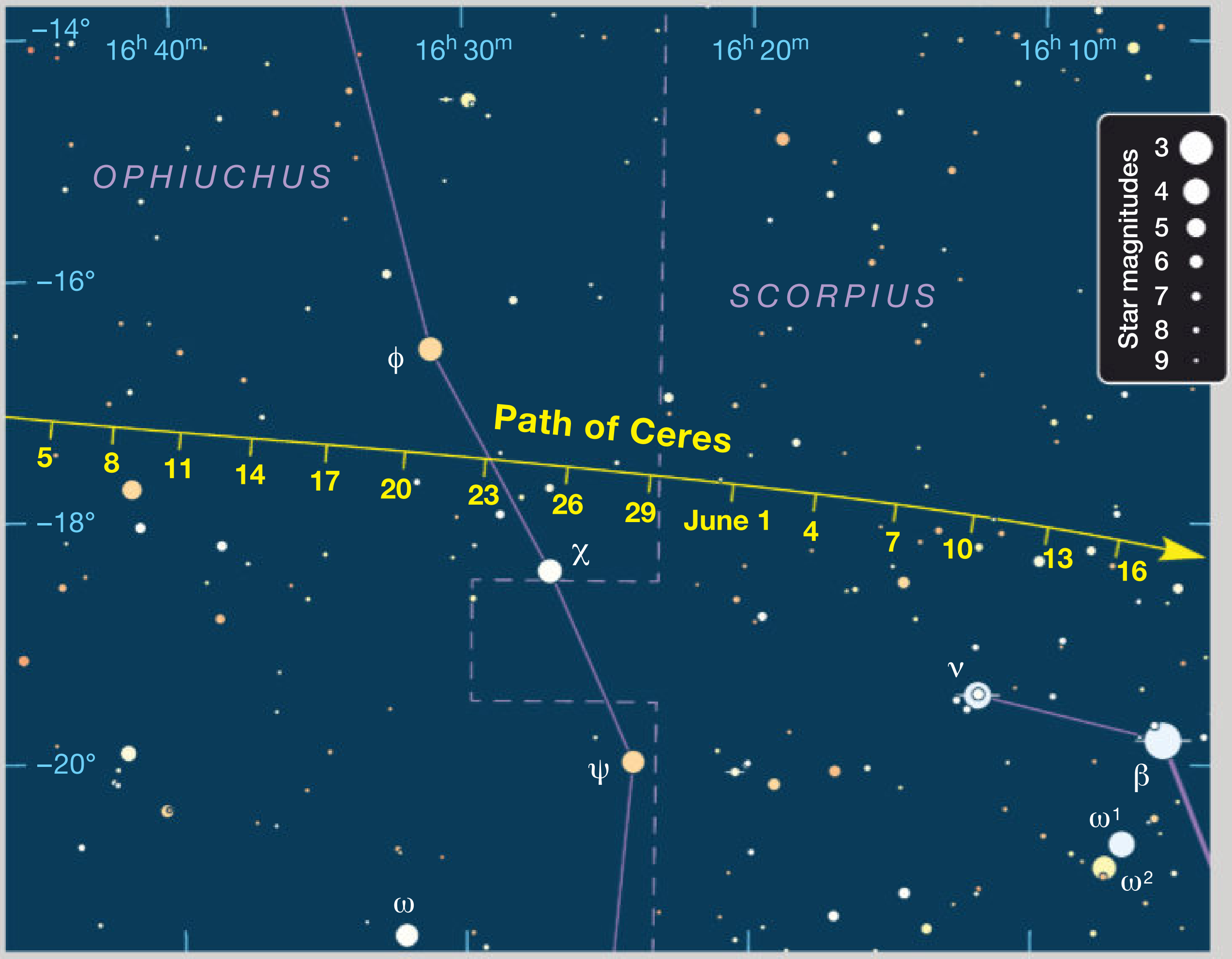


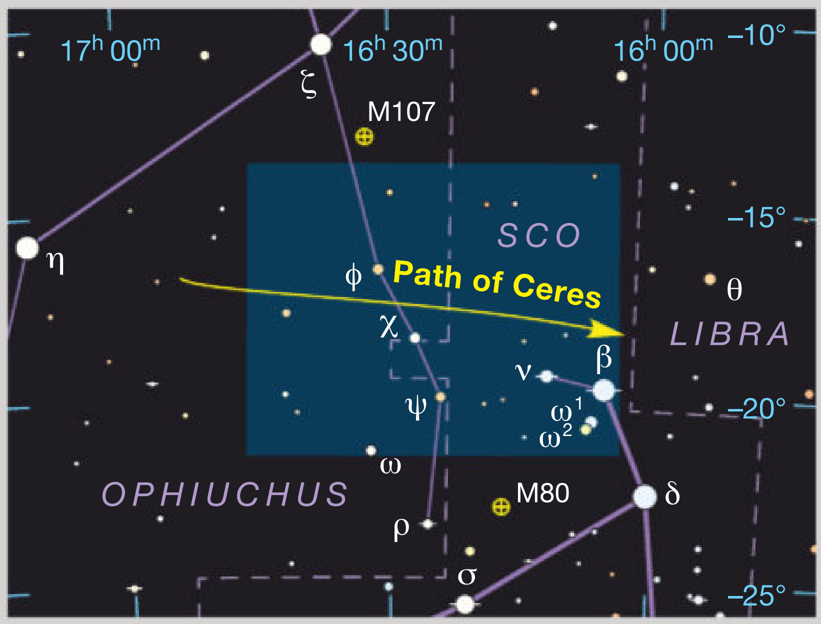




Ceres at Opposition

The biggest asteroid and brightest dwarf planet is at its best for 2019.





▲▶ Asteroid 1 Ceres stands approximately 20° above the south-southeastern horizon on the night of May 28–29. Look for a line of 5 stars with magnitudes ranging from 7.2 to 9.4 northeast of Chi Ophiuchi. The line points to a 9th-magnitude star that lies close to the asteroid's path. Ceres will be less than ½° from that star on May 28th at 10 p.m. local daylight-saving time. The chart above shows Ceres' path, with tick marks indicating the asteroid's position at 0^h UT every three days.

For the ancient Romans, spring was the season of Ceres, the goddess of cereals and agriculture. So it's appropriate that we devote at least some of our May nights to the celestial object named after the deity of seed and growth. **Asteroid 1 Ceres** is well placed for observation all month and reaches opposition on the night of May 28–29, when it moves from Ophiuchus into Scorpius.

Ceres, the first discovered asteroid, was found by the Italian astronomer Giuseppe Piazzi, who spotted the mysterious object on January 1, 1801, while making observations from the Royal Observatory of Palermo in order to correct those published by Frances Wollaston in 1789. The new star, with its feeble 8th-magnitude light and a color similar to that of Jupiter, puzzled Piazzi and his assistants, Niccolò Cacciatore and Niccolò Carioti. After he spent several nights chasing the interloper through the sky with a 5-foot alt-azimuth circle and 4-inch achromatic refractor, Piazzi felt comfortable enough to share his discovery with his colleagues, but not so comfortable as to make a claim as to the object's true nature. Was it a planet or a comet? He was reluctant to take a public stand, though he did confide to astronomer friends that he thought "it might be something better than a comet."

Indeed, it was something better than a comet. At 940 km (585 miles) across, Ceres is the largest object in the asteroid belt, and the only asteroid to also be classified as a dwarf planet. Unlike the smaller company it keeps, Ceres is *differentiated*, or layered. It has a dense rocky core at its center, a 2- to 3-meter-thick icy crust of carbonate or argillaceous water ice at its surface, and an icy mantle in between. Ceres is approximately 25% ice, making it the second-most water-rich body in the inner solar system (Earth holds the H_2O record). And although Ceres lacks an atmosphere, scientists have detected occasional signs of water vapor near the asteroid's surface.

Ceres is the smallest dwarf planet, but because its orbit lies relatively close to Earth — not out beyond Neptune — it's also the brightest. On the night of opposition, Ceres shines at magnitude 7.0, just out of reach of the naked eye but an easy target for small scopes and binoculars. This isn't quite Ceres at its brightest — at more favorable oppositions, it can brighten to 6.7 or so — but it still makes for a noticeable light in

NASA / JPL-CALTECH / UCLA / MPS / DLR / IDA a star field. Don't worry too much if you're clouded out on the night of opposition. Ceres becomes a 7th-magnitude object as early as May 6th and stays that way until June 19th. It's an 8th-magnitude object well into August.

For much of May, Ceres travels across southern Ophiuchus, passing above the heart of Scorpius. Phi (φ) and Chi (χ) Ophiuchi are the nearest signposts this month; on the night of opposition, Ceres is about 1¼° northwest of Chi. By mid-June, star-hops from Nu (ν) and Beta (β) Scorpii should be easy. The Milky Way serves as an ornamental backdrop, but Ceres is bright enough to stand out among the crowd. Look for a slightly thicker dot of light. Some observers have reported that the asteroid appears to have a yellowish tint in the eyepiece.

The caveat here is that Ceres stays low in the southern sky for observers at mid-northern latitudes. It's also a late-night object around the time of opposition, transiting well after midnight. On May 1st, Ceres rises near 10:00 p.m. local daylight-saving time and reaches its highest point, about 33°, around 3:00 a.m. These times shift earlier by an hour by mid-month and are even more improved by June 1st, when Ceres rises before sunset and stands highest before 1 a.m. By mid-June, look for Ceres to culminate around 11:30 p.m.

Asteroids make compelling observing targets. In any given year, there are about 50 that become brighter than 10th magnitude, although a few may be too low for easy observation from mid-northern latitudes. If you discover a desire to capture as many as you can, check out the Astronomical League's Asteroid Observing Program (**https://is.gd/astrcobs**). All you need to get started is a detailed finder chart and a 4-inch telescope or a pair of deep-sky binoculars. Observe the asteroid in two different locations at two different times. This is a good practice not just for asteroids, but other objects that are "on the move," like Ceres' fellow dwarf planet Pluto. Showing that one particular dot has moved against the background stars is the only way to confirm the identity of such remote targets.

The Dawn spacecraft captured tens of thousands of high-resolution images as it orbited Ceres. This image of a crater chain called Gerber Catena was taken on December 10, 2015.

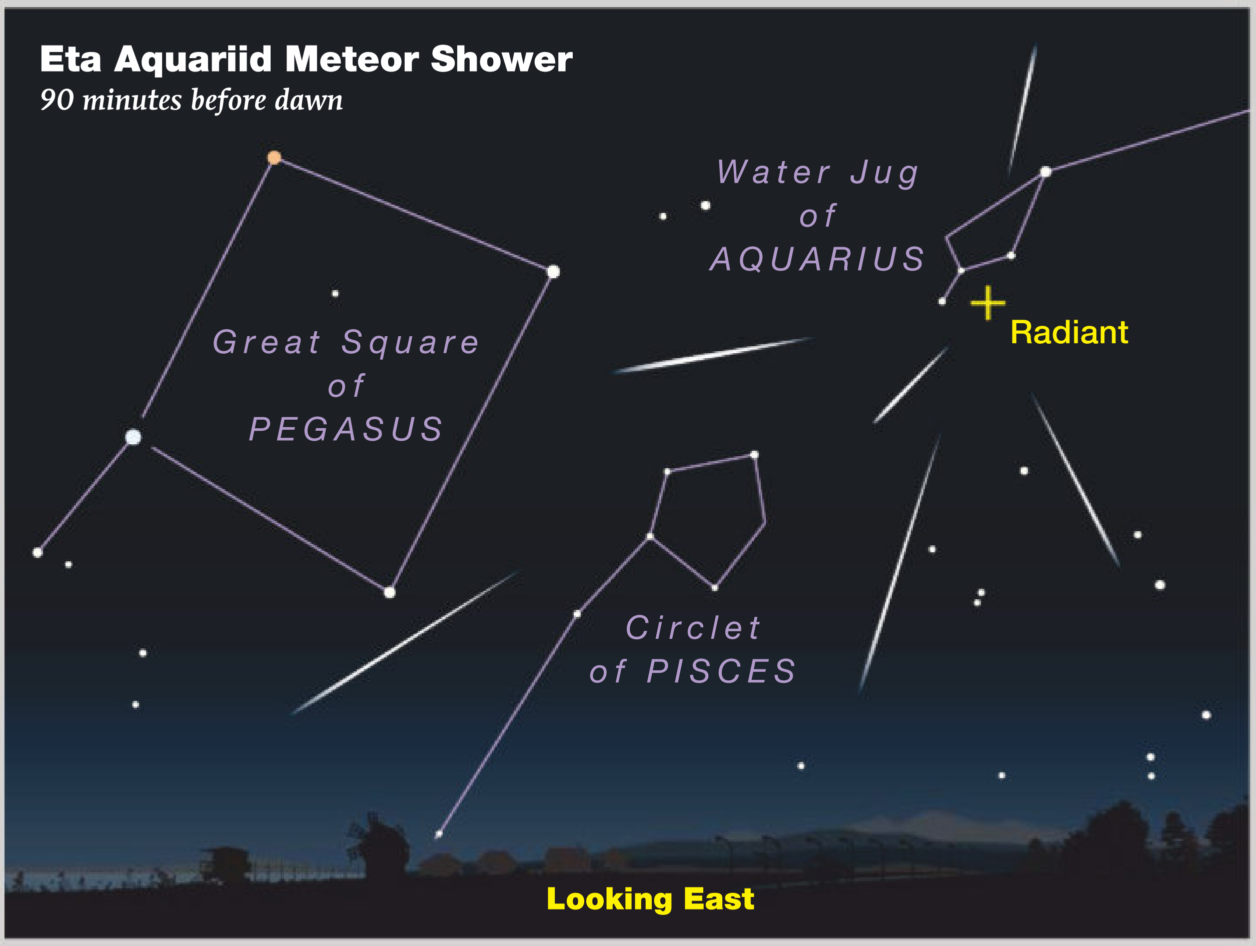
The Case of the Exosphere

Although Ceres lacks a permanent atmosphere, astronomers have detected an *exosphere*, a thin layer of water vapor enshrouding the asteroid. But the water signatures appear to be variable rather than permanent, sometimes detectable, sometimes not. Early hypotheses posited impact activity, localized geysers, and/or *sublimation* (the transformation of solid ice to gas) as possible sources of the vapor. Any of these causes could be linked to the exosphere's variability as well.

Planetary geologists are confident that sublimation, triggered by heating when Ceres approaches the Sun, is probably the original or even an ongoing source for water vapor. But sublimation can't account for it all, particularly because vapor has been detected when Ceres was at an orbital location away from the Sun. When NASA's Dawn spacecraft arrived at Ceres in March 2015, scientists were eager to observe the asteroid's water behaviors and clear up the mystery of the exosphere's origins (*S&T:* Dec. 2016, p. 16).

Based on Dawn's findings, a team of astronomers led by Michaela Villarreal (University of California, Los Angeles) recently argued that the vapor is the result of coronal mass ejections (CME) that accelerate the solar wind. The CME shock waves smash energetic solar particles into the asteroid's surface, freeing water molecules to create a temporary atmosphere. The variability of CMEs also explains the temporary nature of the exosphere. Dawn has detected no water plumes and no significant change in surface water ice features over the long term, making an accelerated solar wind the most likely culprit in the mystery of water vapor above Ceres.

Eta Aquariids Peak



▲ The radiant for the Eta Aquariid meteor shower lies near the Water Jug asterism in Aquarius. From latitude 30° north about 90 minutes before sunrise, the radiant hangs low in the east-southeast. For observers farther north, the radiant is even lower when morning twilight arrives.

EACH YEAR AROUND THIS TIME, Earth travels through one or more dust streams left behind by Comet 1P/Halley as it passed through the inner solar system. Halley returns every 75–76 years and has done so for more than 2,000 years (Chinese astronomers first documented the comet's arrival in 240 BC). That's about 30 documented apparitions, each of which left a dusty mark in space. Every May, Earth skims Halley's outbound path, passing just close enough for older, dissipating dust streams to produce a meteor shower.

The Eta Aquariid shower is visible from both Northern and Southern Hemispheres, but it's usually the year's best for those in the south, offering perhaps 60 meteors per hour before dawn under dark skies. Equatorial observers can catch an estimated 82% of the total activity. Observers at northern latitudes, say above 40° or 45° north, see significantly fewer meteors since the shower's radiant rises late so is quite low in the east-southeast at dawn. However, because the radiant is low, the potential for long, fast meteors along the eastern horizon increases. These earthgrazers often leave *trains*, incandescent trails of particles that last for seconds or even minutes.

The 2019 Eta Aquariid shower is predicted to peak on the morning of May 6th, when the view will be unblemished by moonlight. But unlike most major showers, the Eta Aquariid peak isn't particularly sharp. Instead, the *zenithal hourly rate* (ZHR, the number of meteors visible under dark skies if the radiant were at the zenith) slowly climbs in the nights preceding the peak. Any night of the week preceding or following May 6th could produce good totals.

Action at Jupiter

JUPITER, LINGERING in Ophiuchus, is visible from mid-to-late evening through sunrise this month. By the end of May, the gas giant shines at its highest in the south about two hours past local midnight. Jupiter is on its way to opposition on June 10th, when it will be visible from dusk to dawn. In the meantime, Jupiter grows bolder and bigger: The planet's equatorial diameter expands to 46″ and its brightness builds to magnitude –2.6 by May 31st.

Any telescope shows the four big Galilean moons, and binoculars usually show at least two or three. Use the diagram on the facing page to identify them at any date and time.

All of the May interactions between Jupiter and its satellites and their shadows are tabulated on the facing page. Find events timed for when Jupiter is at its highest in the early morning hours.

Here are the times, in Universal Time, when the Great Red Spot should cross Jupiter's central meridian. The dates, also in UT, are in bold. (Eastern Daylight Time is UT minus 4 hours.)

April 1: 7:53, 17:48; **2:** 3:44, 13:40, 23:35; **3:** 9:31, 19:27; **4:** 5:22, 15:18; **5:** 1:13, 11:09, 21:05; **6:** 7:00, 16:56; **7:** 2:52, 12:47, 22:43; **8:** 8:39, 18:34; **9:** 4:30, 14:25; **10:** 0:21, 10:17, 20:12; **11:** 6:08, 16:04; **12:** 1:59, 11:55, 21:50; **13:** 7:46, 17:42; **14:** 3:37, 13:33, 23:29; **15**: 9:24, 19:20; **16:** 5:15, 15:11; **17:** 1:07, 11:02, 20:58; **18:** 6:53, 16:49; **19:** 2:45, 12:40, 22:36; **20:** 8:32, 18:27; **21:** 4:23, 14:18; **22:** 0:14, 10:10, 20:05; **23:** 6:01, 15:56; **24:** 1:52, 11:48, 21:43; **25:** 7:39, 17:34; **26:** 3:30, 13:26, 23:21; **27:** 9:17, 19:12; **28:** 5:08, 15:04; **29:** 0:59, 10:55, 20:50; **30:** 6:46, 16:42.

May 1: 2:37, 12:33, 22:28; **2:** 8:24, 18:20; **3:** 4:15, 14:11; **4:** 0:06, 10:02, 19:58; **5:** 5:53, 15:49; **6:** 1:44, 11:40, 21:36; **7:** 7:31, 17:27; **8:** 3:22, 13:18, 23:13; **9:** 9:09, 19:05; **10:** 5:00, 14:56; **11:** 0:51, 10:47, 20:43; **12:** 6:38, 16:34; **13:** 2:29, 12:25, 22:20; **14:** 8:16, 18:12; **15:** 4:07, 14:03, 23:58; **16:** 9:54, 19:50; **17:** 5:45, 15:41; **18:** 1:36, 11:32, 21:27; **19:** 7:23, 17:19; **20:** 3:14, 13:10, 23:05; **21:** 9:01, 18:57; **22:** 4:52, 14:48; **23:**

0:43, 10:39, 20:34; **24:** 6:30, 16:26; **25:** 2:21, 12:17, 22:12; **26:** 8:08, 18:03; **27:** 3:59, 13:55, 23:50; **28:** 9:46, 19:41; **29:** 5:37, 15:33; **30:** 1:28, 11:24, 21:19; **31:** 7:15, 17:10.

These times assume that the spot will be centered at System II longitude 302°. If the Red Spot has moved elsewhere, it will transit 1⅔ minutes earlier for each degree less than 302° and 1⅔ minutes later for each degree more than 302°.

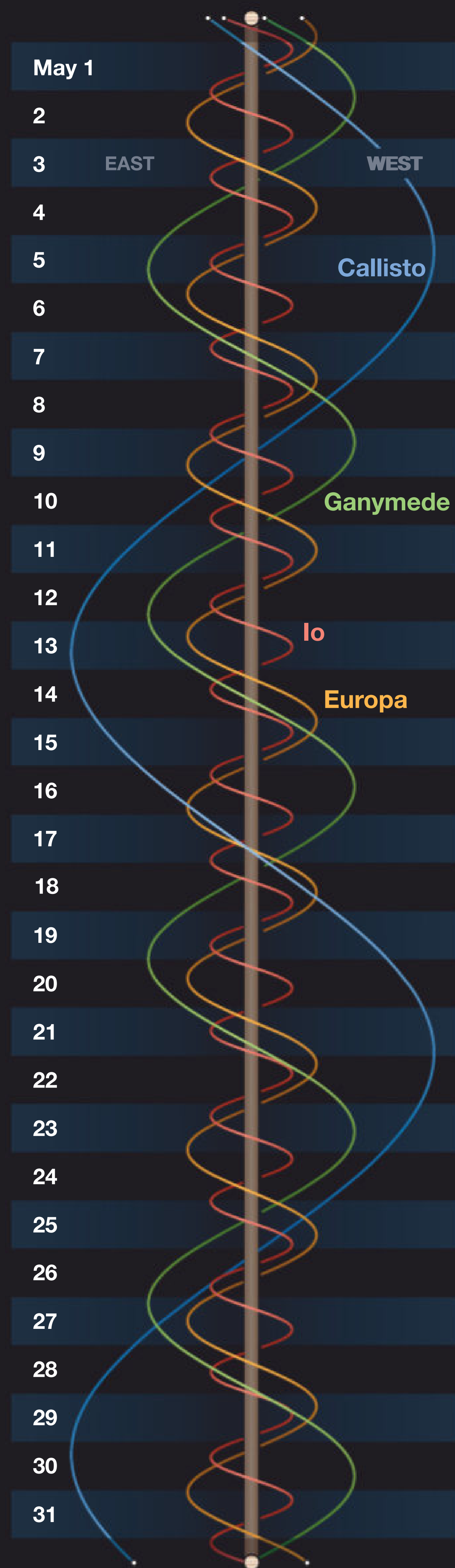
Features on Jupiter appear closer to the central meridian than to the limb for 50 minutes before and after transiting. A light blue or green filter slightly increases the contrast and visibility of the planet's reddish and brownish markings.

Phenomena of Jupiter's Moons, May 2019

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

Every day, interesting events happen between Jupiter's satellites and the planet's disk or shadow. The first columns give the date and mid-time of the event, in Universal Time (which is 4 hours ahead of Eastern Daylight Time). Next is the satellite involved: **I** for Io, **II** Europa, **III** Ganymede, or **IV** Callisto. Next is the type of event: **Oc** for an occultation of the satellite behind Jupiter's limb, **Ec** for an eclipse by Jupiter's shadow, **Tr** for a transit across the planet's face, or **Sh** for the satellite casting its own shadow onto Jupiter. An occultation or eclipse begins when the satellite disappears **(D)** and ends when it reappears **(R)**. A transit or shadow passage begins at ingress **(I)** and ends at egress **(E)**. Each event is gradual, taking up to several minutes. Predictions courtesy IMCCE / Paris Observatory.

Jupiter's Moons



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

Eyeing Jupiter

Get the most out of your time observing the planet king.

As the largest planet in our solar system, mighty Jupiter is in a class by itself. It's one of the brightest objects in the night sky, surpassed only by the Moon, Venus, and occasionally Mars. This year, brilliant Jupiter will be slowly cruising in front of the dense star clouds of the Milky Way in Ophiuchus, close to the border with Scorpius.

The combination of Jupiter's large size, its high surface brightness, and its dynamic atmosphere makes the gas giant an outstanding target for casual observers and solar system aficionados alike. The planet begins the month at a respectable 43.3 arcseconds across, swelling to 45.8″ by the end of May, just shy of its maximum apparent diameter this year of 46″ when it reaches opposition on the 10th of June.

Since the planet lurks at the southerly declination of –22° or lower this year, observers at mid-northern latitudes will require patience while awaiting moments of steady atmospheric seeing for the sharpest views. Plan to observe Jupiter a few hours past midnight in late May as it transits the meridian. This is when it's at its highest, and you can view it through less of Earth's turbulent atmosphere.

Spots, Belts, and Zones

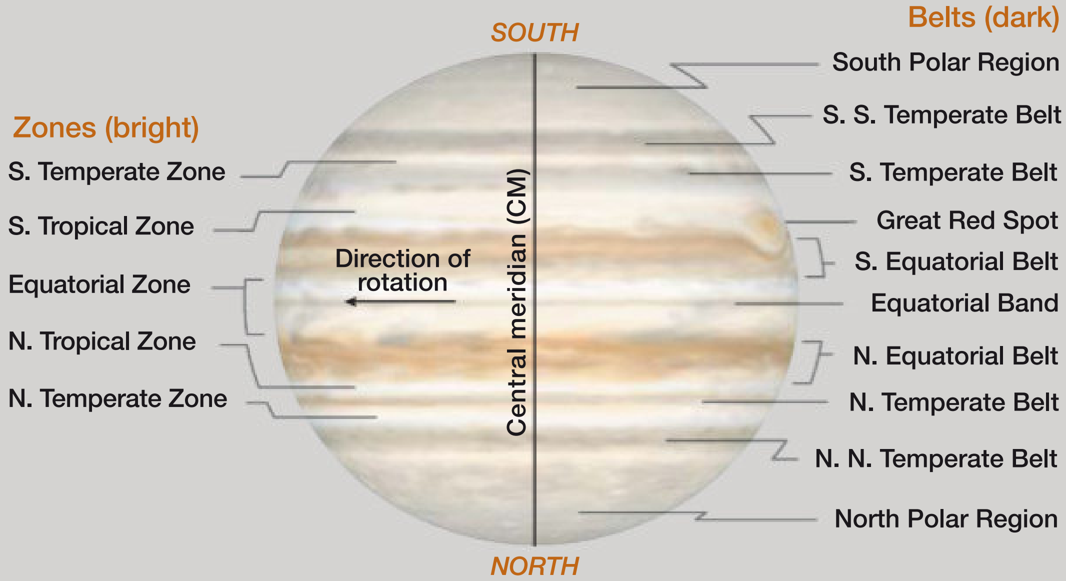
The planet's large size and substantial brightness allow for even modest apertures of 3 inches or more to reveal its most prominent features, the normally dark North and South Equatorial Belts. Between the two is the usually white Equatorial Zone, which has recently undergone a cyclic change. White ammonia clouds that typically encircle the planet's equator have cleared, revealing yellowish and brown cloud bands hidden from view (see page 10).

Other features visible in modest apertures include the narrow, ruddy Temperate Belts closer to the poles, with the South Temperate Belt hosting several large white oval storms and oblong reddish *barges* lasting for months or years. Flanking each of these belts are thin whitish zones closer to each of the majestic planet's grayish polar regions.

Activity within the belts and zones is in a constant state of flux, which observers can easily monitor with a moderate-aperture telescope of at least 6 inches. Barges and ovals slowly pass by or even merge with others, while white ovals have changed color from white to red and back again. Other swirls, streaks, and elaborate festoons are commonly seen along the boundaries of the belts. Even the often pale zones can have disturbances and eruptions of activity.

NASA / JPL-CALTECH / SWRI / MSSS / KEVIN M. GILL

NASA's Juno spacecraft captured this close-up of a reddish-brown barge in Jupiter's North Equatorial Belt as it swooped close to the planet on September 6, 2018.



▲The ever-changing features within Jupiter's cloudtops are identifiable by the belt or zone where they generally reside. South is up to match the view in most telescopes. Features rotate across the face of the planet from celestial east to west.

The Great Red Spot

Of all of Jupiter's swirling cloud features, the long-lived Great Red Spot (GRS) is best known. This immense anticyclonic storm resides in a notch within the South Equatorial Belt known as the Red Spot Hollow. Astronomers have observed this iconic feature continuously since the mid-19th century, but over the past century this gigantic system has been shrinking at an ever-accelerating rate. Spanning a massive 40,000 km during the late 1800s, it has slowly condensed to roughly 16,000 km, or slightly larger than the Earth (*S&T:* Mar. 2016, p. 18).

Although the GRS is relatively stable, it can often fluctuate in color and contrast. Throughout the late 1990s and early 2000s, it appeared a pale orange that was difficult to detect with small apertures. But in the past few years it has regained its distinctive, reddish-orange color, which makes it easy to spot in telescopes with apertures as small as 80 millimeters. Additionally, the whitish Red Spot Hollow helps to boost its contrast with the surrounding SEB. Your best bet for catching sight of this famous storm is to look within an hour of the time it transits the planet's central meridian. A table with the GRS transit times for May can be found on pages 50–51.

Slightly farther to the south of the GRS in the South Temperate Belt is Oval BA. This storm system is the result of three white oval mergers occurring in the late 1990s. Noted planetary imager Christopher Go noticed in early 2006 that Oval BA had changed to orange-red. Recently, Oval BA's color has been fading to the point of appearing white at the start of the apparition this year.

See close-up views of Jupiter in our feature beginning on page 14.

Dance of the Galilean Moons

Beyond the planet itself, Jupiter is attended by the four bright Galilean moons. All four are unique worlds in their own right and would be easily visible to the naked eye if they weren't closely orbiting the gas giant. While visible with any binoculars or telescope, these moons yield subtle, dusky albedo markings with larger instruments of 10 inches or more under exceptional seeing.

Typically, smaller scopes will permit observers to detect the size of each moon, ranging from Ganymede, the largest satellite in the solar system, to ice-covered Europa, which is slightly smaller than our Moon. A 6-inch scope under good conditions will resolve each into tiny disks of differing albedo and hue, ranging from yellowish Io closest to the gas giant at 1.1″ across, brilliant white Europa (1.0″), dusky Ganymede (1.7″), and grayish Callisto spanning 1.5″ farthest from the planet.

The best time to hunt for albedo markings on the Galilean satellites is when they transit the disk of Jupiter. The planet's bright clouds and belts help to significantly reduce the contrast of these icy moons and the background sky, permitting brief glimpses of their varied surfaces. A table of Jupiter's moon phenomena can be found on page 51.

▼Recent changes in the gas giant's Equatorial Zone have turned the normally white zone a yellowish-tan hue. South is up in this image.

Speaking of transits, a particularly spectacular one occurs within a few days of opposition on June 12 at 2:20 UT, beginning with Io and its shadow passing in front of the North Equatorial Belt, followed by Ganymede cutting across the north polar regions approximately one hour later. Occurring so close to opposition, Io's disk will overlay a portion of the moon's shadow. The timing of this event makes it particularly favorable for observers in western Europe, western Africa, eastern North America, and eastern South America.

Jupiter's dynamic atmosphere and attendant moons offer observers an endless source of activity to witness unlike anywhere else in our skies. The constant evolution and appearance of ovals, barges, festoons, and loop structures make the largest gas giant a popular target for imagers and observers alike. Additionally, comets and asteroids have struck the planet several times over the past 25 years, the most recent occurring in March 2016. There's a small chance you might witness a strike yourself. So be sure to turn your scope's gaze toward the king of the solar system early this year. You just might have a hard time turning it away again.

■ **RICHARD JAKIEL** observes and photographs the night sky from his home in the suburbs of Atlanta, Georgia.

JUPITER DIAGRAM: GREGG DINDERMAN / *S&T*; JUPITER: DAMIAN PEACH / CHILESCOPE

Rubies and Sapphires

These brilliant jewels offer respite to the weary soul.

The colors of stars are often compared to those of precious gemstones, with the coolest stars as our rubies and the hottest as sapphires. The stars are certainly precious to those of us who love the night sky, but how red or blue do they really look?

A star's color is rated by measuring its magnitude through two different filters, usually a blue (B) and a visual (V) filter. If you subtract the visual magnitude from the blue magnitude, the resulting number is called the color index (B – V). Very red stars have a positive color index, as much as 5.8, while color index is a negative number for the bluest stars.

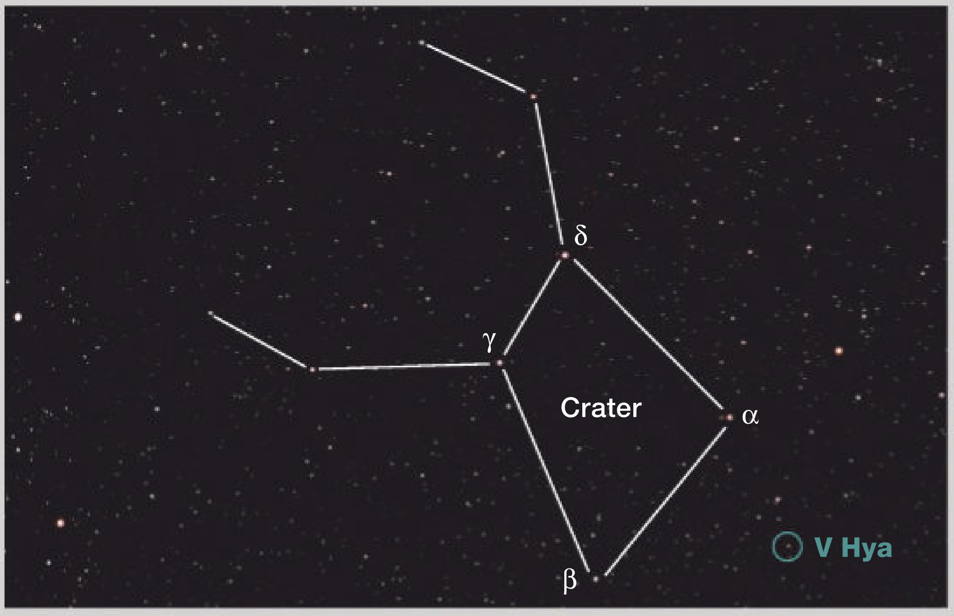
The reddest stars are red-giant carbon stars, which appear enticingly colorful to most observers. Like a normal red giant, a carbon star has a relatively cool surface temperature. But a carbon star's atmosphere is heavily laced with carbon compounds that absorb the blue wavelengths of visible light and leave the reds to reach our eyes. Carbon stars are also variable, and those with a large, slow change in brightness appear ruddiest when near the dim end of their range.

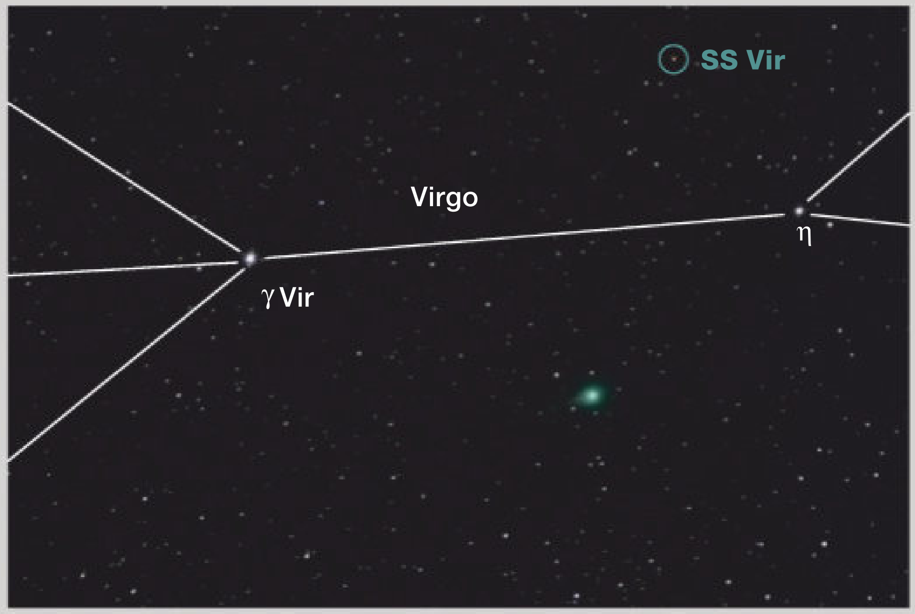
Let's start with one of the reddest carbon stars. **V Hydrae**, with an impressive color index of +5.5, sits beneath the base of Crater, the Cup. This remarkable star is already at its highest point in the sky at darkfall in early May, so it's best to catch it as soon as you can. V Hya has two superimposed periods of variation. The 17-month cycle has an amplitude of about 2 magnitudes, and the 17-year cycle has an amplitude of about 3½ magnitudes. The combined effect of the two periodicities yields an overall magnitude range of 6.0 to 12.3. The current variation is roughly 7th to 9th magnitude, so the star shouldn't be hard to catch. You can compare V Hya to a normal red giant by looking at HIP 53050, an 8.0-magnitude star 17′ to the south-southwest. Quite a difference!

V Hydrae is believed to have a smaller, unseen companion in an orbit that takes it through or near the extended atmosphere of V Hya at closest approach every 8.5 years. This feeds an accretion disk of material surrounding the companion, which then launches high-speed, Mars-size blobs of plasma into space. Studies by Raghvendra Sahai (NASA Jet Propulsion Laboratory) and colleagues suggest that a directional wobble of the plasma-hurling jets makes those great balls of fire pass alternately behind and in front of V Hya. Every 17 years, when the blobs are passing in front of the star, extinction associated with them causes V Hydrae's extra-deep minima.

Spica shines above a snowy field on a cold January morning. The lopsided square of Corvus, the Crow, hangs nearby.

BOB KING





▲ *Left:* Though located in the constellation Hydra, the variable carbon star V Hydrae may be easier to find by star-hopping from Crater, the Cup. Find it 3½° south-southwest of Alpha Crateris and about 5° west-northwest from Beta Crateris. *Right:* The semi-regular variable star SS Virginis is an easy star-hop from Eta Virginis. SS Vir reached maximum in March and is now slowly dimming and reddening. The green light shining south of SS Vir in this 2009 image is the non-periodic Comet Lulin (C/2007 N3), discovered by Ye Quanzhi and Lin Chi-Sheng from Lulin Observatory.

Not quite as red but better placed in the sky, **SS Virginis** gives us a longer window of opportunity. This semi-regular variable has a color index of +4.2 and a period of 361 days. The rise from minimum to maximum light takes up 53% of the cycle. Individual cycles have an amplitude of about 2.2 to 2.6 magnitudes, with some maxima reaching magnitude 6.0 and some minima dipping as low as magnitude 9.6. SS Vir reached maximum in mid-March, and you'll be able to watch the star fade and redden through the summer months for as long as it graces your evening sky.

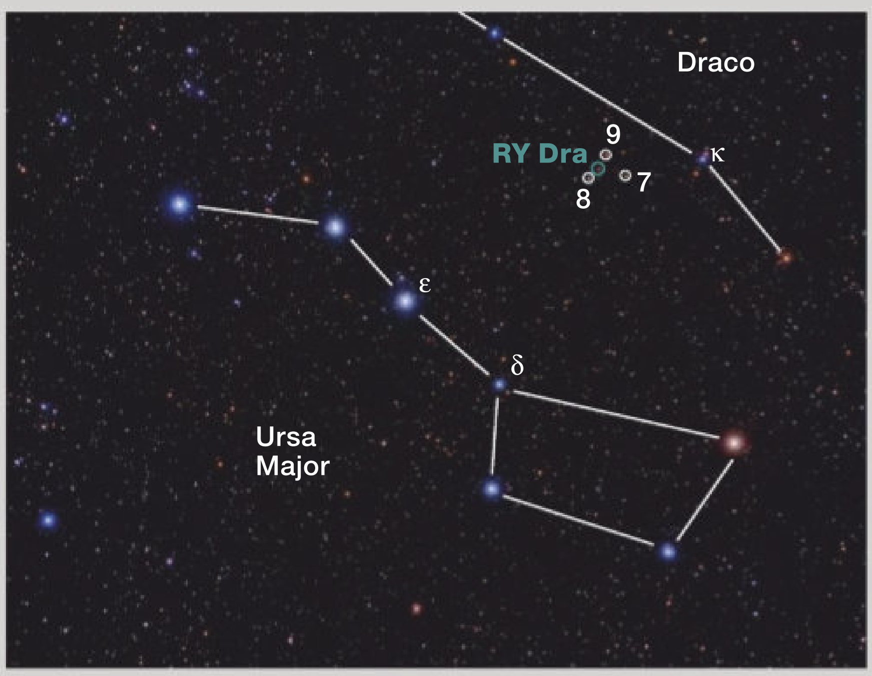
Conveniently located about halfway between 8 Draconis and the red giant 9 Draconis, **RY Draconis** is a semi-regular variable with a color index of +3.3. A 2016 paper by John Percy and Emily Deibert in *The Journal of the American Association of Variable Star Observers* indicates a pulsation period of approximately 277 days and a long secondary period of 1136 days or more. No matter when you see it in its cycle, RY Dra is a cinch to spot because its visual-magnitude range is 5.9 to 8.0. The bracketing stars 8 and 9 Dra shine at magnitudes 5.2 and 5.4, respectively.

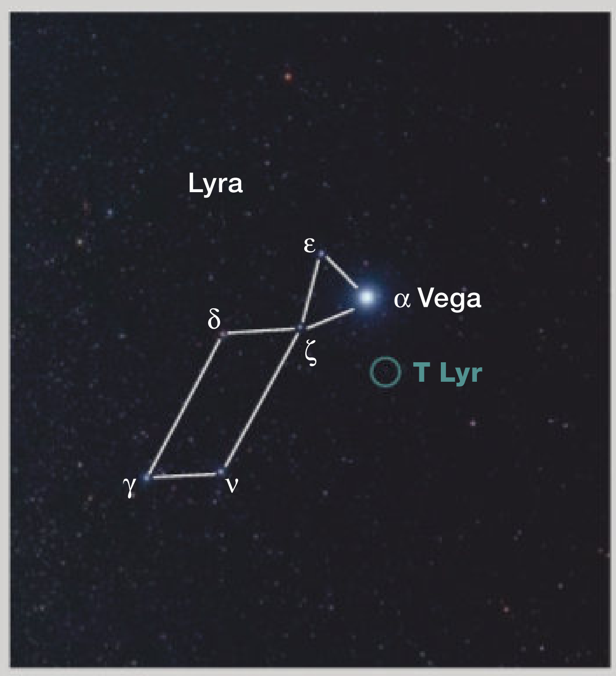
If you miss V Hydrae, you'll have another chance to spot a deeply red star. **T Lyrae** also has a color index of +5.5 and will be with us throughout the summer and much of the fall. According to the International Variable Star Index (**aavso.org/vsx**), this irregular variable shines anywhere from a visual magnitude of 7.5 to 9.2, so it's another carbon star that's easy to observe anytime it's well placed in your sky.

Take the color indices of extremely red stars with a grain of salt. They are well beyond the accurately determined colors of the standard stars that are the basis for calibration. The far blue end of the color scale is also problematic.

The blue of our celestial sapphires isn't as easy to discern as the red of carbon stars. The negative range of a color index is quite small. In fact, for a theoretical star of infinite temperature, the color index would only be −0.46, not very far removed from a star with a color index of +0.2, which appears essentially white to the eye. Because of this, we gather no deep blue sapphires, just pale ones.

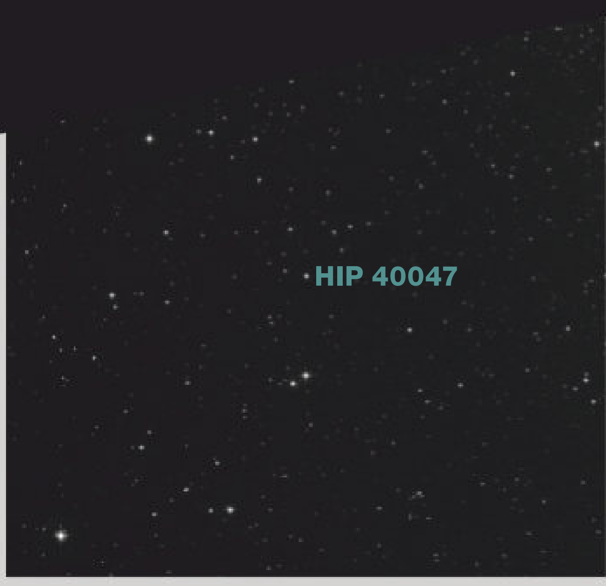
Main-sequence stars (dwarf stars, designated by the letter V) reach their visually bluest at spectral types near O9V. Stars hotter than this release their additional output in the invisible





▶ *Left:* RY Draconis lies near the Dragon's tail, between 8 and 9 Draconis. The line of stars defined by Kappa, 4 Dra, and 6 Dra serves as a convenient starting point for a star-hop. *Right:* The ruby-red carbon star T Lyrae forms a triangle with brilliant white Vega and 4.4-magnitude Zeta Lyrae.

V HYDRAE: TILL CREDNER; SS VIR: JEREMY PEREZ; RY DRACONIS: AKIRA FUJII; T LYRAE: AKIRA FUJII



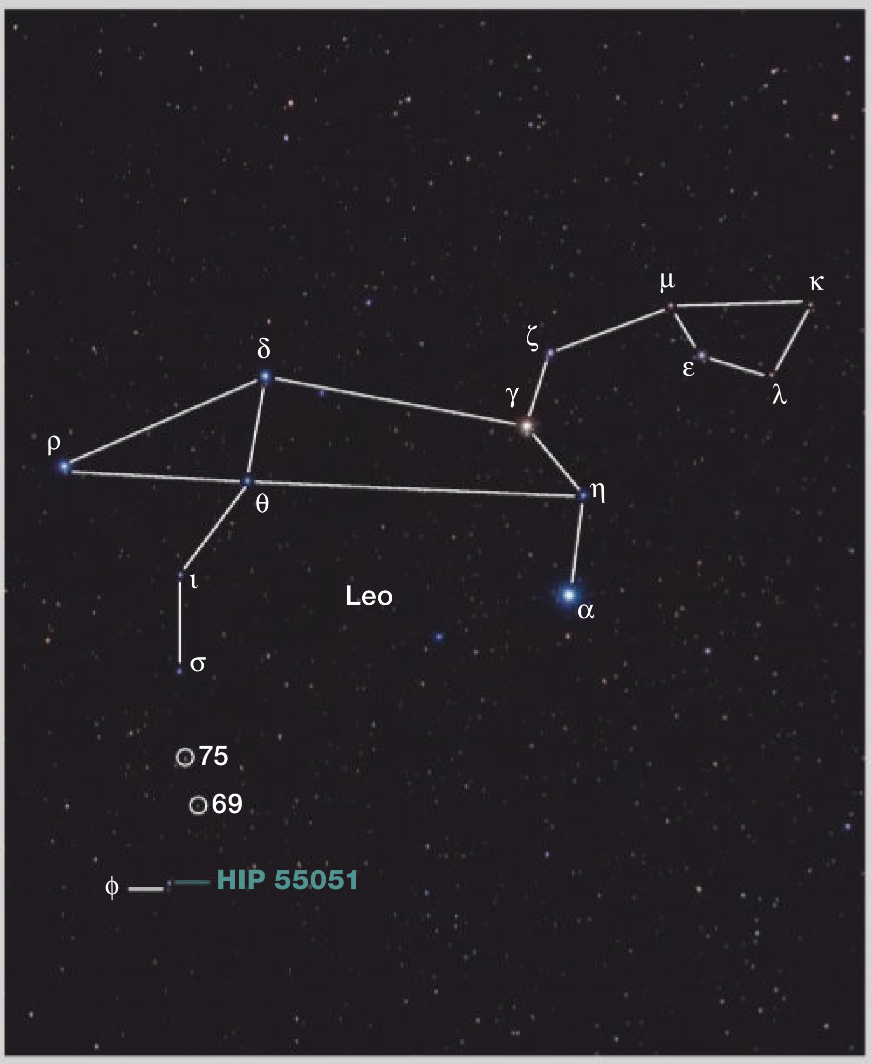
▲ *Left:* The main-sequence subdwarf star HIP 40047 lies in a mostly undistinguished patch of northern sky. However, a pretty pair of stars, the eastern component yellow, the western orange, sparkles 10 arcminutes due south of HIP 40047. *Middle:* The blue light of 7th-magnitude HIP 52849 shines 3½° north-northwest of 46 Leonis Minoris. *Right:* Ophiuchus, the Serpent Bearer, also carries the hot subdwarf HIP 81145. Find the blue star 1¾° south-southwest of 12 Ophiuchi.

ultraviolet, so they don't look any bluer to us. Hot subdwarf stars (sdO and sd*B*) are marginally bluer, but there aren't many bright enough to flaunt their color. Dwarf and subdwarf stars both produce their heat via hydrogen fusion, but subdwarfs are 1.5 to 2 magnitudes dimmer than dwarf stars of the same spectral type.

Beaming at magnitude 9.6, **HIP 40047** in Camelopardalis has a color index of −0.30 and is one of the brightest sdO stars we can see. Although it's a little past its prime when this issue of the magazine comes out, the star is circumpolar at mid-northern latitudes and still high enough to profitably observe at nightfall throughout May. I was rather enamored with this star when I first saw it. Through my 130-mm scope, this is about the faintest blue star whose color I can distinguish. Roughly the same magnitude as HIP 40047, the two stars 10′ to its south cinch the effort, with the eastern star gleaming pale yellow and the western one smoldering orange. Looking from star to star is a big help in assessing the trio's colors.

Keeping to targets brighter than HIP 40047, here are some other blue stars you can try. **HIP 52849** in Leo Minor is a 7.0-magnitude main-sequence star (O9V) with a color index of −0.23. In Leo just 12.8′ north-northwest of Phi (φ) Leonis, 7.4-magnitude **HIP 55051** has a color index of −0.21. It's also a main-sequence star and has a spectral type of *B*2/3V. Compare it to yellowish Phi to see if you can tell the difference. Virgo's brightest star, **Spica**, is a spectroscopic binary whose stars are too close together to view separately. Their spectral types are *B*1V and *B*4V, and their combined color index is −0.24. Spica is rather dazzling through a telescope, and I find it easier to see the color through binoculars. Brighter than our first subdwarf and nearly as blue, the sd*B* star **HIP 81145** in Ophiuchus shines at magnitude 8.9 and has a color index of −0.28.

As Leslie Peltier, author of the charming book *Starlight Nights*, once said, "Were I to write out one prescription designed to help alleviate at least some of the self-made miseries of mankind, it would read like this: One gentle dose of starlight to be taken each clear night just before retiring." Let's take a bit of our ease from the starlight of the night's rubies and sapphires.



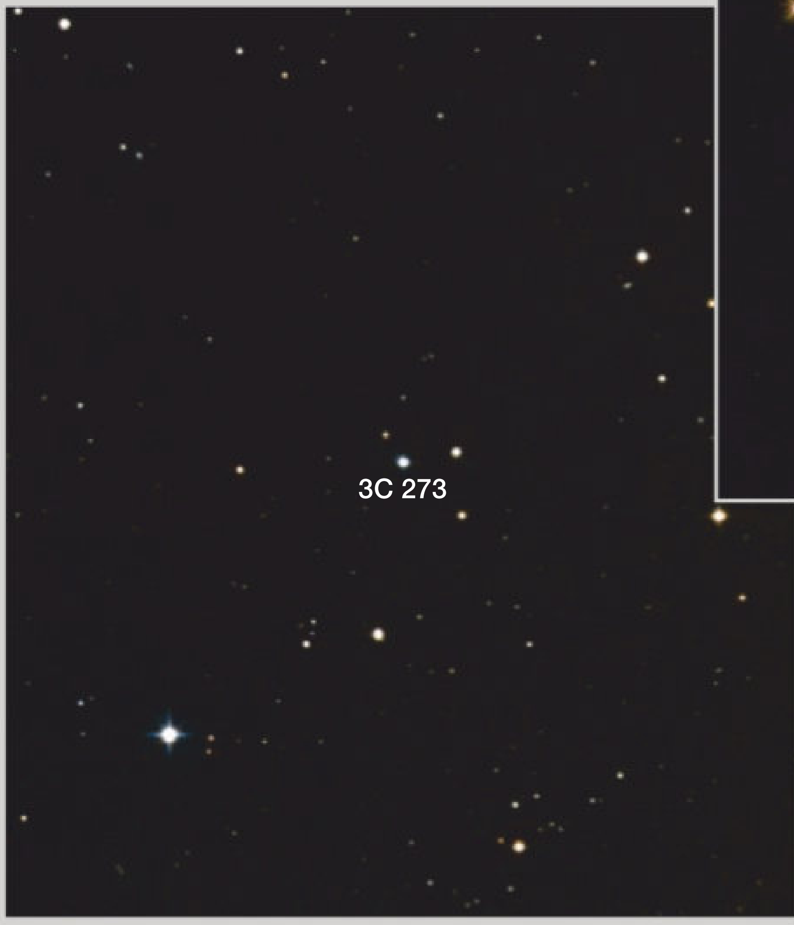
◀ Follow a southern meander from Sigma Leonis, passing through 75 and 69 Leonis to find your way to HIP 55051. This 7th-magnitude star lies less than 13 arcminutes from Phi Leonis.

■ Contributing Editor **SUE FRENCH** welcomes your comments at **scfrench@nycap.rr.com.**

FURTHER READING: Find a data table that includes positions and color indices for the stars discussed here at **https://is.gd/DSWMay2019.**

Join the Billion-Light-Year Club

Photons that have traveled for billions of years instill a sense of awe in the author.



◀▲ **ANCIENT PHOTONS.** The quasar 3C 273, at a distance of some 2 billion light-years in the direction of Virgo, was the first object to be identified as such. A giant elliptical galaxy that hosts a supermassive black hole, it's also the source of relativistic jets. The quasar can be spotted in a 6-inch scope, but a detailed finder chart or image is helpful.

My fascination with billion-light-year galaxies began nearly 40 years ago when I read about the fabulously rich and distant Corona Borealis Cluster (Abell 2065) in *Burnham's Celestial Handbook*. The cluster features several hundred elliptical (E) and lenticular (S0) galaxies packed into a 30′ circle, the size of the full Moon. Due to the remoteness of the cluster, its brightest members are quite dim — close to 16th magnitude — and Robert Burnham, Jr. warned they were "far beyond the reach of the usual amateur telescope."

This was a fair assessment back in the 1970s. But a few years later I netted seven elusive fuzzies using my 18-inch reflector — after considerable effort. All were featureless glows, but the largest was 15.4-magnitude **PGC 54876** — a 15″ smudge just 1.4′ east of an 11.3-magnitude star. Nearby **PGC 54883** and **PGC 54888** formed a tight north-south pair that required high power to split.

PGC 54846, the brightest cluster member, is situated 20′ south-southwest of the core and 1.5′ northeast of a 9.3-magnitude star. When I nudged the star just outside the field, the galaxy was visible with direct vision. But the real reward for this cosmic archaeologist was peering into the distant past and savoring the 1 billion-year-old light.

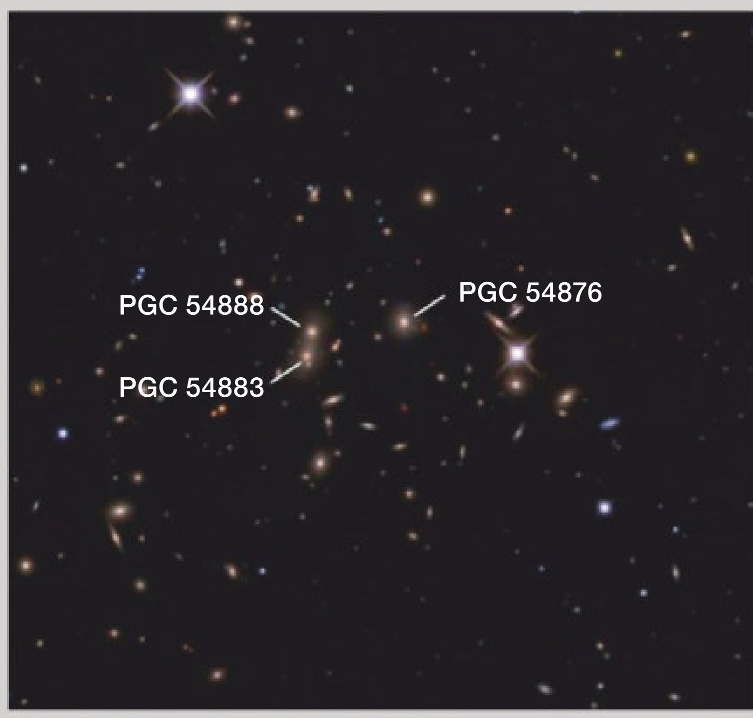
Galaxies classified as type cD are enormous ellipticals that dominate the centers of rich clusters. They've grown in mass and size through mergers and are visible at greater distances than typical galaxies. A gargantuan specimen is **IC 1101**, located 80′ northwest of 5.3-magnitude 3 Serpentis. This galactic leviathan houses a supermassive black hole that weighs in at 40 to 100 billion solar masses. IC 1101 is enshrouded in an immense halo (the largest known) of very diffuse light extending 4 million light-years. The envelope consists of stars stripped from neighboring galaxies in Abell 2029 and would fit 25 Milky Ways side by side.

Despite its vast distance (similar to Abell 2065), IC 1101 shines at magnitude 13.7. It was visible continuously at 280× as a 15″ × 10″ ellipse of even surface brightness. The galaxy is centered within a 9-member circlet of 12th- to 14th-magnitude stars spanning 6′ across.

ESO 146-5 is another monstrous cD galaxy, found in the southern constellation Indus (note that this target is out of reach for observers in North America). This 15th-magnitude heavyweight rules the cluster Abell 3827 and is an extreme case of galactic cannibalism — four giant ellipticals are being devoured in its core.

ESO 146-5 lies ½° southwest of orange 5.6-magnitude Kappa^2 (κ^2) Indi. A 12th-magnitude star is parked 1.4′ northwest, providing a handy reference to pinpoint the location. The galaxy was barely visible in an 18-inch as a feeble 15″ glow — its ancient light having sped across the universe for 1.3 billion years.

A 2010 study using the Gemini South telescope revealed ESO 146-5 has gravitationally lensed a background galaxy at 2.5 billion light-years. The



▶ **A CLUSTER IN CORONA BOREALIS.** Abell 2065, a cluster of galaxies just shy of 1 billion light-years away in the Northern Crown, counts several hundred elliptical and lenticular galaxies. The author was able to spot seven of these faint galaxies using his 18-inch reflector. How many can you see?

▲ *Left:* IC 1101 houses a supermassive black hole that weighs in at 40 to 100 billion solar masses. The diffuse halo that surrounds the galaxy extends for some 4 million light-years, the largest known to date. Galaxies such as this cD elliptical are thought to grow to their gargantuan sizes through mergers. *Right:* ESO 146-5 is a cD galaxy in the southern constellation Indus. (This is not accessible to North American observers — you'll have to travel south to see this target.) This supergiant elliptical in the cluster Abell 3827 appears to be devouring at least four other galaxies. It also shows features of the gravitational lensing of a background galaxy that shows up as the wispy blue structures in the image.

IC 1101: NASA / SDSS; ESO 146-5: ESO

lensed image forms a ring-shaped structure that threads around the core. And a more distant galaxy (4.5 billion light-years) is gravitationally distorted into an extended tangential arc. Based on these features the mass of ESO 146-5 is up to 30 trillion solar masses — the highest known for any galaxy out to 1.5 billion light-years.

The farthest cD galaxy I've managed is 15.2-magnitude **PGC 37477** (also known as MCG +04-28-097), a short 2° star-hop from 6.6-magnitude 1 Comae Berenices. This giant X-ray-emitting galaxy anchors the rich cluster Abell 1413. It displays a highly elliptical halo that mimics the north-south elongation of the cluster, an alignment feature seen with other cD galaxies. I've only viewed this galaxy in my 24-inch reflector, but it should be within reach of an 18-inch.

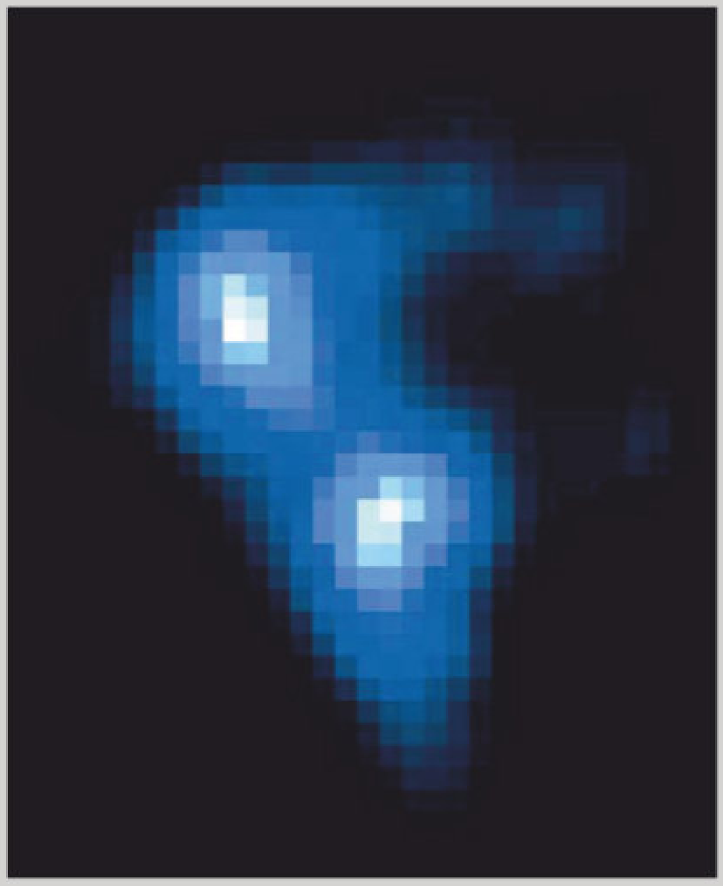
In 1956 American astronomers Milton Humason, Nicholas Mayall, and Allan Sandage published a landmark survey of 800 galactic redshifts that provided a solid basis for the Hubble constant (H_0). The shifts in the spectral lines of PGC 37477 implied a high recessional velocity of 42,844 km/s. Using an average modern value for H_0 of 70 km/s/Mpc, its light-travel time is a whopping 1.8 billion years.

To reach further back in time let's take a look at a few quasars, the most luminous objects in the universe. The optically brightest quasar, **3C 273**, was first cataloged as a radio source in 1959. A lunar occultation in 1962 allowed Caltech astronomer Maarten Schmidt to associate 3C 273 with a 13th-magnitude stellar object. In December that year Schmidt obtained a spectrum using the 200-inch Palomar telescope, but he couldn't make any sense of the emission line wavelengths. The "eureka" moment came a month later when he suddenly realized the hydrogen emission spectrum (Balmer series) was redshifted by 16%, implying a light-travel time of an incredible (at the time) 2 billion years.

Quasar 3C 273 shines with a mean visual magnitude of 12.8 and is visible in a 6-inch scope, but over time it can vary from 12.2 to 13.6. You'll need a detailed finder chart to make a positive identification as a half-dozen Milky Way stars from 12th to 13th magnitude lie within 10′. The quasar displays a knotty, relativistic jet with optical, radio, and X-ray emission. Although the jet isn't considered within range of amateur telescopes, I've glimpsed it at 813× as a thin spike through Jimi Lowrey's 48-inch telescope in west Texas.

CTA 102 was discovered in Pegasus in 1960 at Caltech's Owens Valley Radio Observatory, and it's the rock star of quasars. Russian astronomer Nikolai Kardashev caused a stir in 1963 when he proposed CTA 102 was a beacon from an advanced civilization based on the shape of its radio spectrum. Follow-up observations, which showed CTA 102 was a variable radio source with a period of 100 days, added fuel to this speculation. In 1965 Maarten Schmidt determined a redshift of 1.037, yielding a light-travel time of 8 billion years. But the media excitement inspired The Byrds to muse on extraterrestrial life in the 1967 recording "C.T.A.-102."

CTA 102 is classified as an optically violent variable quasar. It contains high-energy plasma jets launched from a supermassive black hole — one of which is pointed in our direction. As we look down the throat of the jet, changes in the black hole's accretion disk can trigger dramatic flares. CTA 102 has a normal quiescent brightness of only 17th magnitude, but it staged an epic show that began in November 2016. It was fascinating to follow the gyrations in brightness over several nights. The outburst peaked on Decem-



▲ *Left:* Abell 1413, a cluster that houses PGC 37477 among its 300 members, is located between Leo and Coma Berenices at a distance of almost 2 billion light-years. Strong interactions between the gravitationally bound galaxies heat up the intergalactic gas to such high temperatures that it emits X-rays. *Right:* The quasar APM 08279+5255 lies more than 12 billion light-years away. This means that the photons that left it have traveled for some 90% of the age of the universe. This Chandra X-ray image of outflows from the source shows a double structure that results from gravitational lensing by a massive foreground object.

ber 29th at an astonishing apex: The pre-solar light of CTA 102 reached magnitude 11.3 and was easily in the range of a 4-inch scope!

But of all my observations of ancient light, the long-distance title is held by 16.2-magnitude **APM 08279+5255**. This radio-quiet quasar in Lynx was found serendipitously in 1998 during a spectroscopic survey of carbon stars. With a phenomenal light travel time of 12.1 billion years, APM 08279+5255 appeared to researchers to be "easily the most intrinsically luminous object known." But they cautioned, "the prodigious nature of this object is most likely a consequence of gravitational lensing."

Follow-up investigations in 1999 utilized the near-infrared camera on the Keck I telescope and the near-infrared spectrometer (NICMOS) on the Hubble Space Telescope. These studies confirmed there are three lensed images separated by 0.4″ with the light amplified between 90 and 100 times. A 2008 analysis of the molecular CO properties trimmed the magnification boost to 4, indicating the quasar's intrinsic luminosity exceeds 1,000 trillion times (10^{15}) the Sun's luminosity.

Visually, APM 08279+5255 was just a barely-there speck in my 18-inch scope. But it was simultaneously thrilling and humbling to contemplate that those few photons had been traveling at 186,000 miles/second for nearly 90% of the age of the universe!

■ Contributing Editor **STEVE GOTTLIEB** is often looking for new "far out" experiences at dark sites in Northern California. His email is **astrogottlieb@gmail.com**.

The Billion-Light-Year Club

Object	Mag(v)	*z*	Light Travel Time (Gyr)	RA	Dec.	Comments
PGC 54876	15.4	0.07	0.9	15^h 22.4^m	+27° 43′	Abell 2065
PGC 54846	15.1	0.08	1.0	15^h 21.9^m	+27° 25′	Abell 2065
IC 1101	13.7	0.08	1.1	15^h 10.9^m	+05° 45′	Abell 2029
ESO 146-5	15.0	0.10	1.3	22^h 01.9^m	–59° 57′	Abell 3827
PGC 37477	15.2	0.14	1.8	11^h 55.3^m	+23° 24′	Abell 1413
3C 273	12.8	0.16	2.0	12^h 29.1^m	+02° 03′	First identified quasar
CTA 102	17.3	1.04	7.9	22^h 32.6^m	+11° 44′	V=11.3 maximum
APM 08279+5255	16.2	3.91	12.1	08^h 31.7^m	+52° 45′	Most distant viewed

Distance is expressed as light travel time. An average value of H_0 = 70 km/s/Mpc was used to calculate distances using redshifts. Visually, an object's size is often smaller than the cataloged value and varies according to the aperture and magnification of the viewing instrument. Right ascension and declination are for equinox 2000.0. For more targets, see **https://is.gd/GDMay2019**.

PGC 37477: ESA / HUBBLE / NASA; APM 08279+5255: NASA / CXC / PSU / G. CHARTAS / M. WEISS

The Omegon Mini Track is a low-cost and lightweight tracker with a purely mechanical, spring-driven drive. It mounts to any solid tripod for tracked wide-field images of the night sky.

A Low-Tech Sky Tracker

The new Omegon Mini Track LX2 provides no-frills sky tracking for wide-field astrophotos, no batteries required!

A CLASS OF PRODUCT that has seen a lot of entries in the last few years is the low-cost sky-tracker. These motorized mini-mounts allow for tracked images of the Milky Way and large deep-sky targets through camera lenses with a minimum of cost and fuss to set up. I have several and love them.

But as might well have happened to you, I've found myself at a dark site only to find the tracker fail just when I needed it most. Its batteries were dead on arrival or died in the night. Did I have a spare set? Of course not!

Here's an answer: The Omegon Mini Track LX2, a tracking head that doesn't require batteries. Its rotation is driven by a clockwork mechanism, which is in fact a repackaged kitchen timer. You just wind up the LX2, frame your subject, and it ticks away and tracks!

ALL PHOTOS BY THE AUTHOR

Mini Track LX2

U.S. Price: $129
($159 with ball head)
omegon.eu

What We Like

Low-tech reliability

Lightweight and inexpensive

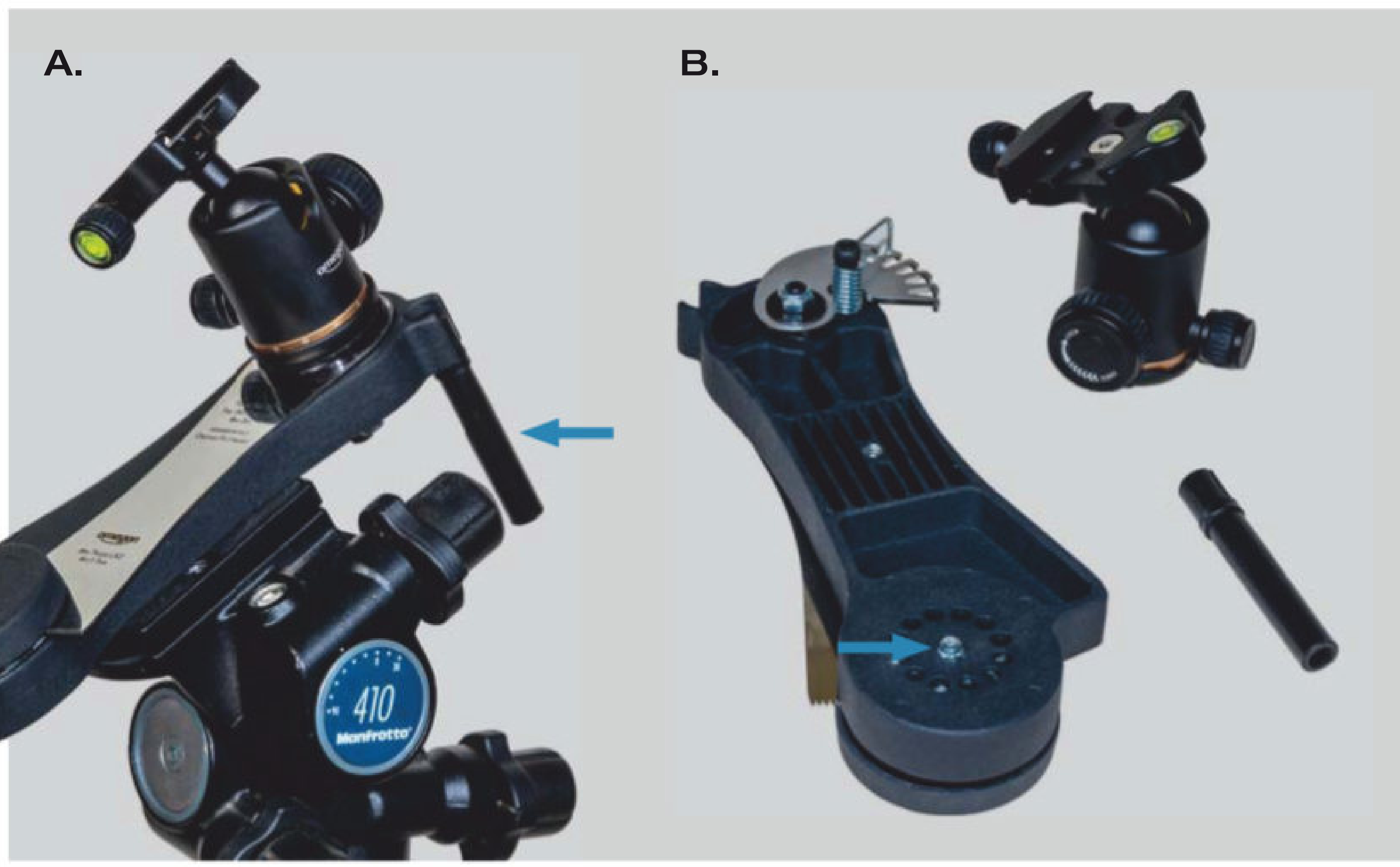
Refreshingly analog!

What We Don't Like

Rough tracking accuracy and polar alignment

Less accurate with telephoto lenses

Limited nightscape capability



Low-Tech Design

The design is an invention of Italian astrophotographer Christian Fattinnanzi and has been brought to market by the German telescope shop Omegon. Fattinnanzi's goal with the Mini Track was to produce a tracker that was reliable, low-cost, and lightweight. The design works well on all those points.

The Mini Track's sector drive provides an hour of tracking before it needs to be rewound and reset. That's more than enough for most wide-field images anyone is likely to want to take. With the fast lenses normally employed in tracked landscape astrophotography, exposures are typically no more than 2 to 4 minutes each, so an hour of tracking provides plenty of time to shoot lots of sub-frames for later stacking.

The Mini Track, with its optional ball head, weighs just 0.8 kg (1.7 pounds). This is less than the 1.3 to 1.7 kg (2.8 to 3.7 lb) weight, with batteries and ball head, of some of the motorized trackers I have. That could be important for airline travel. And its compact design makes it easy to stow in a kit bag for use at any time.

The bottom surface is tapped with a single ¼-20 socket for attaching the tracker to any tripod head. The top has a ⅜-16 stud bolt for attaching any standard ball head. Our test unit came with the Omegon-branded ball head. It worked very well, providing a solid but easy-to-adjust head to handle even heavy DSLRs and lenses, with the caveats noted below.

In keeping with the no-frills design, polar alignment is suitably low-tech, consisting of nothing more than a hollow plastic sighting tube. You simply adjust your tripod head to place Polaris in the soda-straw field of view. It worked well enough for wide-angle lenses.

I shot 3-minute test exposures over an hour with a 24-mm lens, and all but the very first and last frames showed untrailed stars. I found that the first frame or two were often trailed slightly as the tracker's spring settles in and begins turning at the correct rate. After that, it does turn at a consistent speed for the rest of the hour, with a satisfying "tick-tock" sound of its clockwork mechanism.

The last frame of any sequence, when the wind-up timer runs out of tension and stops tracking, is bound to be trailed. When the Mini Track ends a track it does so with a charming "ding!" of its little bell.

Design Limitations

The instructions, and even the engraved faceplate, state that the maximum recommended exposure time with the Mini Track, in minutes, is equal to 100 divided by the lens focal length. A 24-mm lens can be used for up to 4-minute exposures, more than enough

▼ **A.** The Mini Track body has a solid metal construction. To polar align, a hollow plastic tube (arrowed) is supplied for sighting Polaris. For testing, the author placed the Mini Track on a geared tripod head to ease aiming the rotation axis at Polaris. **B.** The bottom surface has a single ¼-20 hole for mounting the Mini Track on any solid tripod head. The little screw (arrowed) on the bottom of the clockwork timer is not to be loosened! Do so and it can be difficult to get the timer's little spur gear to mesh again with the sector gear without binding or play. **C.** The toothed sector gear provides the promised hour of tracking, from the starting position (tinted green here in this double exposure) to the end position (tinted red). Marks on the top plate indicate the time left. The drive goes "ping" when it ends. **D.** The tracker's spring tension can be adjusted with the multi-position prong. This notch (arrowed), labeled Position 1 in the instruction manual, works well for most loads and camera positions. **E.** When a heavy lens is aimed to the west with the camera off-balance, the spring might have to be set to Position 4 (arrowed) or 5. If the tracker slips when at the starting point of its track, increase the tension.

C.

D.

E.

for an f/2.8 or faster lens even under the darkest skies. Telephotos such as a typical 135-mm lens will be limited to no more than 1-minute exposures.

I confirmed this by shooting sets of 1- and 2-minute shots, each over an hour with a 135-mm lens. The thirty 2-minute shots were all unacceptably trailed, but of the sixty 1-minute shots, only about one in three showed noticeable trailing. The rest were fine, and they aligned and stacked well.

However, getting a well-exposed image in only a minute will require either a fast f/2 lens or the use of a higher, noisier ISO setting. Both might be a challenge for beginners equipped only with slow "kit zooms" and noisier, entry-level cameras.

Part of the tracking issues stem from the rough polar alignment possible with just a sighting tube. That caused the field to drift by several degrees over the span of an hour and contributed to the trailing at longer focal lengths. But in the 2-minute shots with the 135-mm lens, trailing also varied from frame to frame, from just acceptable to lots! The Mini Track's kitchen-timer drive is not an example of precision gearing, so adjust your expectations accordingly.

A version of the tracker is available to use in both Northern and Southern Hemispheres (Mini Track LX2 NS for $159), though it requires dissassembly to install an additional gear track and flip the mechanical drive. While I did not review that model, I would dread trying to polar align on Sigma Octantis using just a hollow tube! I have difficulty enough in Australia and Chile

A set of ten 3-minute exposures with a 24-mm lens aligned and stacked well. The Mini Track is best used with wide-angle lenses forgiving of the rough polar alignment and tracking inherent in the low-tech design.

using a good polar-alignment scope with an accurate reticle.

The advertising depicts many nightscape scenes taken with the Mini Track. Indeed, when I saw it I thought that this might be a great device for nightscape images, where you shoot, then later composite, tracked images of the sky (for untrailed stars) with untracked images of the ground (for the sharpest foreground detail). With motorized trackers that's easy to do — you simply turn off the motor for the ground shots.

However, once the Mini Track is turning there is no way to fully disengage the gears, stop tracking, and have the camera remain pointed at the same place. While winding the clockwork mechanism to the end of the track does stop it, doing so turns the camera up to 15°, thus ruining your composition and alignment of tracked and untracked images.

So this is not a device I can recommend to landscape photographers wanting to get into tracked Milky Way nightscapes on a budget. Nor is it suitable for advanced projects requiring tracking the same field all night, such as for a tracked time-lapse video.

Conventional motorized trackers, while more expensive, do make it possible to easily shoot images for tracked/untracked nightscape composites, or projects requiring unlimited tracking time, and from either hemisphere.

◀ When using a 135-mm telephoto lens, most 1-minute exposures (at left) were only slightly trailed. But every 2-minute exposure (at right) showed some level of trailing, in keeping with the Mini Track's exposure limit engraved on its sector gear.

Recommendations

The Omegon Mini Track LX2 is an ingenious and well-made device that delivers its promised reliable performance. There is no fuss over dead batteries, broken wires, or mobile apps that need programming. Just wind it up and it goes. It might be ideal for use in winter when the cold can kill batteries. As they said about Timex watches, it can take a licking and keep on ticking!

However, the price to pay is its limited abilities. I feel the Mini Track works best with wide-angle lenses for constellation and Milky Way images. While it could be utilized for some nightscapes, in practice it will be usable only for scenes where blurring of the dark ground in tracked images might not be objectionable.

With those limitations in mind, the LX2 is a fine entry-level tracker for beginners. Even more experienced photographers might like to have one in their kit bag as a backup should the high-tech tracker not work on that critical night under dark skies — or you forgot to bring fresh batteries.

■ Contributing Editor **ALAN DYER** remembers the days when trackers used to cost $1,000. He can be reached through his website at **amazingsky.com.**

 by Richard S. Wright, Jr.

Insect Eyes on the Deep Sky

A team of astronomers uses an innovative approach to create the world's fastest telescope system.

They say two heads are better than one. When it comes to astronomy, it's also true that two *optics* are better than one. As an amateur astrophotographer, I find it exhilarating to have two mounts running simultaneously, taking exposures of the same target. It's like getting two nights for the price of one! The first time I tried such a thing, I jokingly called it parallel processing. As a career software developer, the idea of using multiple CPUs to speed up a computational task is as obviously beneficial as having multiple painters working on your house at the same time. You get nearly a linear performance gain for every processing unit you can throw at it.

The same goes for professional astronomy. There are some areas of research where a parallel approach to imaging might be profitable, perhaps even to the point of leapfrogging what the world's largest instruments can do. One such application came up serendipitously in a discussion between two friends having dinner at a Toronto restaurant.

Those friends were Roberto Abraham of the University of Toronto, and Yale University's Pieter van Dokkum. Both were frustrated with the fact that most research projects have a budget and lifespan that far exceed the typical graduate student's tenure. It seemed nearly impossible to engage a graduate student on the new construction of an instrument through its completion, much less for him or her to use it to gather data. It would be great if it were possible to build an entry-level, cutting-edge system that didn't cost a minimum of $10 million or take 10 years to finish.

Both professors were trying to detect extremely low surface brightness features around galaxies. Current models predict that most galaxies should be surrounded by debris from their formation, observable as large swaths of stars in faint glowing halos. These halos are hard to detect, however. They are also thought to be quite large and extended, requiring wide-field instruments with fast focal ratios. But backscattered light commonly plagues fast optics and large mirrors, which creates even more challenges for detecting the very faintest of signals necessary for this kind of observational confirmation.

Then one professor had a crazy idea. For extended objects, all that's needed is a fast focal ratio on an optic with very low light-scattering characteristics. Van Dokkum, who is also an avid wildlife photographer, learned that Canon had just introduced a revolutionary new nano-coating technology with a subwavelength structure that the manufacturer claimed had unprecedentedly low-light-scatter characteristics. His idea was to put a commercial CCD camera behind one of these new lenses and shoot some galaxies to see if the camera picked anything up around it. Abraham didn't think it would work due to all the additional lens elements in a high-end telephoto lens, but van Dokkum was confident that Canon's new nano coatings might do the trick, so they agreed to give it a try.

CROWDED GAZE
Seen at left and above, **Dragonfly 1** stands ready for an evening of observing. Each of its 24 specially coated Canon 400mm f/2.8 lenses is mated with its own SBIG STF-8300M CCD camera. All 24 are aligned to image the same target simultaneously. Unless otherwise noted, all photos were provided by the Dragonfly team.

DENNIS DI CICCO (2)

The two acquired one of the Canon lenses and borrowed a slew of amateur equipment, including a tracking mount, a CCD camera and autoguider, and a commercial lens adapter. Without telling colleagues of their plan, they drove out to an observatory in Quebec. Their first target was M51, and after some modest integration time with the Canon 400mm f/2.8 lens, they found that it easily brought out the known stellar plumes around M51 and its companion, NGC 5195.

▲ **TRIPLED GAZE** Roberto Abraham mounts an autoguider camera on the proof-of-concept three-lens prototype.

A Dragonfly Is Born

With the proof-of-concept testing a success, the team decided to acquire three lenses and cameras, in order to accumulate more data simultaneously and get a stronger signal during each outing. The plan was to wait until there was a weather break and simply run out and get some data. However, every seasoned amateur knows what happens to the weather when you buy new gear. After several weeks without a clear night or with conflicting schedules, the team reevaluated its approach. The project really required a permanent home under better skies. It was then that they contacted Mike Rice, proprietor of New Mexico Skies (**newmexicoskies.com**), a remote telescope hosting facility, and the Dragonfly project quickly took root.

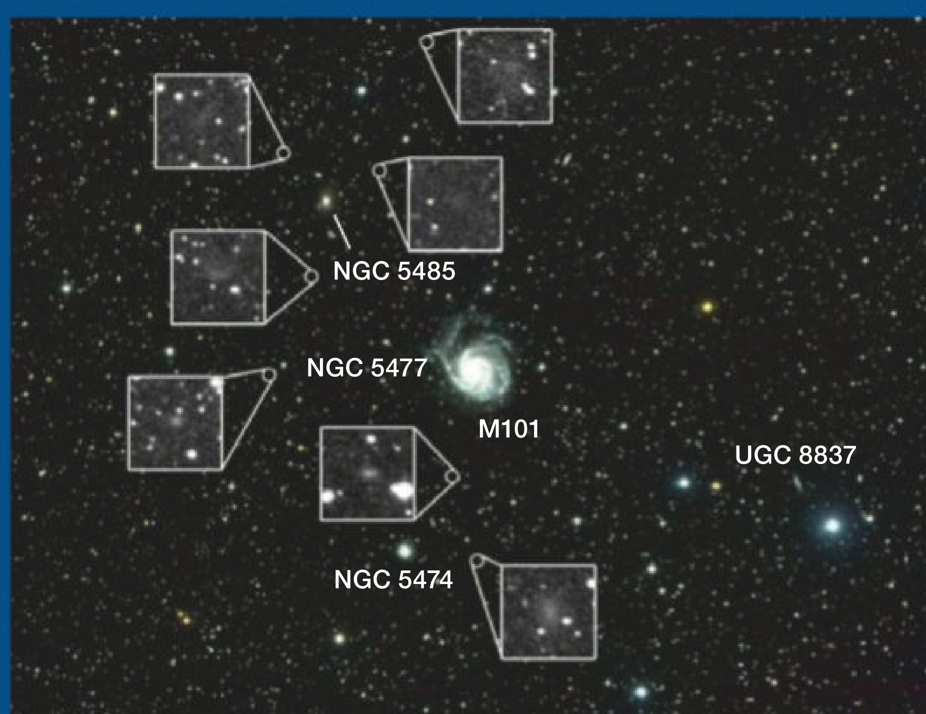
The first system assembled at New Mexico Skies in 2013 consisted of Canon 400mm f/2.8 lenses attached to individual SBIG STF-8300M CCD cameras riding atop a Software Bisque Paramount ME German equatorial mount as a proof-of-concept experiment. Proving its worth beyond a doubt, it quickly expanded to 5 lenses, then 8, 10, and 24. Currently, a whopping 48 lenses make up two sets of 24 on a pair of Paramount Taurus fork mounts. These two sets of "compound eyes" make up the Dragonfly Telephoto Array, a name bequeathed from their resemblance to the compound eyes of a dragonfly. The name also acknowledges the discovery of the nanostructure found on insect wings that inspired Canon's new nanocoatings as well as van Dokkum's fondness for photographing small creatures.

If a large segmented mirror is considered a single, large-aperture reflector, it's not a stretch to call a large, multi-lens refracting system all pointing at the same target in unison a large refractor. Forty-eight separate 400-mm f/2.8 telephoto lenses operating at full aperture have an effective aperture of almost 1 meter. The focal length, however, is still only 400 mm, and thus the *effective* focal ratio of the Dragonfly system is a staggering f/0.39. This is actually faster than the theoretical limit (f/0.5) for a single optic, making Dragonfly the world's fastest telescope system.

While this is amazing in terms of photographic speed, it is not without its tradeoffs and technological challenges. The system does not perform any interferometry to increase its angular resolution, so it operates at 0.8-arcsecond resolution, about the same resolving power as a 6-inch telescope. That's still a fairly good match to the atmospheric seeing conditions at a decent site.

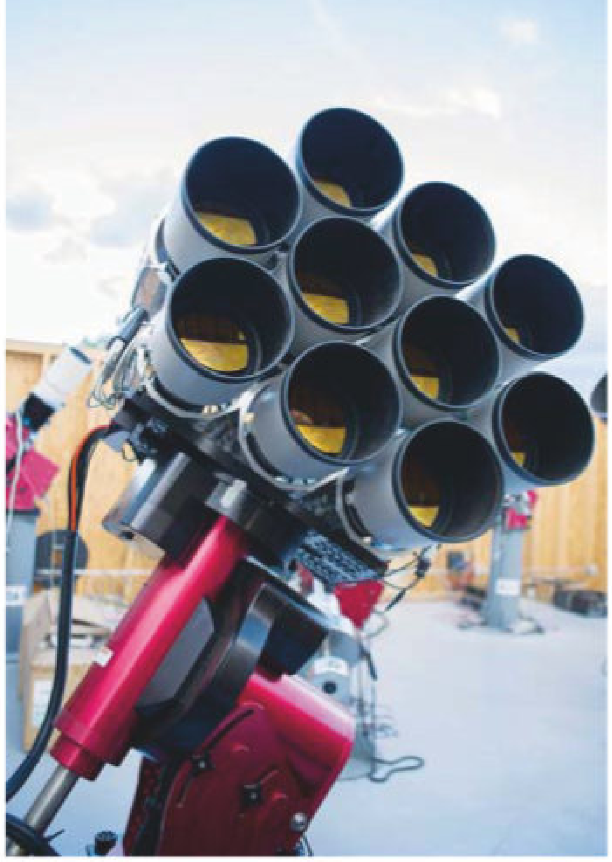
There is a strong allure to just stacking OTAs or camera lenses together to increase your imaging throughput. Plus, it sounds pretty easy, right? Just keep adding lenses. But the success of Dragonfly would not have been possible without the help of Mike and Lynn Rice, who solved some very significant logistics problems.

EIGHT EYES Dragonfly briefly operated with 8 lenses, producing the team's first discoveries of dwarf galaxies around M101 (inset). Current galaxy-formation models predict that large galaxies should be surrounded by hundreds of faint dwarf galaxies. Of the 7 that Dragonfly detected, only 3 were found to orbit the large spiral.



Think about all the things that can go wrong in an evening with just a single system — and then multiply that by 48. With decades of experience keeping systems going with as little intervention as possible, Mike Rice guided the growth of Dragonfly from just a few lens/camera combinations to the behemoth it is today.

Perhaps the biggest challenge was controlling 48 imaging systems simultaneously. A single computer controlling 48 cameras and focusers was simply not practical. Instead, each camera-and-lens combination has its own Intel Compute Stick computer running a special version of *Microsoft Windows 10*. One computer controls one camera and one focuser. Each of these computers connects via gigabit Ethernet to a master computer that sends commands to the individual units, all running independent copies of Software Bisque's *TheSkyX Professional* with camera control. Abraham wrote specialized automation code to create the scripts and send commands to each computer. All 48 systems operate as if they are lone instruments taking pictures on their own mount. Tell all 48 of them to run their autofocus routine, and they are off, all focusing in parallel. If there is a problem with one lens, only that one system is affected. Even if a catastrophic failure occurs with one optic, 47 other optics can still collect data.



▲ **NEW CAGE** The next step in the expansion of the array was to add two more optics and fabricate a custom cage that allowed for precise aiming of each lens while minimizing flexure between each instrument.

So how do you focus with a telephoto lens on a CCD camera? Each lens is connected to an SBIG CCD camera using a motorized adapter by Birger Engineering Inc. (**birger.com**) that can be controlled via a serial RS-232 interface. A custom focusing script and algorithm coded by Abraham focuses each lens independently.

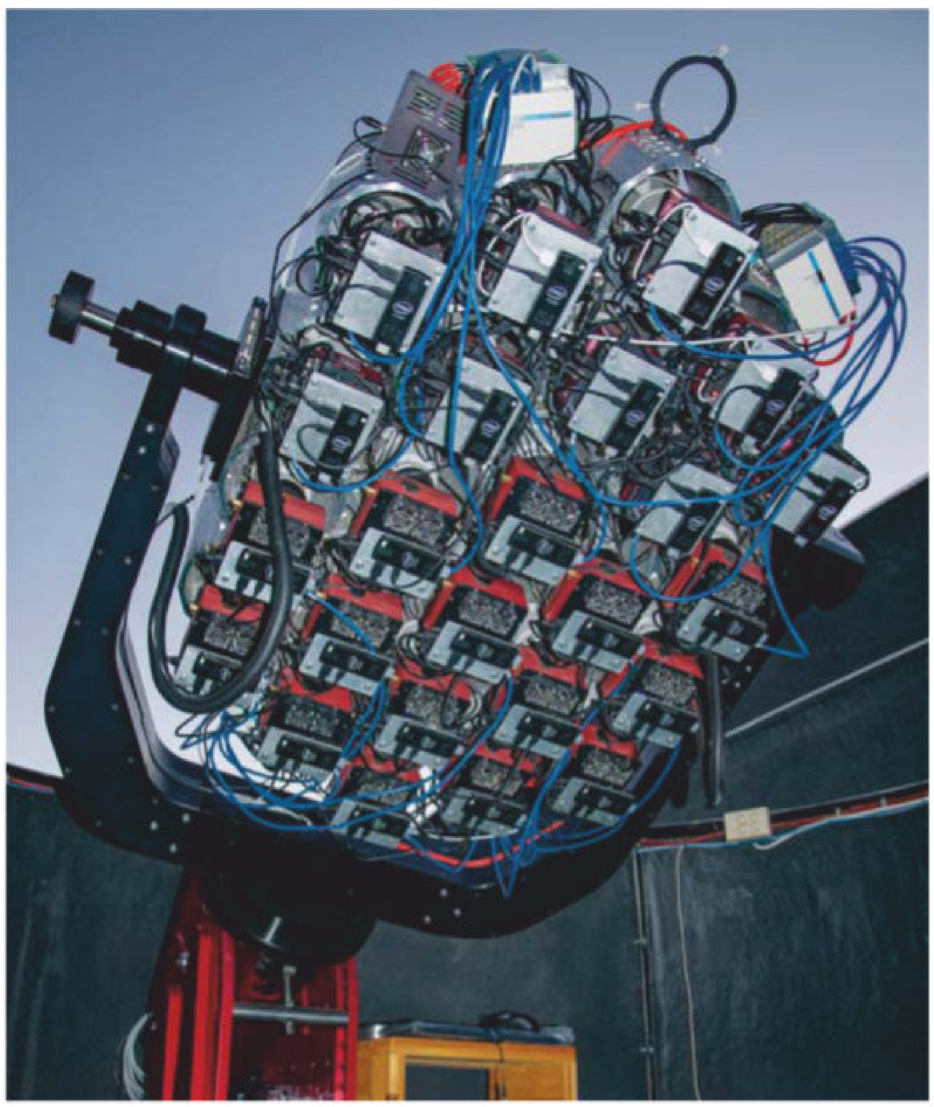
With 48 separate computers, cameras, focusers, optics, and power supplies, all networked together and mounted in a cage system that minimizes flexure, Dragonfly starts to sound more like a pretty sophisticated system with a world of complexities that need to be managed effectively. Managing the cables alone takes a considerable amount of planning and forethought. Nevertheless, the concept is wonderfully scalable, as there is no real limit to the number of "eyes" that can be deployed. There is, of course, no requirement that they all be in the same location either — they could be deployed anywhere in the world.

The next problem that also scales well is the vast amount of data coming out of Dragonfly. Four-dozen cameras taking images every 10 minutes will accumulate a significant amount of data that needs to be reduced (calibrated in amateur imager-speak). All data reduction takes place in the cloud. Compute Canada (**computecanada.ca**) provides cloud-based computing resources to researchers in Canada, and at the request of Abraham or his graduate students, thousands of virtual machines spring into life, crunch through the data, then graciously disappear when finished, leaving behind a pile of data ready for further analysis. This is truly parallel processing at its finest.

Data and Discoveries

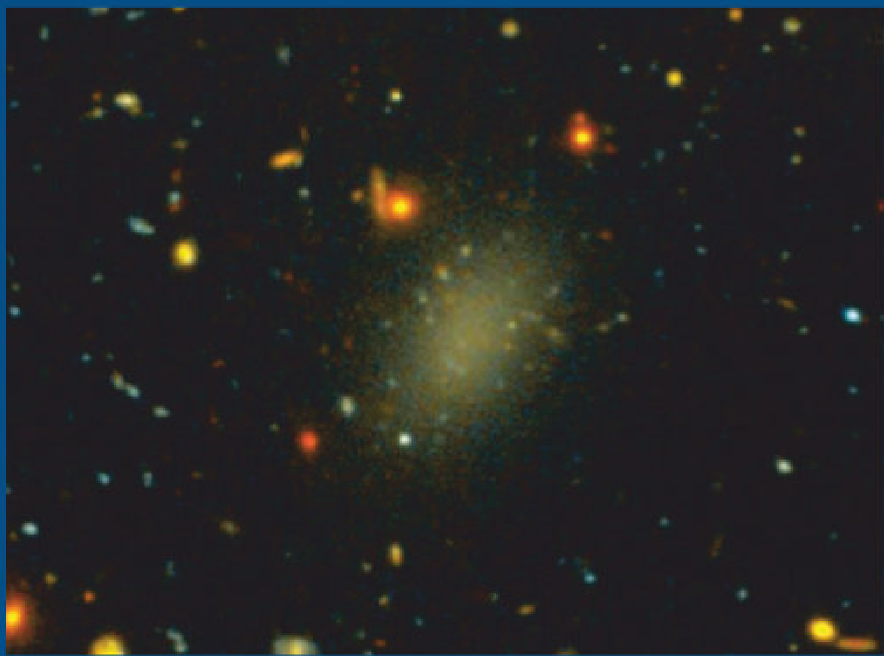
While Dragonfly is an impressive technical instrument in its own right, let's not forget what it was designed to do: detect ultra-low surface brightness objects and structures around galaxies. Abraham and van Dokkum are not theorists but observers. To help them interpret Dragonfly's discoveries, they invited Harvard University Professor of Astronomy Charlie Conroy to join the team.

Among the first published results was an effort to spot a tenuous "stellar halo" predicted to exist around all massive galaxies. To their surprise, the stellar halo around their first target was found to be incredibly faint — far fainter than predicted by models. This narrative (later confirmed by the

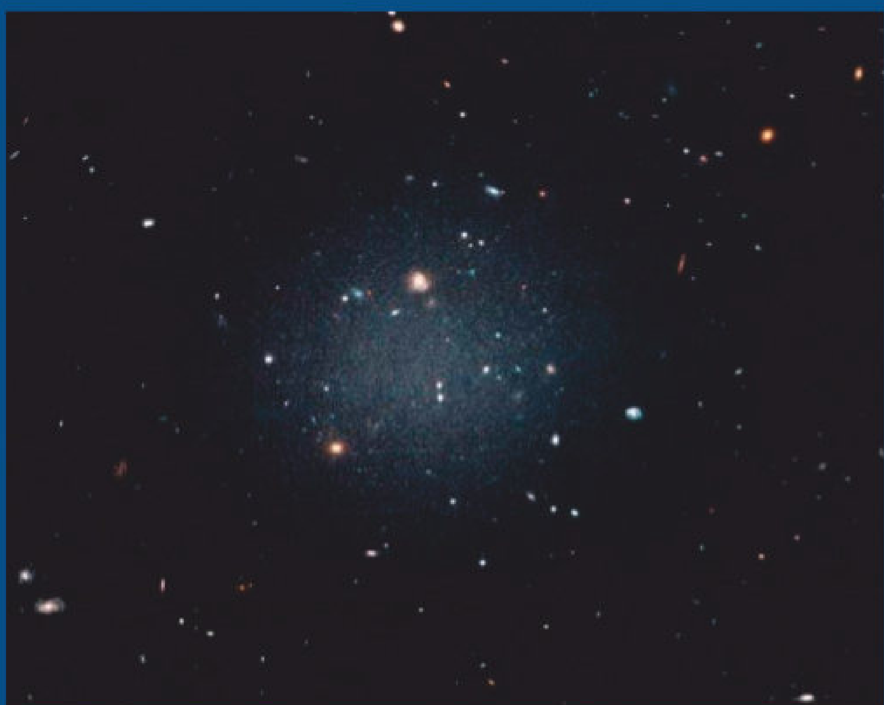


▶ **CORD MANAGEMENT** Powering each array's 24 computers, CCD cameras, and electric focusers requires careful planning.

BACKSIDE: DENNIS DI CICCO



▲ **DARK MATTER** Discovered while studying the Coma Cluster (Abell 1656), DF 44 is an ultra-dim dwarf galaxy that is 99.9% dark matter.



▲ **ALL MATTER** In contrast to DF 44, Dragonfly 2 (NGC 1052-DF2) was found to contain virtually no dark matter.

▲ **CIRRUS EVERYWHERE** Besides its galaxy research, Dragonfly is finding faint nebulosity, sometimes known as galactic cirrus or integrated flux nebula, virtually everywhere it targets.

Hubble Space Telescope) has been repeated over and over with Dragonfly: The array keeps finding surprises that challenge current models of galaxy formation and that astronomers need to follow up on using the world's largest telescopes.

In another early example, Dragonfly undertook an investigation of dwarf galaxies surrounding M101 (*S&T:* Sept. 2015, p. 16). Current models predicted that there should be hundreds of leftover dwarf galaxies in orbit around M101. Although Dragonfly discovered 7 dwarf galaxies, the data suggests that only 3 of those were orbiting the galaxy, while the other four were not.

"The fun of Dragonfly is that almost everything you turn it to seems to yield something new," says Abraham. As part of another survey, Dragonfly turned its eyes to the nearest large galaxy cluster, the Coma Cluster (Abell 1656), which is among the most well-studied areas in the extragalactic sky. Surely, there was nothing new to find there. But what Dragonfly uncovered there was even more surprising.

In the case of Abell 1656, Dragonfly detected a substantial population of large but faint galaxies, a class of objects that have come to be known as *ultra-diffuse galaxies*. These objects are extremely hard to detect, and they didn't exist in the leading models of galaxy formation. Objects similar to ultra-diffuse galaxies have been seen before but only as very rare oddities. In its first observation of the Coma Cluster, Dragonfly discovered 47 of them *by accident* (*S&T:* Mar. 2015, p. 12). Using the Dragonfly data as reference for recalibrating their search, the Subaru 8-meter telescope soon turned up over 700 more! Understanding the nature of these mysterious galaxies has turned into a major focus for observational astronomers.

Abraham points out that astrophysicists knew about low surface brightness galaxies similar to ultra-diffuse galaxies for decades before Dragonfly rekindled interest in them. But

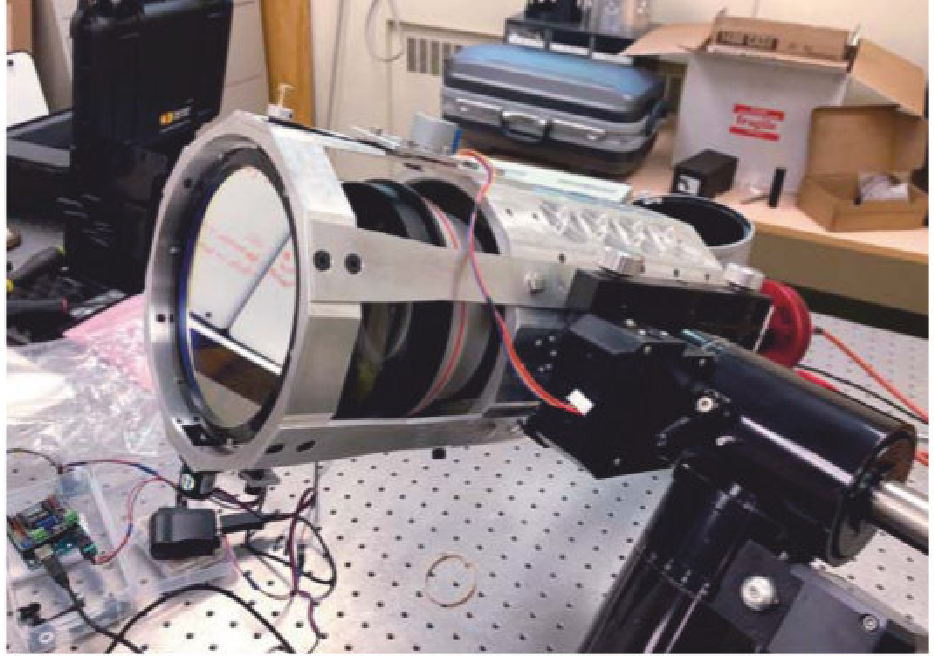
▼ **DOME HOMES** Both Dragonfly 1 and 2 reside in Astro Haven clamshell domes at the New Mexico Skies telescope hosting facility.

DARK MATTER: P. VAN DOKKUM / R. ABRAHAM / GEMINI OBSERVATORY / AURA; MATTER: P. VAN DOKKUM / R. ABRAHAM / STSCI; DOMES: DENNIS DI CICCO the significance of the current new focus on the low surface brightness universe cannot be understated. It's not simply that a new type of galaxy was discovered, but that these previously hidden galaxies are now turning up all over the place and in great numbers. As is typical in science, one new answer generates even more interesting follow-up questions. Some 20% to 30% of these newly discovered galaxies have enormous populations of very luminous globular clusters as well. Is there a relationship between globular cluster abundance and dark matter? Follow-up spectroscopic observations on ultra-diffuse galaxies using the Keck telescopes on Mauna Kea show this to be the case.

The best example of a large ultra-diffuse galaxy with enormous amounts of dark matter but hardly any stars is Dragonfly 44 in the Coma Cluster, which is 99.9% dark matter. On the other hand, Keck observations reveal that another newly discovered galaxy near NGC 1052. In spite of having a huge population of ultra-luminous globular clusters, NGC 1052-DF2 contains almost no dark matter at all. It is becoming increasingly clear that galaxies in the ultra-diffuse domain have as much diversity as the more readily visible galaxies we've been detecting since the advent of astrophotography. They are also challenging our current assumptions and raising new questions about galaxy formation.

While astronomers can use existing instrumentation to detect all of these things, Dragonfly simply makes it far easier. The array is producing groundbreaking discoveries and observational confirmations very early in its career. How long would we have had to wait to find ultra-diffuse galaxies in the Subaru data had it not been for the pioneering work by the Dragonfly array pointing the way?

▼ **TEAM PLAYERS** Dragonfly Telephoto Array team members and graduate students seen from left to right: Roberto Abraham, Pieter van Dokkum, Jielai Zhang, Shany Danieli, Lamiya Mowla, Deborah Lokhorst, and Allison Merritt.



▲ **COMING SOON** A 6-element "Son of Dragonfly" array will utilize full-aperture narrowband filters in front of each lens to search for faint hydrogen emissions predicted to connect galaxies.

It's clear from this example alone that Dragonfly's parallel-processing approach to astronomical research can supplement and enhance the work of the world's largest instruments. Dragonfly seems to make finding otherwise challenging objects incredibly easy, acting in some cases as a kind of finderscope for larger telescopes, which then know where to look. Think of Dragonfly as a bloodhound for ultra-dim targets.

What's Next?

Dragonfly has garnered a lot of attention in the astronomical community, inspiring similar projects. In development are the Huntsman Telephoto Array at Siding Spring Observatory in Australia, as well as smaller experimental arrays that both the University of Alabama and York University are assembling.

As for Dragonfly itself, there are several new and exciting projects that go well beyond the team's original vision. The Naiad Array in development will effectively be the "Son of Dragonfly." This 6-lens array will have full-aperture, 6-inch narrowband filters. Astronomers will use the array to look for weak luminescence from hydrogen gas trapped by dark matter filaments in the cosmic web, a predicted (but not yet observed) connection between all galaxies in the universe. In the meantime, researchers are using the main array to undertake a wide-area survey in a search for very nearby ultra-diffuse galaxies and are producing exciting new results in a range of other areas. This includes looking for light echoes from past supernovae, which would reveal the type of supernova responsible for the explosion long after it happened.

There's no question that results from Dragonfly are changing our understanding of the universe, revealing fascinating new details on the structure and origin of galaxies, and will continue to do so for years to come. Is this a new paradigm for small, powerful, low-cost astronomical observatories? Probably, and it will be exciting to see how Dragonfly and other projects inspired by it evolve in the coming years. You can follow their progress at **dragonflytelescope.org**.

■ RICHARD S. WRIGHT, JR. is a senior software engineer for Software Bisque. Follow his *Sky & Telescope* astrophotography blog at **https://is.gd/imaging**.

A Low-Cost Camera Controller

This project is as easy as Pi.

WHEN OHIO ASTROPHOTOGRAPHER Jack Frillman was preparing to watch the August 2017 total solar eclipse, he knew he didn't want to waste any of the precious totality time fussing with camera gear. So he designed and built a camera controller that would automate the entire process of photographing the eclipse. Centered around a Raspberry Pi computer and using a custom-made circuit board to drive the camera, this device worked so well that when he got home he modified it so he could use it for his nighttime astrophotography, too.

There are many commercial hardware/software packages available for controlling cameras, but Jack's system has the advantage of being small, light, easy to program, and inexpensive. Jack spent about $150 for the whole works, including the Raspberry Pi. You can build one, too.

Jack built his controller to work with his Pentax K20D DSLR camera, but it should work with any camera that has a bulb setting and a receptacle for a shutter release cable. The basic concept is to use the Raspberry Pi as the brains of the operation, interpreting Jack's commands (pre-loaded as text files) and sending those commands to the camera via the circuit board, which also displays what it's doing on a small readout. A rotary encoder lets Jack select from several programs, so he can photograph many different objects without having to reprogram anything on the fly.

The Raspberry Pi is a full-function, Linux-based computer system, so you can plug a keyboard and monitor into it and program it indoors before taking it out for a night's photo session. "The software portion is pretty straightforward, and how complicated it gets all depends on how many bells and whistles you want to add," Jack says. "A novice programmer will not have too many problems writing the software since there are a lot of examples and tutorials on how to write programs for the Raspberry Pi, and how to use the LCD display and rotary encoder. In fact, to save some time, I used someone's example code for reading the rotary encoder."

▲ The controller's display lets you know what it's doing at the moment, as does the knob's color. In this example it's taking five 30-second exposures, it's on exposure number three with 22 seconds left, and the blue knob indicates that the shutter is open.

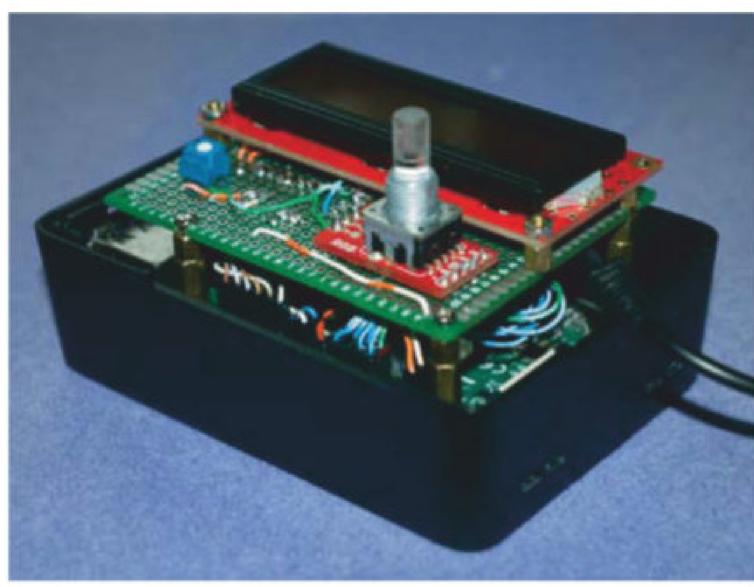
The rest of the project is pretty simple, too. Jack states, "As for building the circuit board, as long as you can read a circuit diagram and can do some basic soldering, you will be fine. I'm terrible at soldering, and if I can do it anyone can."

The cable connecting the controller to the camera is a simple remote switch cable purchased for $8. Jack cut the switch portion off and connected the wires to the circuit board, which becomes an automatic "thumb."

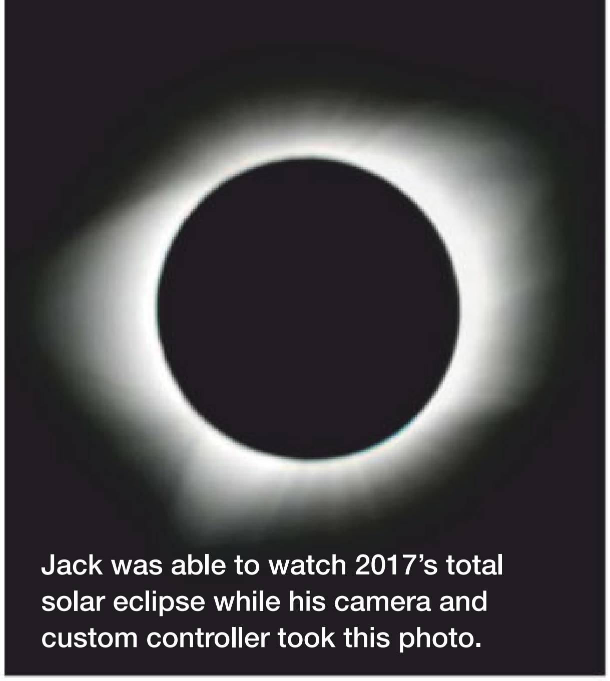
The camera control files themselves are just text files containing commands as basic as "e 10, p 5," which means expose for 10 seconds, then pause for 5 seconds (to allow the camera to write its sensor data to the SD card before taking the next exposure). In the field, Jack can select from several command sequences using the rotary encoder and alphanumeric display. Different-colored LEDs in the dial indicate at a glance what opera-

◀ The entire setup, including computer and battery, is easily portable.

▼ The Raspberry Pi and custom control circuit fit in a small project box.



ALL PHOTOS COURTESY OF JACK FRILLMAN



Jack was able to watch 2017's total solar eclipse while his camera and custom controller took this photo.

tion it's performing at the moment.

The 2-line × 16-character LCD display shows what command file is running, the exposure count, the command currently being executed, and the time remaining in that operation. When one command file is completed, you can simply dial up another one and continue. Jack uses program names like "10x30s," which will take ten 30-second exposures, or "5x2m," which will take five two-minute exposures.

The programs can also include recording dark frames, pauses for changing filters or making other adjustments, and even autofocusing when using the camera's normal lenses.

The whole works is powered by a small lithium-ion battery pack of the type used to recharge cell phones. The computer and control circuit sandwich nicely into a medium-sized project box, giving the finished product a smooth, professional look.

Jack went through several stages of breadboarding, programming, and debugging before winding up with his final project, but now that he has pioneered the way, you can benefit from his experience and build directly toward his final product. Jack is happy to share his circuit diagram and programming experience with anyone who's interested in building this camera controller. It's not difficult at all, and once you've got it built, neither is astrophotography!

For more information, contact Jack Frillman at **jcf20010@gmail.com**.

■ Contributing Editor **JERRY OLTION** was an astrophotographer back when that meant hand-guiding a film camera with a "bulb" setting.

THE MOON AND STARS

Donald Nakic

This long exposure reveals many stars in the constellation Cancer surrounding the Moon near the midpoint of the total lunar eclipse of January 21.

DETAILS: *Takahashi FSQ-106EDIII astrograph with Canon EOS 5D Mark III DSLR camera. Total exposure: 15 seconds at ISO 100.*

▷ A FIERY MOON

Ross Sackett

The red ring of countless sunrises and sunsets due to the refractive and scattering properties of Earth's atmosphere is projected onto the Moon during the partial phase of January's total lunar eclipse.

DETAILS: *Stellarvue SV60EDS refractor with ZWO ASI174MC CMOS camera. Stack of 1,800 video frames.*

▽ A PLANET'S SHADOW

Benjamin Gomes-Casseres

This composite image combines exposures of the Moon at five intervals during January's total lunar eclipse, revealing the shape of Earth's shadow.

DETAILS: *Takahashi Epsilon 160 astrograph with modified Canon EOS 450D. Total exposure: 1/500 second during partial phases, 4 seconds during totality.*

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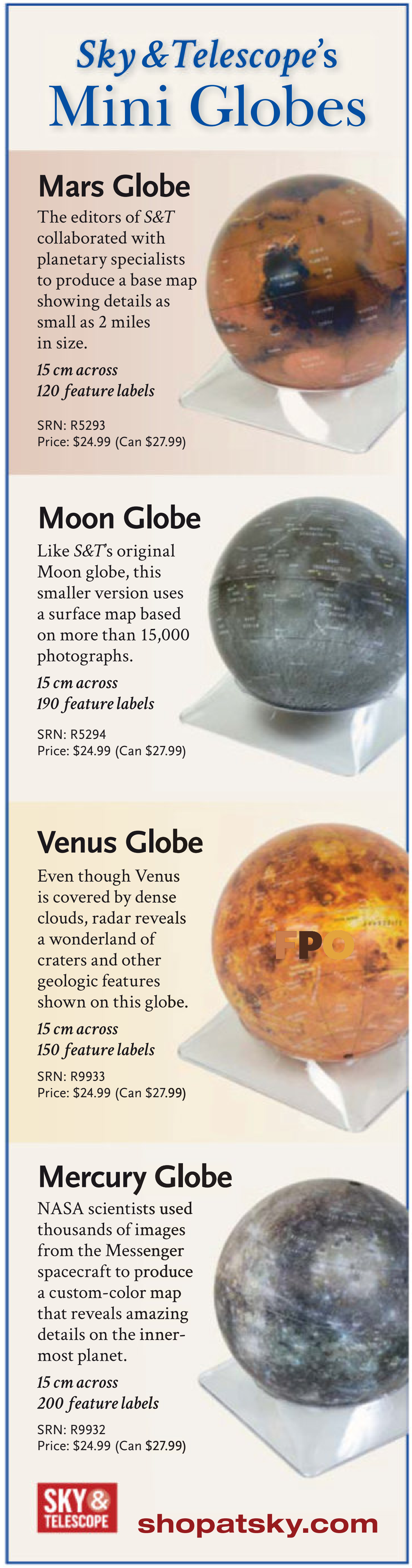
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Uluru & Sydney Opera House: Tourism Australia; observatory: Winton Gibson

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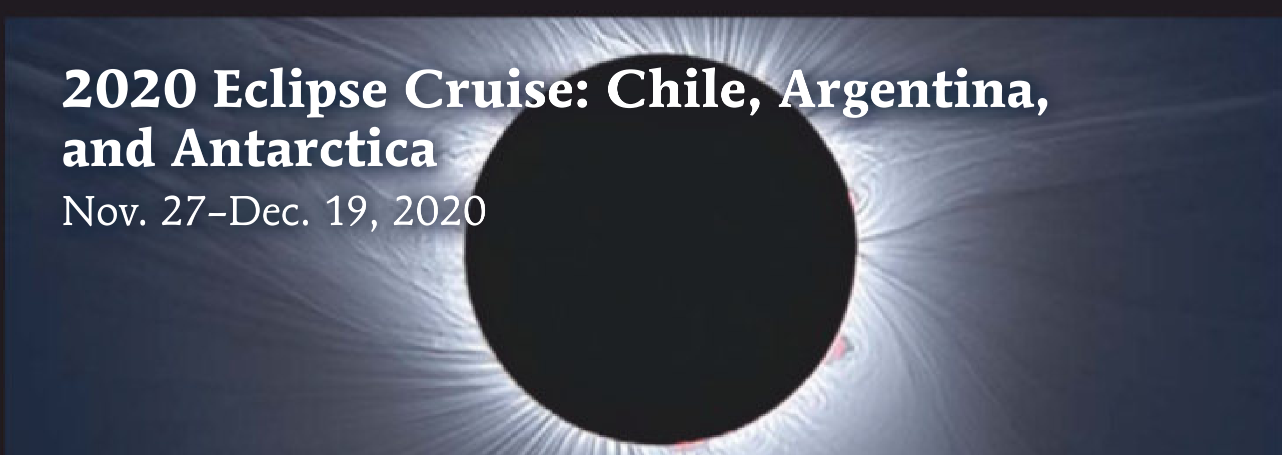
Nov. 27–Dec. 19, 2020



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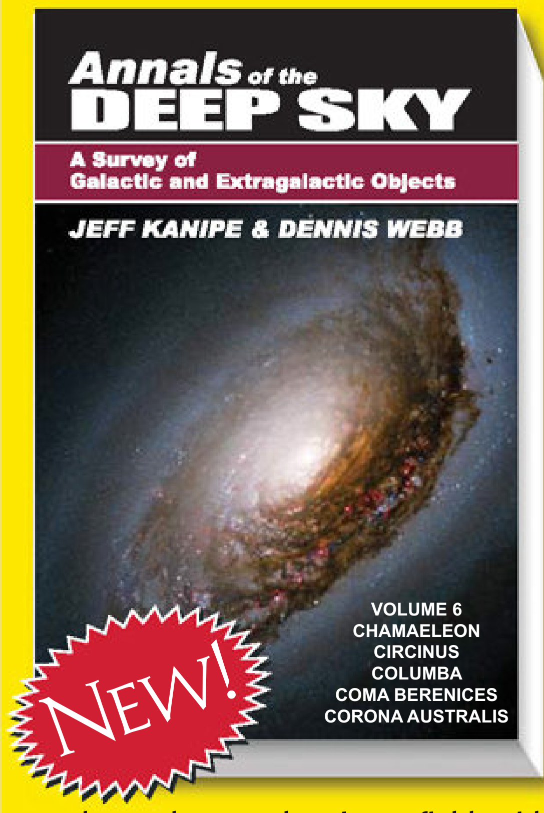

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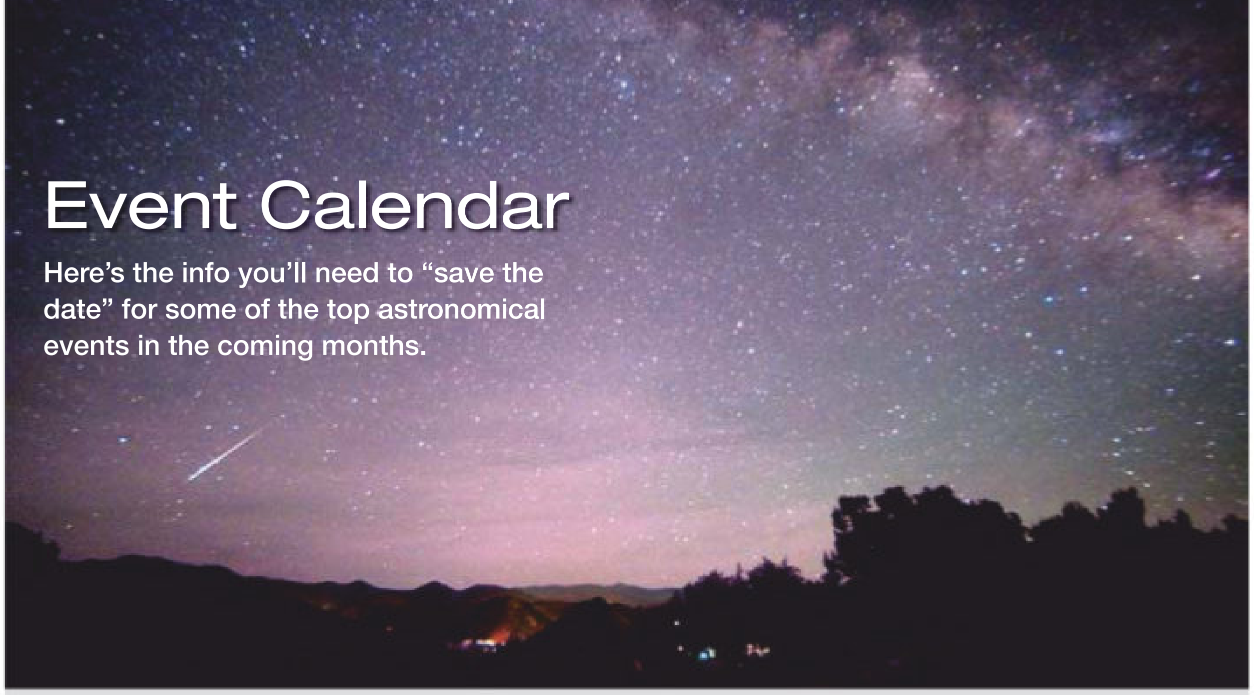

Event Calendar

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

March 31–April 7
INTERNATIONAL DARK SKY WEEK
Everywhere!
https://is.gd/darkskyweek2019

April 3–6
MIDSOUTH STARGAZE
French Camp, MS
rainwaterobservatory.org/events

April 4–7
SOUTHERN STAR
Little Switzerland, NC
https://is.gd/southernstar2019

April 6–7
NORTHEAST ASTRONOMY FORUM
Suffern, NY
rocklandastronomy.com/neaf

April 28–May 5
TEXAS STAR PARTY
Fort Davis, TX
texasstarparty.org

May 11
ASTRONOMY DAY
Events across the continent
https://is.gd/AstronomyDay

May 30–June 2
CHERRY SPRINGS STAR PARTY
Coudersport, PA
cherrysprings.org

June 22–29
GRAND CANYON STAR PARTY
Grand Canyon, AZ
https://is.gd/GCSP2019

June 26–30
ROCKY MOUNTAIN STAR STARE
Gardner, CO
rmss.org

June 29–July 3
GOLDEN STATE STAR PARTY
Adin, CA
goldenstatestarparty.org

July 24–August 4
SUMMER STAR PARTY
Plainfield, MA
rocklandastronomy.com/ssp

July 28–August 2
NEBRASKA STAR PARTY
Merritt Reservoir, NE
nebraskastarparty.org

July 30–August 3
TABLE MOUNTAIN STAR PARTY
Oroville, WA
tmspa.com

July 30–August 4
OREGON STAR PARTY
Indian Trail Spring, OR
oregonstarparty.org

August 1–4
STELLAFANE CONVENTION
Springfield, VT
stellafane.org/convention

September 19–22
RTMC ASTRONOMY EXPO
Big Bear City, CA
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• For a more complete listing, visit https://is.gd/star_parties.

Why Stargaze?

"Let me list the reasons," an astronomer tells an inquiring young person.

RECENTLY, A HIGH SCHOOL STUDENT emailed the Ladd Observatory asking why someone would want to become an amateur astronomer. Eventually, it reached my desk. In his note, he asked for at least two reasons.

I gave him six.

First, just going outside and savoring the night. In addition to the beauty of the sky, you might hear many sounds of nature not present during the day, such as the chirp of crickets or the hoot of an owl declaring its territory. Also, for many the night air has a cleaner, fresher scent of its own.

Looking up, you are immediately gazing back in time. You're seeing planets and stars as they appeared from just a few minutes to possibly thousands of years ago.

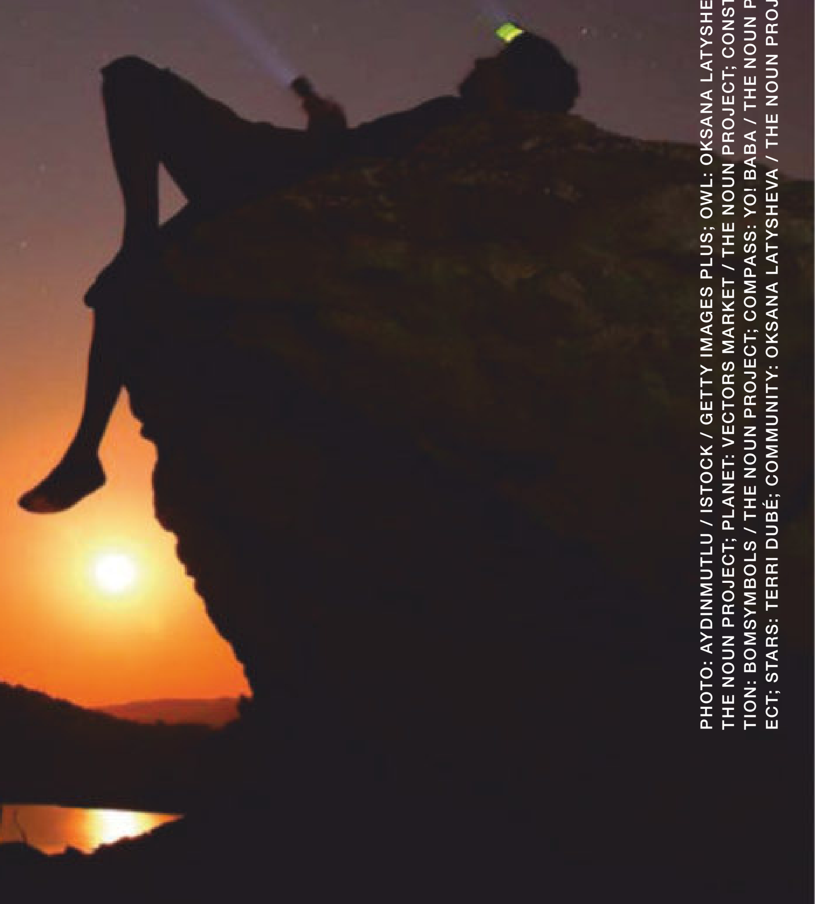
The constellation patterns are part of our history and that of cultures around the world. Different peoples have connected the stars differently, and the myths they created about them and share with their children are closely aligned to their various societies.

The stars were also, for thousands of years, the only way people had for finding their way around the world. Long before GPS, any adventurers having to travel far from home — and return — had to depend upon their knowledge of the sky.

Today, for many people with high-pressure jobs, peering up and savoring the beauty of the night sky is an incredible way to unwind and let the troubles of the world slip away. A friend who is a retired international pilot emphasized this to me once. While still working, he'd be gone for several days at a time, and when he returned the first thing he'd do was pull his telescope out of the garage, set it up in his driveway, point it upward, and relax. The world and he himself were now at peace.

Finally, many people enjoy being part of the amateur astronomy community. Many of them have little basic knowledge of the subject but want to commune with others and learn about the stars. And sometimes amateur astronomers discover a new object or see something no one has previously recorded, thereby aiding in the advancement of the science and possibly even gaining fame for themselves.

The student did send me a thank-you note, but as yet he doesn't appear to have visited any of the neighborhood observatories. I do hope that in the future, when perhaps the pressures of school are behind him, he can come, observe, and be welcomed into the wondrous world of amateur astronomy.



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