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SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

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DECEMBER 2017

SKY & TELESCOPE

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HOWARD BANICH

December 2017

VOL. 134, NO. 6

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ON THE COVER

Juno flies over the Great Red Spot in this artist concept, from Voyager data.

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Welcoming New Staff

VETERAN *S&T* EDITORS never fully retire. They just step back a respectful distance and take it a bit easier, like experienced observers at a star party letting others enjoy most of the time at the eyepiece.

Roger Sinnott, who joined our ranks in 1971, still edits "75, 50 & 25 Years Ago" and creates our annual *Skygazer's Almanac* and other indispensable magazine components. Dennis di Cicco (1974) continues to write and edit test reports and Hot Products. Lester Stockman (1976) still lends an invaluable hand with advertising sales.

The latest to take a step back is Alan MacRobert (1982). After 35 years of exceptional work for *S&T*, Alan dropped back to one day a week this fall. He will continue to produce This Week's Sky at a Glance for the website and SkyWeek app each week, and his byline will still appear in the magazine now and then.

Alan's impending move to part-time was just the initial flake in a flurry of staff refinements that swept through this year, some planned, some not.

In May, Janine Myszka came aboard as Digital Content Strategist. This is a new position meant to enhance *S&T*'s presence in the increasingly pertinent online sphere. Janine earned a BS in astronomy and astrophysics from Villanova University and an MSc in science communication from Imperial College London. She will work closely with Monica Young, formerly Web Editor, now News Editor — another shift meant to help better position us in the online astronomy space.

Editorial refresh: Alan, JR, Monica, Janine, and Diana (clockwise from Alan)

SEAN WALKER / *S&T*

Later in the spring, Peter Hardy decided to seek a new challenge after 18+ years as our Advertising Sales Director. We thank him for his dedicated service and wish him all the best. In July we hired his successor, Tim Allen. Tim has over 20 years' experience in advertising sales for the likes of the Tennis Channel, Accuweather, NFL Network, and CNBC.

Alan's quasi-retirement triggered a few changes of its own, of course. JR Johnson-Roehr, Observing Editor since 2014, has been promoted to Associate Editor, and she has taken over much of Alan's former beat, most notably Celestial Calendar. And in August we hired Diana Hannikainen as our new Observing Editor. Diana, who previously worked in high-energy astrophysics, received her BS in physics and astronomy from the University of Edinburgh, Scotland, and her MS and PhD in astronomy from the University of Helsinki, Finland. (I'm proud to say we now have three PhDs in our midst: JR's doctorate is in early modern astronomy and Monica's is in quasars.)

With these new hires and appointments, we are putting into place the next generation of *S&T* editors — without ever letting go of the previous one.

Peter

Editor in Chief

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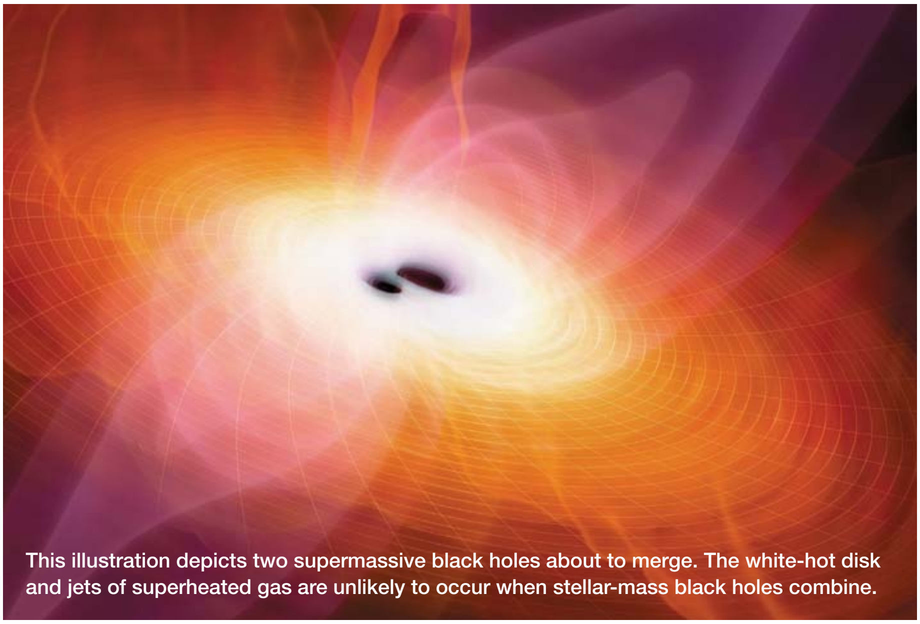

This illustration depicts two supermassive black holes about to merge. The white-hot disk and jets of superheated gas are unlikely to occur when stellar-mass black holes combine.

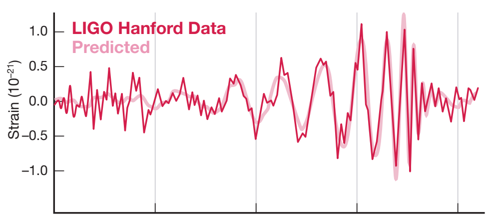
Catching the Waves

I've subscribed to *S&T* for more than 30 years, and Vicky Kalogera's article about the recent trio of gravitational-wave detections (*S&T:* Sept. 2017, p. 24) is one of the best I can remember. She really captured the joys and uncertainties of science, in a human and personal way that is accessible to all. She has clearly experienced the thrill of understanding nature writ large, of predicting and seeing things literally unimaginable until now. And that's well conveyed in writing that is understandable, informative, and insightful and with clear, well-crafted illustrations.

Olin Sibert
Billerica, Massachusetts

The three graphs of the gravitational-wave signals received at LIGO's Livingston and Hanford sites (on page 28) puzzle me, particularly regarding shape of the "Predicted" curves. First, why do the predictions for Livingston and Hanford look different? I would assume they should be the same. Second, why do the predictions look so irregular rather than like a sine wave, in particular in the early parts of the curve?

Stephan Bock
Olching, Germany



Vicky Kalogera replies: Great questions! Indeed, the purely theoretical waveform that comes from solving Einstein's equations is smooth. However, we have to combine that waveform with each detector's noise before we can compare the prediction with our data — hence the "noisy" look. Our prediction must account for the fact that each detector's sensitivity depends on both the direction to and frequency of the source. Recall that, with older analog TVs, you could adjust the antenna to get optimal reception. But LIGO doesn't have this luxury. Instead, we account for the detectors' orientations mathematically. In addition, like human hearing, interferometers detect certain frequencies better than others. Since lower frequencies are harder to detect, the prediction is suppressed at early times, when frequencies are lower. The remaining "fuzz" is somewhat akin to low-level buzzing from an amplifier.

Kalogera notes that prior to the GW150914 event, the most massive stellar black hole known contained about 20 solar masses. Although the 29- and 36-solar-mass components of the merging binary detected by LIGO seem to extend that upper limit and are probably the remains of individual, albeit massive, stars, how do we know that each of them wasn't built up from earlier mergers of smaller black holes left behind by less-massive stars?

Hal Heaton
Damascus, Maryland

Camille Carlisle replies: We don't know for certain that the progenitors involved in the GW150914 event were the remains of one dead star each — the possibility that they're the result of previous mergers remains. Recent modeling by Maya Fishbach (University of Chicago) and two colleagues suggests black holes that formed via mergers spin at about 70% of their maximum allowed rate. It's still a speculative result, but if we can determine a black hole's spin rate we might be able to infer its origin. However, Kalogera suggests that we'll probably need roughly 10 detections that support this idea before we can be comfortable in assuming it's a valid indicator.

More on Meteor Sounds

Regarding the physics of how we might "hear" a meteor entering Earth's atmosphere, I know *exactly* how a bright fireball sounds because I was an "ear witness" to one.

On June 2, 2016, I was camping atop a remote spur of the Mogollon Rim about 40 miles northeast of Payson, Arizona. Everything outside was as dark and quiet as the grave. Then a large meteor arrived. I awoke, aware of an extremely bright, flickering light from outside that lit up everything as though it were broad daylight. At the same time, I *heard* a loud, crunching, crackling noise — akin to truck tires crunching along on a gravel road, but three to four times louder. I assumed it was right outside my camper. Finally, perhaps 2 or 3 seconds later, the sound of two massive nearby explosions shook the ground, jolting everything and quite literally reverberat-

MARK GARLICK / SCIENCE PHOTO LIBRARY / GETTY IMAGES

ing in my chest. The loud booms were distinctly separated by approximately 1 full second. Within the next 3 or 4 seconds the crackling sounds faded as if receding into the distance.

So I guess it was a near miss. Sometimes you just get lucky.

Stephen Launi
Goodyear, Arizona

Fool Me Once . . .

As author Jerry Lodriguss points out in his excellent article on photographic plagiarism and fraud (*S&T:* Sept. 2017, p. 66), it's difficult to fool astronomers — but it happens. However, it is *very* easy to fool the general public.

Perhaps the most blatant example is the ongoing "Mars hoax" — the anonymous e-mail that has circulated every year since 2003. It invariably shows a doctored photo of the Moon and Mars, declaring that, on a certain date in August, those two objects will be the same size in the night sky. Every astronomer knows better, of course. But it isn't *our* gullibility that the anonymous perpetrators prey upon. Rather, every year thousands of people go outside expecting to see an event that supposedly won't happen again for 60,000 years — only to be disappointed when it does not occur.

Bill Warren
Griffin, Georgia

A Matter of Perspective

Given how technical and "sterile" astronomy has become today — for both professionals and amateurs — it's good to keep in mind these words from James Muirden's *Amateur Astronomer's Handbook*: "The study of the heavens from a purely aesthetic point of view is scorned in this technological age. Let us never forget that astronomy loses half of its meaning for the observer who never lets his telescope range across the remote glories of the sky with uncovered head and humble heart."

James Mullaney
Lewes, Delaware

Notebook Envy

Bob King's article on keeping an observing log (*S&T:* Sept. 2017, p. 32) shows some pages from S. N. Johnson-Roehr's notebook. Where can I obtain that notebook — less the sketches, of course?

Grant Thompson
Summerland, British Columbia

JR replies: Unfortunately, it's not in print anymore. Wish I'd bought 10 of them when I had the chance.

FOR THE RECORD

• In the news item about Ceres (*S&T:* July 2017, p. 11), the citation should be to this magazine's December 2016 issue.

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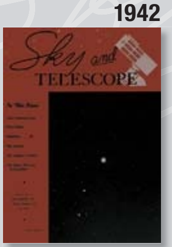
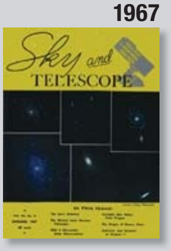
75, 50 & 25 YEARS AGO by Roger W. Sinnott

1942



1967



1992

December 1942

Nova News "[F]inding a new star must rank with the greatest of thrills. At least two regular readers of *Sky and Telescope* were fortunate in spotting Nova Puppis before they had heard of it from others . . .

"[From] Wm. J. Gallagher, of Cincinnati, Ohio, we received the following 'prediction' of the discovery by Dr. Dawson: 'There is a new star. I think it is in Argo. (I have no maps.) I first saw it at 4:00 a.m., today (November 11th). It appeared to be about as bright as Regulus at that time, but it was as bright as Aldebaran by 6:00 a.m.'"

Nova Puppis 1942 was big news in that December issue. The third brightest nova of the 20th century was first spotted by Bernhard H. Dawson in Argentina on November 8–9. Gallagher was correct about its location in Argo, since 12 years earlier that ancient constellation had been officially subdivided into several smaller ones, including Puppis.

December 1967

Potassium Flares "HD 117,043 is a rather ordinary dwarf star of spectral type G6. Very surprisingly, on one coudé spectrogram obtained with Haute Provence Observatory's 76-inch reflector, this star showed *bright* lines of neutral potassium, at wavelengths of 7665 and 7699 angstroms.

"When a second such 'potassium flare' was detected a couple of years later in the spectrum of a K7 dwarf, HD 88,230, a systematic search for new cases of the puzzling phenomenon was started at the French observatory . . . [Another] search for potassium emission among 162 bright stars was undertaken at the University of California . . ."

When no more flares were found, astronomers looked for an artificial origin. Spectra of the flames of ordinary matches were obtained with the coudé spectrograph of the Lick 120-inch reflector, and they showed strong emission lines of potassium. It seems likely that a smoking astronomer at the guiding eyepiece had been the unwitting source of stray light!

December 1992

Voyagers Sail On "NASA's most famous interplanetary spacecraft recently celebrated their 15th year in space. Generally, the two probes continue to operate well. A key component of Voyager 1's telemetry system failed on September 1st, but an onboard computer immediately switched to a backup unit. Scientists hope the far-flung twins will survive until one of them crosses the heliopause, the outer limit of the Sun's magnetic influence, and moves into interstellar space."

Voyager 1 did just that, in 2012, while Voyager 2 has yet to leave the heliopause. Early on, both spacecraft visited Jupiter and Saturn, then Voyager 2 made flybys of Uranus and Neptune (the only craft to do so). NASA officials marked the 40th anniversary of the Voyagers' launches a few months ago.

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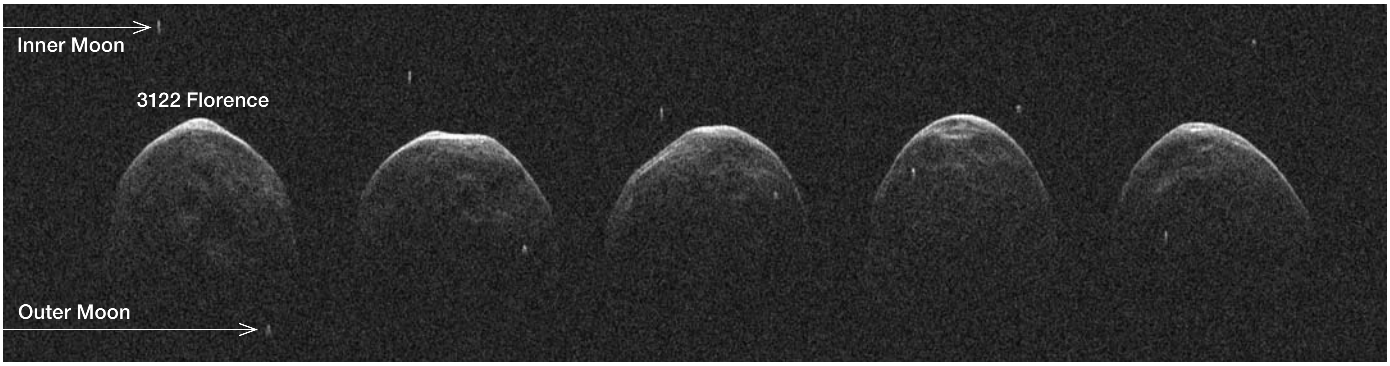


3122 Florence Flies By, Reveals Two Moons

▲ A radar image reveals asteroid 3122 Florence and the motion of its two small moons over 1½ hours. The direction of the radar illumination (and thus the direction toward Earth) is from the top.

ASTEROID 3122 FLORENCE sailed by Earth on September 1st at 12:06 UT (8:06 a.m. EDT), revealing its lumpy shape and a pair of moonlets.

At about 4.5 km (2.8 miles) across, the rock is the fourth-largest near-Earth asteroid. Although it came no closer than 7.0 million km (4.4 million miles), thanks to its size backyard astronomers saw it brighten to magnitude 8.7. It remained at 10th magnitude or brighter through the evening of September 5th.

"Florence is the largest asteroid to pass by our planet this close since the NASA program to detect and track near-Earth asteroids began," says Paul Chodas (Jet Propulsion Laboratory). This pass marks its closest approach since 1890 and the closest it will come until after 2500.

During the asteroid's leisurely encounter, planetary astronomers probed the world with the big radar-equipped dishes at NASA's Goldstone tracking station in California and at Arecibo Observatory in Puerto Rico. A team of scientists at NASA's Center for Near-Earth Object Studies soon announced that a pair of small moons orbits Florence. The inner moon, some 180 to 240 m (600 to 800 feet) across, takes roughly 7 to 8 hours to complete an orbit — the shortest orbital period for any of the 60 near-Earth asteroids known to have companions. The outer moon, whose diameter is 300 to 360 m (1,000 to 1,200 feet), takes 21 to 23 hours to go around. Both are elongated in shape and orbit with the same hemisphere constantly facing inward.

Knowing the orbits' periods and radii (about 4 and 9 km, respectively) leads to an estimated mass for Florence. This, together with its size, yields a density estimate of 1.4 grams per cubic centimeter — much less dense than rocks on Earth. Yet spectral observations suggest that Florence *is* stony, so apparently its interior is quite porous.

Chodas and colleagues Lance Benner, Shantanu Naidu, and Marina Brozović (all JPL) had good reason to think they'd find one or more moons. Prior ground-based observations had shown that Florence spins quickly, once every 2.4 hours, and such rapid rotation usually means there's a companion. But triples remain rare among the 16,000+ known near-Earth asteroids — Florence is only the third to date, and all three were found through radar observations.

"When I posted the echo power spectrum and collage of images [on August 29th], I didn't think there was any sign of a companion," says Benner. "But when we processed the data at higher resolution late in the afternoon, the characteristic signature of a satellite appeared."

The radar data also confirm that Florence itself is rather spherical, as had been assumed from prior studies with ground-based telescopes and the NEOWISE spacecraft. But the radar images also reveal a ridge along its equator, at least one large crater, two large flat regions, and numerous other small-scale topographic features. If further analysis shows that the moons orbit near Florence's equatorial plane, then the ridge might be a pile of accumulated debris that fell back onto the surface after the impact event that catalyzed the moons' formation.

■ J. KELLY BEATTY & BOB KING

ASTEROIDS: ARECIBO OBSERVATORY / PATRICK TAYLOR ET AL.

IN BRIEF

Solar Power vs. Total Eclipse

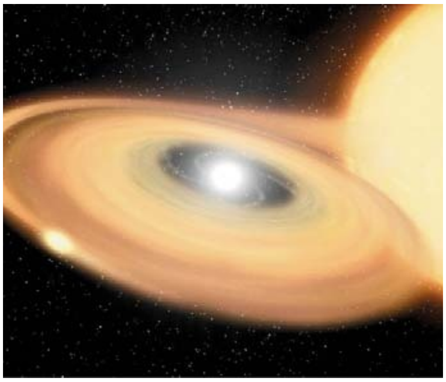
On August 21st, solar energy generation in the U.S. dipped as the Moon's shadow covered solar panels across the country. Although totality was only visible from 14 states, incoming sunlight decreased nationwide. Solar power accounts for roughly 1% of all the energy the country uses, but some states, such as California, are more solar-dependent. Adapting to the quick drop in incoming sunlight on eclipse day required careful planning. Operators typically switch from one energy source to another as power from renewable sources fluctuates, but on eclipse day providers had to compensate at a rate two to three times faster than usual. No problems were reported.

■ JAVIER BARBUZANO

TRAPPIST-1 Star Is Old

A new study suggests that TRAPPIST-1, a faint, *M* dwarf star with seven planets *(continued on page 13)*

STARS



▲ An artist's illustration depicts a white dwarf siphoning gas from its companion star.

The White Dwarf That Survived The Blast

A RECENTLY DISCOVERED white dwarf might be the remnant of a failed Type Ia supernova explosion, which some astronomers have theorized exists but have never found.

Type Ia supernovae occur when a white dwarf steals material from a companion star until it tips the scale at 1.4 solar masses. The high internal pressure ignites a nuclear chain reaction that typically leads to self-destruction.

But not always. Recent findings show that some Type Ia explosions might not obliterate the white dwarf. Such failed detonations could lie behind so-called *Type Iax supernovae*, which show lower luminosities and lower ejecta velocities than other Type Ia events.

In the August 18th *Science*, Stéphane Vennes (Czech Academy of Sciences) and an international group of astronomers describes the discovery of LP 40-365, a white dwarf that might be the remnant of such an explosion.

LP 40-365 is tiny: The team estimates that it has only 0.14 solar mass and is a mere 8% as wide as the Sun. Spectral analysis shows an unusual lack of hydrogen and helium on its surface — consistent with a white dwarf that has expelled its outer layers of lighter elements into space during a subluminous supernova. A powerful explosion could also explain the object's tremendous speed, which puts it on a course to eventually escape the Milky Way.

Ryan Foley (University of California, Santa Cruz), an astronomer familiar with Type Iax supernovae who was not involved in the study, is puzzled by the absence of heavier carbon atoms on the star's surface. The research team argues that the carbon could have been converted into heavier elements, or it might have sunk deep inside the core.

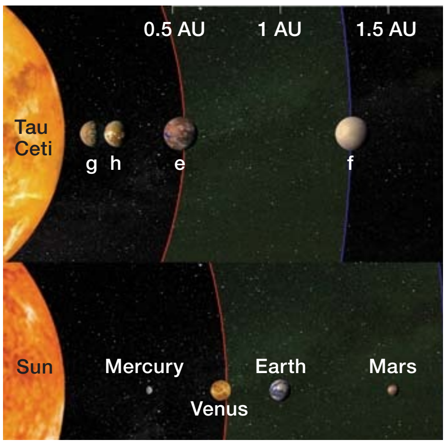
Regardless, Foley considers the new observations consistent with the Type Iax scenario, where a subluminous supernova leaves the white dwarf intact.

"We think that in at least some cases the white dwarf doesn't get completely disrupted and there is a gravitationally bound, battered-and-bruised star left behind," Foley says. "We call these 'zombie stars,' since they died in the explosion but keep on 'living.'"

According to Foley, there could be many zombie stars in the Milky Way, with one created about every 300 to 1,000 years. "If this is one, it could help us start to understand this new population of objects in our galaxy," Foley said.

■ JAVIER BARBUZANO

EXOPLANETS



▲ Tau Ceti system vs. the solar system

Four Planets for Tau Ceti

ASTRONOMERS USED an innovative method to detect four super-Earth-size exoplanet candidates orbiting Tau Ceti, a Sun-like star 12 light-years away.

The study, to be published in the *Astronomical Journal*, takes a new approach to the radial velocity technique, whereby planets are detected by the wobble their gravity induces in the star's position. The smaller or farther away the planet, the tinier the wobble it induces on its host star, so the technique has mostly remained limited to detecting larger planets in closer orbits. The tug of an Earth-size planet at an Earth-like distance would cause its star to wobble by just 0.1 m/s — a signal that has proven difficult to disentangle from stellar and instrumental noise.

Now, Fabo Feng (University of Hertfordshire, UK) and colleagues have applied a new technique that removes all known sources of noise from 9,000 spectroscopic measurements of Tau Ceti, collected using the High Accuracy Radial Velocity Planet Searcher (HARPS) spectrograph installed on the 3.6-meter telescope at La Silla Observatory in Chile.

When the team's analysis was complete, four regular signals, potentially from four super-Earths, remained.

Astronomers had previously suspected the existence of Tau Ceti e and f, which orbit in the star's habitable zone. With masses of at least 4 times Earth's mass, and sizes still unknown, it remains unclear whether these planets are solid super-Earths or gaseous mini-Neptunes (*S&T:* Mar. 2017, p. 22).

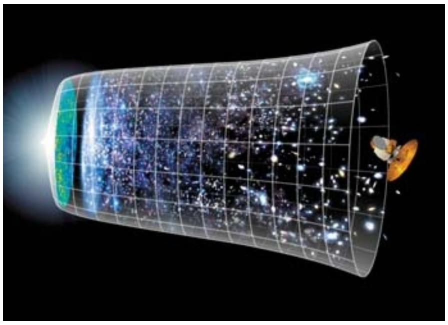
The other two candidates (Tau Ceti g and h, with tight orbits of 20 and 49 days, respectively) are brand-new finds. The candidates' gravitational tugs induce Tau Ceti to wobble by as little as 0.3 m/s, which means that the HARPS instrument has almost reached the capability of discovering an Earth-size planet in an Earth-like orbit.

"Regardless of whether all four candidates stand the test of time, this work represents an important effort to advance our ability to distinguish bona fide planets from astrophysical and instrumental noise," says Paul Robertson (Penn State).

■ MONICA YOUNG

WHITE DWARF: NASA / JPL-CALTECH; TAU CETI: F. FENG / UNIV. OF HERTFORDSHIRE

COSMOLOGY



▲ A representation of the universe's evolution

Does Dark Energy Change Over Time?

SCIENTISTS ARE considering whether dark energy — the mysterious "force" that has accelerated the universe's expansion over the last half of its cosmic history — could change with time. The idea could help solve an ongoing conflict over the measurement of the universe's current expansion rate, dubbed the Hubble constant.

The Hubble constant determines some important characteristics, such as the universe's age and size. But after nearly a century of study, astronomers still don't entirely agree on how fast the current rate of expansion is. Those using the cosmic microwave background favor a value of about 67 kilometers per second per megaparsec (km/s/Mpc, where a megaparsec is 3.26 million light-years). Those using supernovae and other, closer cosmic tools home in on a value of about 73 km/s/Mpc. The current disagreement might be merely a matter of analysis and assumptions, but a new understanding of dark energy is also a possibility.

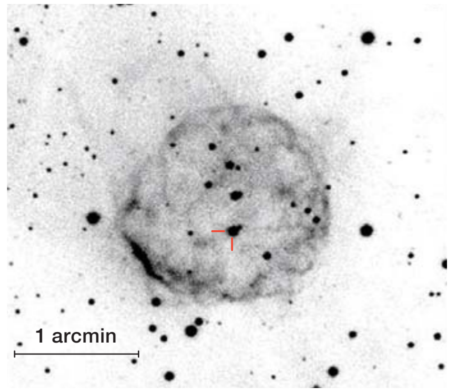
Although we don't know what dark energy is, one idea is that it's an energy inherent to space itself. If so, then as space expands, dark energy will increase with it, maintaining the same density. Observations so far have supported the idea that dark energy remains constant over time, but there's some wiggle room.

Drawing from a large, diverse set of observations, Gong-Bo Zhao (Chinese Academy of Sciences) and colleagues conclude in the September *Nature Astronomy* that it is possible to relieve the tension in the Hubble constant with dynamic dark energy, one whose density oscillates over time, both decreasing and increasing as the universe expands. However, their analysis is not statistically strong enough to prove that an evolving dark energy is the right answer. More data will help: The team points to the upcoming Dark Energy Spectroscopic Instrument (DESI) survey, which aims to begin creating a 3D cosmic map in 2018.

■ CAMILLE M. CARLISLE

● Dive into dark energy's cosmological role at https://is.gd/evolvingdarkenergy.

NOVA



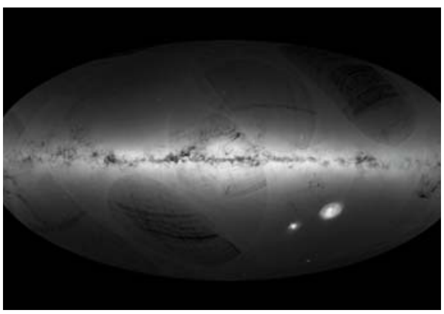
▲ This image shows the ejected shell of the recovered Nova Scorpii 1437. The red tick marks show the current location of the source.

Historical Observations Reveal an Ancient Explosion

ASTRONOMERS and historians have discovered the source of a 15th-century classical nova, pointing to a unified life cycle for these types of binary systems.

In 1437 Korean royal astronomers saw a "guest star" appear in the constellation Scorpius then fade from sight after 14 days. They had witnessed a classical nova — the outburst of a white dwarf in a close binary system that has collected too much hydrogen from its companion star. The fresh gas accumulated on the white dwarf until a runaway thermonuclear reaction ensued within the thin surface layer.

STARS



▲ Gaia's first map of 1 billion stars

Heavy Local Stellar Traffic

A NEW ANALYSIS SHOWS that nearly 100 stars buzz our solar system every million years. Such stars regularly pass close enough to perturb the Oort Cloud — that vast, faraway shell populated by trillions of comets — potentially jostling them from their peaceful orbits and hurling them toward Earth.

Coryn Bailer-Jones (Max Planck Institute for Astronomy, Germany) used data from the Gaia satellite to trace the paths of some 320,000 nearby stars, from 5 million years in the past to 5 million years in the future. His map of past and future close encounters, to be published in the journal *Astronomy & Astrophysics*, shows that 87 or so stars come within 6.5 light-years of the Sun every million years, about twice as many as expected.

Perhaps the most intriguing result — at least according to Paul Weissman (Planetary Science Institute), who was not involved in the study — is a new measurement of the approaching star Gliese 710, which puts its closest pass at just 16,000 astronomical units. The new estimate places the star firmly within the inner Oort Cloud 1.3 million years from now. Weissman thinks that Gliese 710 could increase the number of comets entering the solar system by a factor of 100, 10% of which might collide head-on with planetary bodies.

Bailer-Jones plans to extend his probe of the stellar neighborhood from 10 million years to 50 million years with the next Gaia data release in 2018.

■ SHANNON HALL

COSMIC TIMELINE: NASA / WMAP SCIENCE TEAM; NOVA: AMNH / K. ILKIEWICZ AND J. MIKOLAJEWSKA; GAIA SKY MAP: ESA / GAIA / DPAC

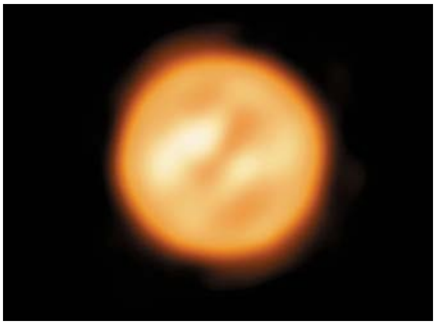
A team led by Michael Shara (American Museum of Natural History), with help from historian F. Richard Stephenson (Durham University, UK), went looking for the stellar system responsible for the ancient guest, now called Nova Scorpii 1437. The search bore fruit thanks to records from the Digital Access to a Sky Century at Harvard (DASCH) project, a digital collection of roughly 500,000 photographic plates taken by Harvard astronomers between 1885 and 1993 (*S&T:* May 2015, p. 20).

A 1923 image taken from a Harvard Observatory station in Peru is the first in the collection to show Nova Scorpii 1437, the team writes in the August 31st *Nature*. Later DASCH images of the same system in 1934, 1935, and 1942 show the classical nova reborn as a dwarf nova, exhibiting weaker eruptions as it captures less gas from its companion.

These observations suggest that all kinds of cataclysmic variable stars, including novae, recurrent novae, nova-like variables, and dwarf novae, could be a single type of object that astronomers observe at different stages of life.

■ JAVIER BARBUZANO

STARS



ESO / K. OHNAKA

▲ Image of red supergiant star Antares

Astronomers Image Surface of Antares

RESEARCHERS HAVE constructed a detailed view of the surface of the red supergiant star Antares, revealing a chaotic atmosphere powered by mechanisms that are still poorly understood.

Antares is a massive star nearing the end of its life, with 15 times the mass, 883 times the girth, and 10,000 times the visible luminosity of our Sun. If it replaced the Sun, it would fill the solar system to beyond the orbit of Mars. So although it lies 550 light-years away in the constellation Scorpio, Antares is big enough to make it an ideal candidate for direct imaging.

Keiichi Ohnaka (Catholic University of the North, Chile) and colleagues observed Antares for five nights using the Very Large Telescope Interferometer. Ohnaka's team combined near-infrared data from three of the VLTI's 1.8-meter telescopes to achieve the sharpness equivalent to an 82-meter instrument.

The observations, unprecedented for any star other than the Sun, appear in the August 17th *Nature*. In addition to finding two large bright spots on the star's surface, researchers also identified several clumps of gas moving within the atmosphere at speeds of 20 kilometers per second (45,000 mph). These up-and-down motions are part of the red supergiant's surprisingly turbulent wind, which carries vast amounts of atmospheric material into space. The new observations could help uncover the forces that power this stellar wind. In the future, Ohnaka's team also intends to create maps at different depths in order to construct a 3D view of the star's stormy atmosphere.

■ JAVIER BARBUZANO

IN BRIEF

(continued from page 10)

(*S&T:* June 2017, p. 12), could be much older than the Sun. Reporting in the August 20th *Astrophysical Journal*, Adam Burgasser (University of California, San Diego) and Eric Mamajek (JPL) pulled together several observations of TRAPPIST-1, and of red dwarfs more broadly, to determine the star's age based on its chemical composition, its motion through the galaxy, and how often it flares. Using those characteristics, the team estimates that TRAPPIST-1 is between 5.4 and 9.8 billion years old. That's consistent with a previous estimate (*S&T:* Sept. 2017, p. 11) but leans more toward the older end of the range than many had suspected.

■ CAMILLE M. CARLISLE

New Exomoon Candidate

Astronomers have found one of the best exomoon candidates based on data collected by the Kepler spacecraft. Alex Teachey (Columbia University) and collaborators used a powerful statistical method to examine a population of known Kepler exoplanets, quantifying how often massive moons, like the Galilean moons of Jupiter, might exist. The team reports the answer in a paper posted July 20th to arXiv.org: 1 out of 6 planets might host a massive exomoon. But that's not what got everyone's attention. During the course of their analysis, the astronomers uncovered Kepler-1625b-i, a potential exomoon in the Kepler-1625 system. Unfortunately, Kepler had only captured three of the planet's transits in front of its host star, making the identification of its moon uncertain. The candidate would be huge — the size of Neptune, orbiting a planet that's a little larger than Jupiter and ten times Jupiter's mass. The team will test the exomoon's existence with Hubble observations later this year, which will examine an upcoming transit of the planet and, potentially, its moon.

■ JOHN BOCHANSKI

Rogue Planets Not Plentiful

A new study finds that rogue planets — those not bound to any star — aren't as plentiful as once thought. Using the Optical Gravitational Lensing Experiment (OGLE), astronomers monitor the sky for *microlensing events*, when a star's light is briefly magnified by the gravitational effect of an object passing in front of it. A 2011 study based on 474 events suggested that rogue planets might outnumber our galaxy's stars two to one (*S&T:* Aug. 2011, p. 17). Now, a study using the same technique but with 2,617 events detected between 2010 and 2015 has toned down that result. The analysis, published by Przemek Mróz (Warsaw University Observatory, Poland) and colleagues in the August 10th *Nature*, suggests that our galaxy might have less than one Jupiter-size rogue planet for every star. Even that is likely a vast overestimate, as most of these detections could be attributed to bound planets on very wide orbits.

■ MONICA YOUNG

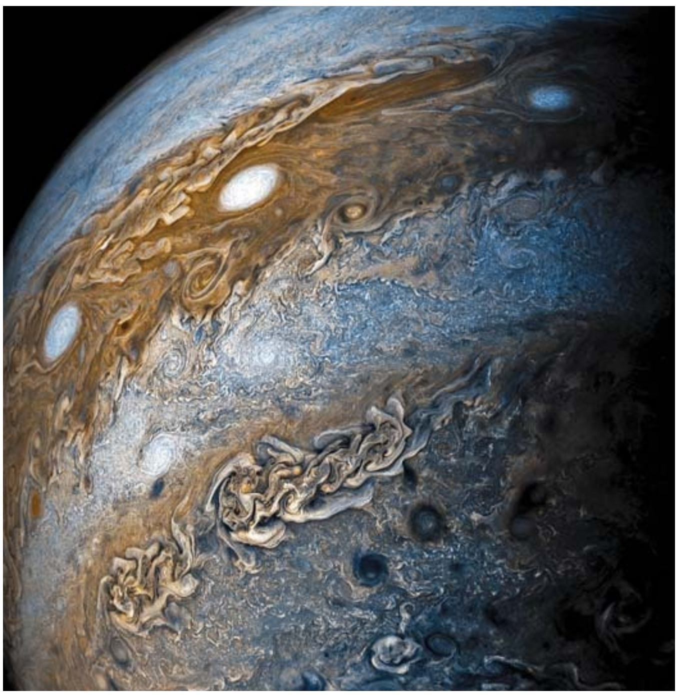
 by Fran Bagenal

Jupiter Rediscovered

NASA's Juno mission is revealing that our solar system's largest planet is a fantastic, cyclone-festooned world with a strange interior. What's the scoop after 18 months in orbit?

For many of us, the planet Jupiter conjures mental images of a giant ball with latitudinal stripes of red and white all the way from pole to pole, with the most remarkable anomaly being the Great Red Spot. We've had little reason to question this scheme: The glimpses that previous spacecraft have caught of high latitudes looked striated.

But Juno changed that. Upon the spacecraft's arrival at Jupiter in July 2016, its JunoCAM wowed us with the first views ever captured looking directly down at the poles. Above about 50° latitude, it turns out, the planet darkens and takes on a blue tinge. Images show spectacular eddies and a chaotic mass of jostling storms.



Particularly intriguing is the fact that Jupiter's polar regions are so different from Saturn's. While rotation dominates the atmospheric dynamics of both planets, their polar weather systems seem to be fundamentally different. Saturn has a single deep, fast vortex centered on each pole, top and bottom, with the north pole surrounded by a remarkably long-lived, hexagon-shaped wave. In contrast, we've found by comparing Juno images from orbit to orbit that Jupiter's numerous, smaller-scale polar vortices move around in a semi-random way. They remain tightly packed around the pole and do not merge.

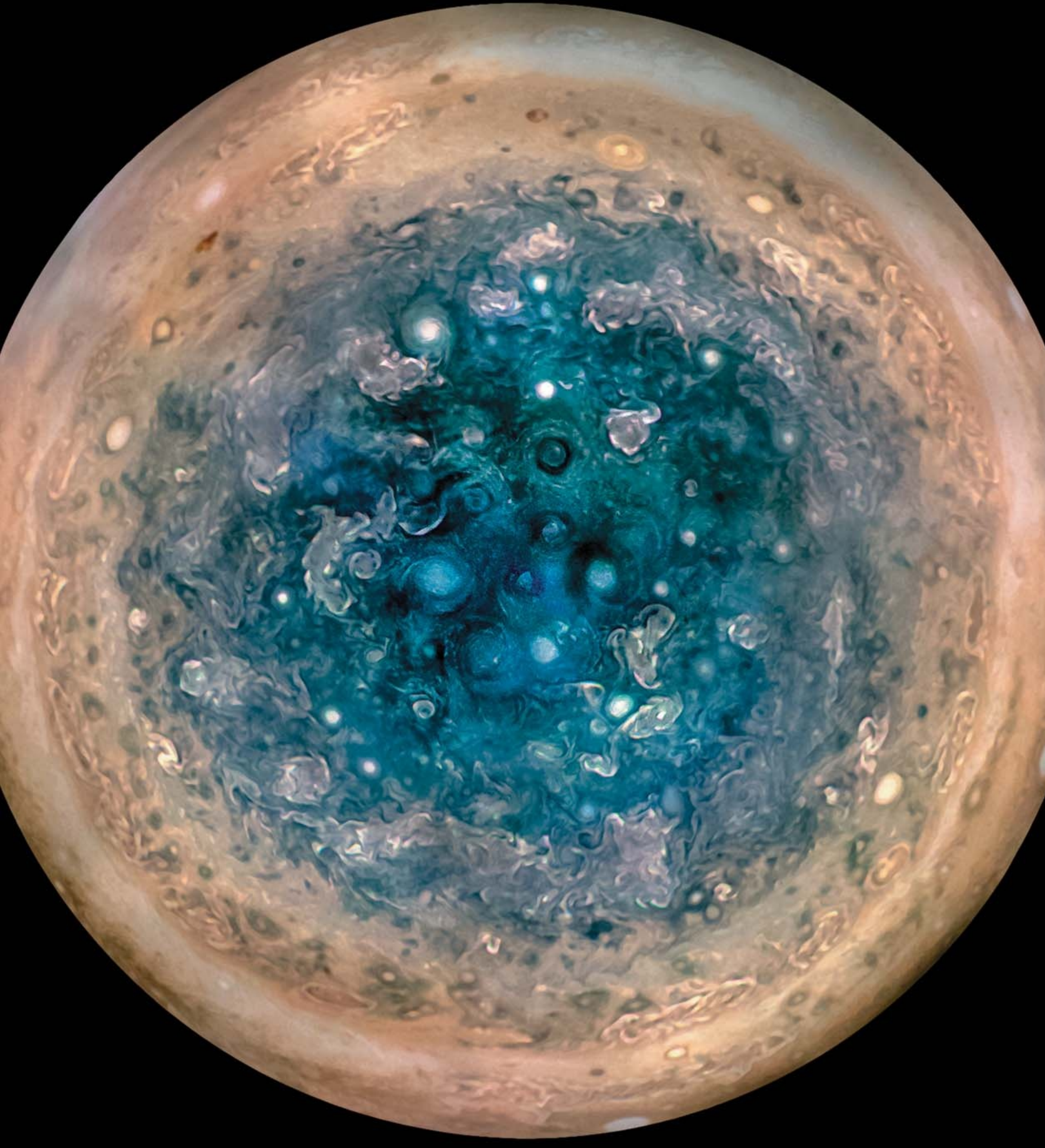
Jupiter's poles are illustrative of Juno's early discoveries: The closer we look at this planet, the more structure we see. My article last year (*S&T:* July 2016, p. 18) listed Juno's scientific aims, including the determination of the planet's bulk composition and how much water is inside it. We cannot yet answer these two fundamental questions; first Juno will need to finish mapping the planet's gravity field and microwave emissions, respectively. Nevertheless, what we've learned from Juno's first seven flybys is enough to dazzle and amaze.

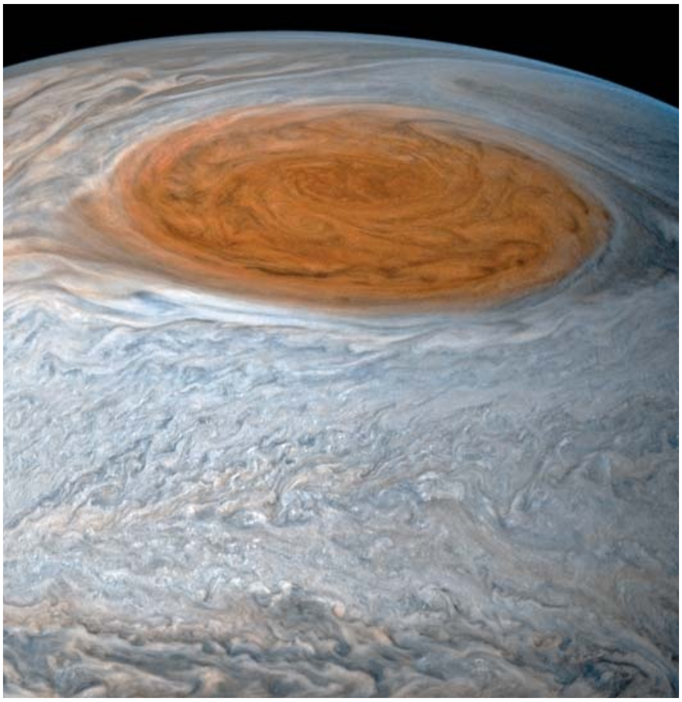
Swirls Within Swirls

Juno loops around Jupiter once every 53 days, whizzing in for a closest approach, or *perijove*, of about 4,300 km (2,700 miles) above the cloudtops. Although this might seem far away, it still gives us incredible close-ups of the planet — Voyager 1 was 65 times farther away on its 1979 flyby.

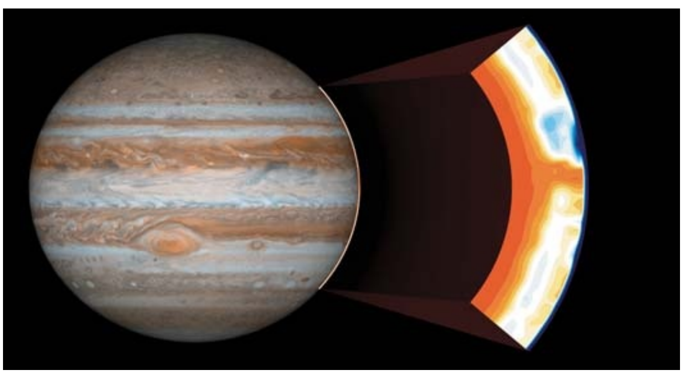
▲ **BEJEWELED** Three of the white oval storms known collectively as the "String of Pearls" appear near the top of this enhanced-color image, created by JunoCam participants Gerald Eichstädt and Seán Doran. Each of the alternating light and dark bands is wider than Earth. The lighter bands are regions where gas is rising; the darker ones, where gas is sinking. **Facing Page:** This enhanced-color mosaic combines images from three flybys to reveal the planet's nether regions, unseen until Juno. The ovals are cyclones, the largest 1,000 km (600 miles) wide. Juno took the images from 52,000 km above the south pole's cloudtops.

PEARLS: NASA / JPL-CALTECH / SWRI / MSSS / GERALD EICHSTÄDT / SEÁN DORAN; FACING PAGE: NASA / JPL-CALTECH / SWRI / MSSS / BETSY ASHER HALL / GERVASIO ROBLES





▲ **LO, THE GREAT RED SPOT** JunoCam took this true-color image *(top)* from 13,917 km (8,648 mi) above the cloudtops on July 10th. Contrast enhancements and white-balancing of another image from the same pass *(middle)* reveal glorious details the eye might overlook.



◀ **IN MICROWAVES** The cut-out shows data from Juno's Microwave Radiometer, which detects microwaves emitted from ammonia in Jupiter's atmosphere down to 350 km. Colors correspond to abundance, with orange being more and blue less. Scientists had thought the ammonia would be uniformly mixed, but the data reveal a deep circulation pattern, including an equatorial band (the prominence-like column).

This dramatically smaller perijove gives Juno a much different perspective than the Voyager spacecraft had. The twin craft took weeks-long movies of Jupiter's dramatic global weather systems, showing bands of white clouds zooming left to right and deep red bands streaming right to left. It's interesting to contrast these Voyager movies with the still views Juno is getting 38 years later. On a spinning spacecraft and a 2-hour pole-to-pole dash, Juno's camera sees only snapshots of atmospheric activity. But these close-ups reveal small-scale structures that were blurred at Voyager's distance from the planet.

In fact on every scale, down to the 50-km resolution of JunoCAM, we see structure in Jupiter's atmosphere — vortices, thunder clouds, waves, and turbulence. In retrospect, we probably shouldn't have been so surprised, since nature across the universe tends to get more structured when we zoom in.

Jupiter is more than 11 times wider than Earth, yet it spins around in just under 10 hours — the shortest day of the major planets. This rotation drives the dynamics in the shallow, outermost layer of the mid-latitude atmosphere, where the multiple red "belts" and white "zones" mark striped weather systems. Convection and turbulence spur small-scale structure, and spots grow by merging together. We've seen large-scale order emerging from small-scale chaos in a number of planetary atmospheres, but Jupiter is the best example.

Why has Jupiter's rotation not smoothed out this small-scale structure? If you put milk in your coffee and give it a stir, it quickly becomes a uniform mixture. Jupiter has been "stirring" for billions of years, so what causes these structures to persist? The answer is similar to the ongoing activity in Earth's atmosphere. On Earth, the water cycle feeds weather patterns, keeping our atmosphere in a constant state of transformation. On Jupiter, ammonia plays a similar role as water on Earth. As a blob of air with ammonia vapor rises, it cools. Eventually the vapor condenses, releasing energy into the surrounding gas, making the gas rise higher in the atmosphere. Such feedback systems persistently drive small-scale structures and prevent the atmosphere from mixing into a great bland ball.

And then there's the Great Red Spot. On July 10, 2017, Juno flew directly over the giant storm that astronomers have observed since at least the 19th century (*S&T:* Mar. 2016, p. 18). More than 16,000 km across but less than 300 km deep, the GRS is like a spinning New York pizza — except it's made out of hydrogen. Voyager 2's movie of the Great Red Spot shows the vast storm gobbling up smaller eddies and sometimes spitting them out again. Juno's zoomed-in pictures show turbulent structure within the GRS's twirling vortex. To the south of the GRS, small, fresh, white clouds poke up like monsoon thunderheads on an afternoon in the Rocky

TOP: NASA / JPL-CALTECH / SWRI / MSSS / BJÖRN JÓNSSON; MIDDLE: CREDIT: NASA / SWRI / MSSS / GERALD EICHSTÄDT / JUSTIN COWART; BOTTON: NASA / JPL-CALTECH / SWRI

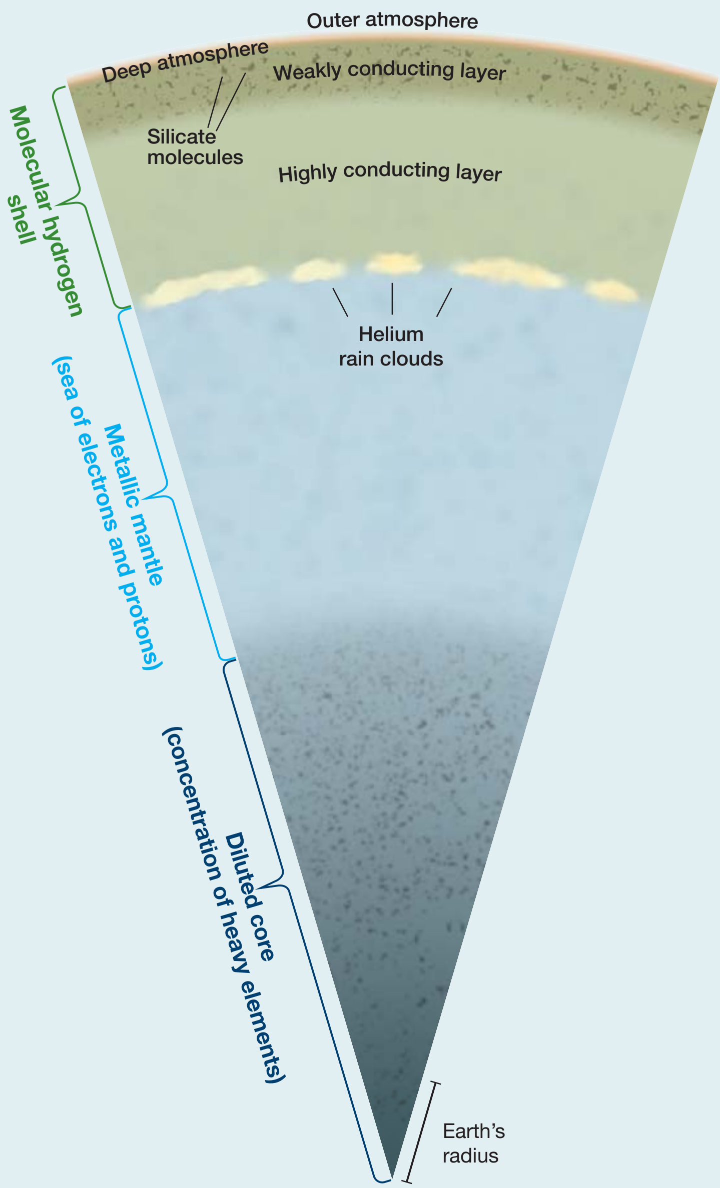
Mountains. The clouds we see on Jupiter are predominately ammonia (NH_3), and the red coloration of Jupiter's belts and the GRS are likely photochemical products (such as phosphine, PH_3) that have accumulated over years of exposure of the outer atmosphere to ultraviolet radiation from the Sun.

The Microwave Miracle

Juno also looks below the turbulent clouds. The beauty of the mission design was the realization that a microwave detector could see what's going on beneath the chaos of clouds. The Microwave Radiometer (MWR) instrument is revealing a totally different weather system down there. But it's not the uniform, static deep atmosphere imagined before Juno. The MWR data reveal an equatorial belly-band of ammonia, formed by a large, upwelling plume and extending down about 300 km. We don't know yet whether this deep circulation system varies around the planet, or whether it might extend toward the poles. It probably goes about its business unaffected by the belts and zones we see at the cloudtops.

In some ways, Jupiter's upper weather patterns and the deeper circulation system can be compared with the combined system of Earth's atmosphere and oceans. Both have distinct layers, with the lighter gas above and the denser fluid below. These layers circulate on different temporal and spatial scales, separated but with some dynamical linkage. With further MWR observations, we aim to discover what scale the lower wind system operates on and just how separate the flows are from the familiar belts and zones above.

JUPITER'S LAYERS



GREGG DINDERMAN / *S&T*

• The **outer atmosphere** comprises molecular hydrogen with layers (from top to bottom) of ammonia clouds, ammonium hydrosulfide, and water. Zonal flows (the belts and zones) characterize the large-scale dynamics, accompanied by small-scale vortices and turbulence.

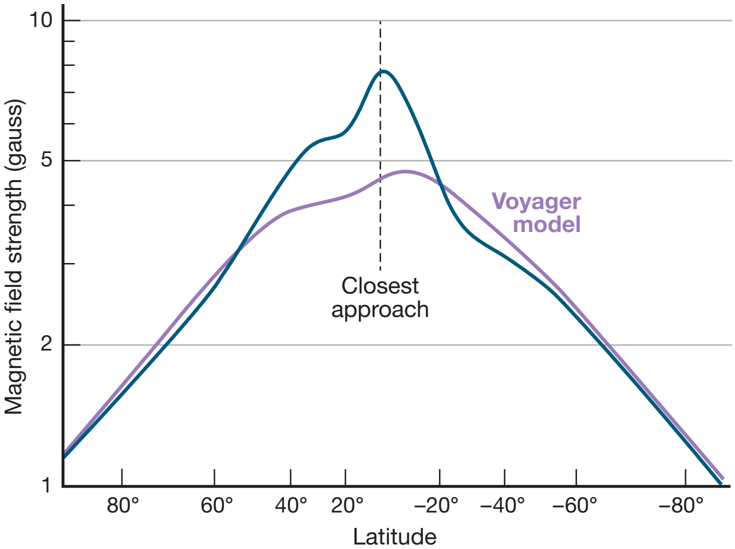
• The **deep atmosphere** extends about 300 km (200 miles) below the clouds. Microwave data suggest a separate flow regime, decoupled from the belts and zones above.

• The **weakly conducting molecular shell** lies above the magnetic-field-creating mantle, but it might be coupled to the magnetic field if its zonal flows are strong. The top of this region is defined by where the zonal flow weakens to less than about 1 m/s (2 mph). This is also roughly where the diffuse "rock clouds" of silicate molecules form. May extend down to about 2,000 km (the upper 3% of Jupiter's radius).

• In the **highly conducting molecular shell**, hydrogen is mostly in molecular form, but the molecules trade enough electrons to make the hydrogen electrically conducting — a prerequisite for a magnetic dynamo. Thus the shell might support magnetic dynamo activity, in addition to the mantle below it. It might extend from about 95% or 90% of Jupiter's radius down to 80%.

• The **metallic mantle** takes up most of Jupiter's volume. Here, high pressures break the hydrogen molecules apart to form a "sea" of electrons and protons. This makes the liquid electrically conducting. The combination of a big volume of conducting material, motions spurred by heat from below and cooling from above, and the planet's rapid rotation drives Jupiter's strong magnetic field. This region is bounded above by clouds of helium rain — the place at which helium becomes partly insoluble in hydrogen and, being denser, its droplets sink down until they hit the high-pressure metallic region.

• The **core** is an enrichment of elements heavier than hydrogen and helium near the center of Jupiter. It's probably not solid, nor does it consist purely of rock or ice-forming compounds. It doesn't have a clear outer boundary, either. It extends out to half the planet's radius yet still occupies only about 10% of the volume.



▲ **JUPITER'S MAGNETIC FIELD** Juno's magnetometer data from the first flyby reveal that the planet's magnetic field is stronger in some places than scientists predicted based on Voyager data. (The plot peaks at the equator only because Juno flies much closer to the planet there, not because the field is intrinsically stronger at the equator than the poles.)

The deep atmospheric layer might hold a bizarre twist. Scientists looking at the Juno data conjecture that there may be a layer of silicate molecules, perhaps primordial, perhaps coming from meteoritic impacts. Some people call these "rock clouds" — but don't conjure up visions of lumps of rock you can hit with a hammer or rock faces to climb in Jupiter's atmosphere! At most we are talking about traces of silicate molecules dispersed in the atmosphere as droplets — like the water raindrops we have on Earth, only made of very hot rock.

Digging Deeper

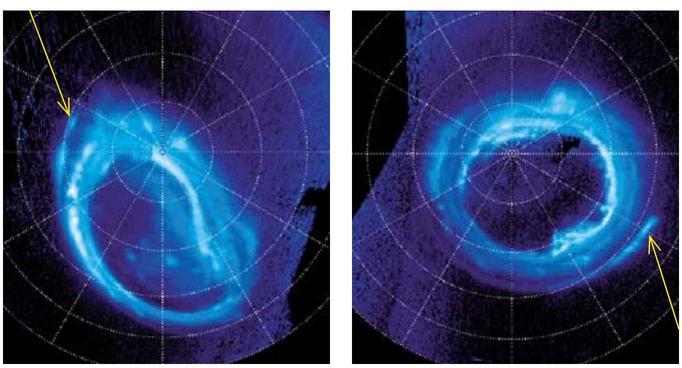
The microwave observations only probe the outermost skin of Jupiter — not even 1% of the way to the center. Below the deep atmosphere lies molecular hydrogen tainted with helium. According to atmospheric theory, as we descend pressures rise to such extremes that the hydrogen molecules break apart, creating a sea of electrons and protons. We call this substance metallic hydrogen, because the free-moving electrons make the liquid electrically conducting. The pressure also makes helium insoluble, and it precipitates out at this region's upper boundary as "rain." The metallic hydrogen mantle is the source of the planet's magnetic field.

To work out what Jupiter looks like deeper down, we need to consider the shape and strength of Jupiter's gravitational field. We map these by carefully measuring small variations in Juno's motion as it orbits the planet, using the same Doppler shifting of Juno's radio communication frequency as traffic police use with radar to check speeding cars.

For this mapping to work, it is vital to get up close to the planet. That's why we chose Juno's polar orbit to skim over the clouds and duck inside the radiation belt. We've spaced the north-south passes longitudinally such that we cut the planet into equal slices as Juno spirals around, with the first 8, then 16, and finally 32 passes following roughly equally separated paths. This allows models to match the data with increasing fidelity over the mission.

While we must patiently wait for Juno to finish mapping out Jupiter's magnetic field, the data from the first few passes show significant small-scale structure — a "patchy" field that varies up to 2 gauss from place to place. Combined with the field's surprising strength, this variation hints that the field's generator, or dynamo, lies closer to the surface than we might expect, perhaps extending beyond the metallic hydrogen layer and into the region of molecular hydrogen above.

Juno's preliminary results also show that the interior structure of Jupiter does not match the standard cartoon planet of distinct layers with sharp boundaries. Textbooks usually show Jupiter with a solid core of rock and "ice" (molecules like water and ammonia, though not frozen) at the center. Instead, things change gradually with depth. Juno's data suggest that the core has much fuzzier boundaries. It's likely a large, diluted region where elements heavier than helium mix with the surrounding metallic hydrogen. This fuzzy core extends roughly halfway up to the surface.



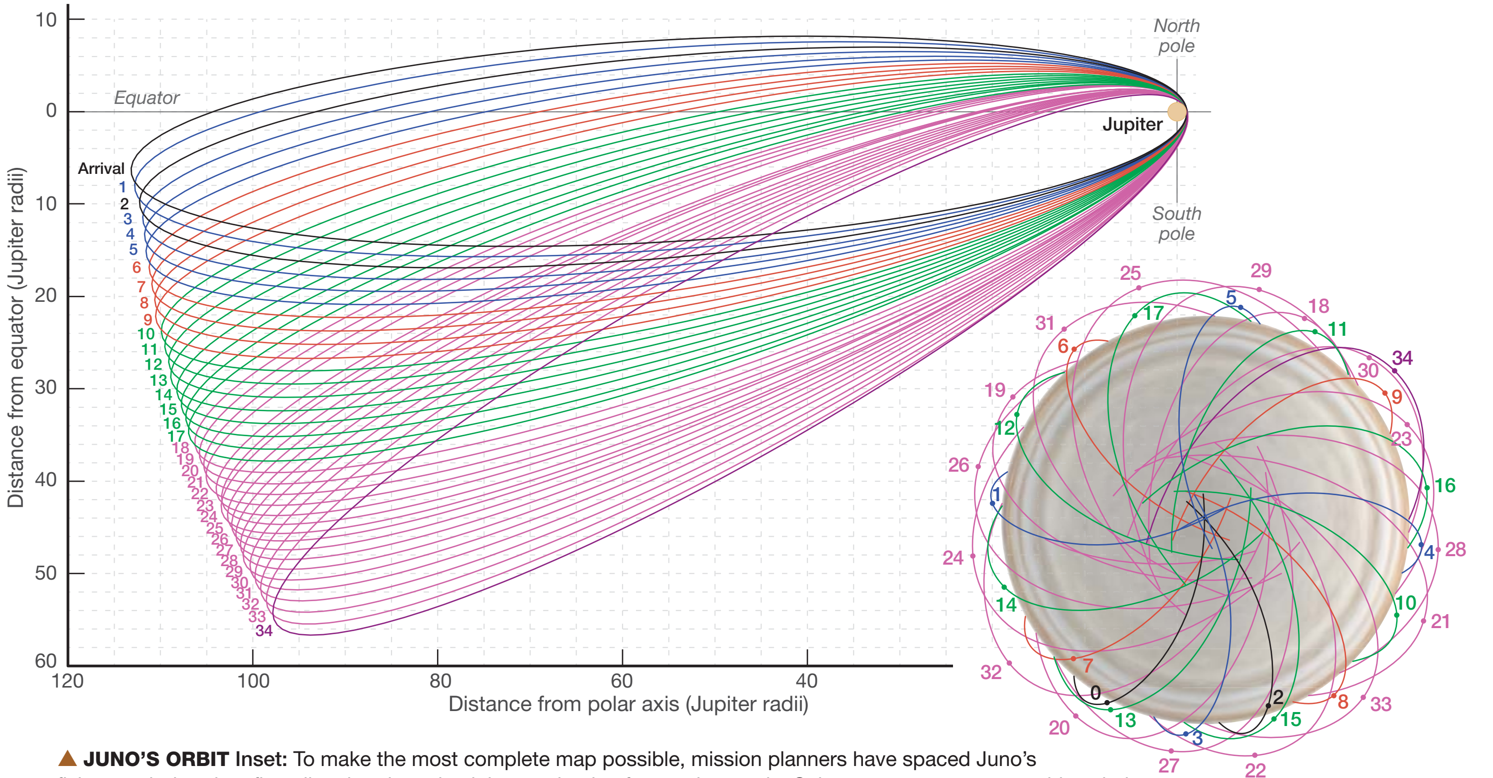
▲ **AURORAL OVALS** Images of Jupiter's northern (left) and southern aurora obtained by the Juno UVS instrument. Yellow arrows indicate emissions related to the moon Io.

Flying Through the Aurora

Jupiter's magnetic dynamo gives structure to the vast magnetosphere surrounding the planet, most "visibly" manifested by Jupiter's strong auroras. These ultraviolet and infrared glows are excited by charged particles streaming along the magnetic field lines and slamming into the planet's atmosphere. The ultimate source of most of the charged particles trapped in Jupiter's strong field is the inner Galilean moon Io, which spews volcanic gases into space. These sulfur and oxygen atoms are then broken down and ionized, becoming trapped with their companion electrons in Jupiter's magnetic field and forming a plasma that's carried around by the spinning planet.

Juno's polar orbit gives us a special view of the aurora and what boosts the particles to the speeds at which they slam into the atmosphere. Not only do the ultraviolet (UVS) and infrared (JIRAM) instruments look directly down on the

GRAPH: GREGG DINDERMAN / S&T, SOURCE: NASA / GSFC / SWRI / JACK CONNERNEY; AURORAS: JUNO UVS / VINCENT HUE (2)



▲ **JUNO'S ORBIT Inset:** To make the most complete map possible, mission planners have spaced Juno's flybys such that they first slice the planet in eight equal strips from pole to pole. Subsequent passes rotate this spiral so that the planet is cut into smaller, roughly equal slices as the mission continues. **Background:** Shown here are all planned flybys as seen from the side (looking along Jupiter's equator) and flattened into the same plane. Over time, the gravitational pull of the planet's equatorial bulge will cause the orbit to slowly precess downward, inevitably bringing the trajectory through the dangerous radiation belts, around the equatorial plane.

auroral emissions, but the particle instruments JADE and JEDI simultaneously measure how many charged particles are streaming along the magnetic field. By pulling together the data from these different instruments, we can learn about the processes that accelerate the particles.

The most intense auroras on Earth are generated when electrons are accelerated in a region above one of Earth's poles where an electric potential exists between locations with opposite polarities — like a battery. Weaker terrestrial auroras are caused instead by electrons scattered by electromagnetic waves. As Jupiter's aurora is orders of magnitude more powerful than Earth's, we naturally assumed that the former process was responsible.

Yet Juno's results puzzle us. We do see potentials of up to 400,000 volts, 10 to 30 times larger than what's observed at Earth. But such static, high-voltage structures would produce beams of electrons all with about the same energy — something that's rarely observed by the JEDI instrument. More commonly observed by JEDI as it passes over Jupiter's aurora are electrons with a broad range of energies, which is what we'd expect if the electrons are interacting with — and getting an energy boost from — waves in the plasma above the aurora. But we still do not know what generates the waves.

What's Next?

These preliminary discoveries are only from Juno's first seven orbits, less than a quarter of the planned number of passes. Because Juno is staying in its 53-day orbit instead of closing in for the intended 14-day circuits, a plan shelved after an engine anomaly arose (*S&T:* June 2017, p. 8), it will take more than 4½ years to complete the 32 flybys that we need in order to fully map out the small-scale structure of the magnetic and gravitational fields. The initial plan envisioned Juno operating for less than 18 months in its tighter orbit.

Moreover, in 4½ years Jupiter covers over a quarter of its orbit around the Sun. Juno's orbit remains fixed with respect to space, but Jupiter's day-night terminator shifts. Thus even though Juno's flybys are spaced to see different parts of Jupiter, the local time of the pass wasn't originally supposed to shift much. But in the new situation, Juno will eventually pass closest to the planet near local noon and near midnight when at *apojove* — instead of the persistent dawn-dusk orbit orientation the mission planners designed for. Now the Juno team is juggling how to keep the solar-powered spacecraft oriented toward the Sun while optimizing observations of Jupiter with science instruments that were designed for the original geometry. Such is the business of space exploration.

We're still a long way from answering the fundamental questions Juno set out to answer. In the meantime, though, we have plenty of discoveries to chew on.

■ **FRAN BAGENAL** is a researcher at the University of Colorado, Boulder, and co-chairs Juno's Magnetospheric Working Group and Scientific Planning Working Group. For more information about Juno, visit **missionjuno.swri.edu** and **nasa.gov/mission_pages/juno**.

 by Monica Young

Machines Learning Astronomy

The new era of artificial intelligence & Big Data is changing how we do astronomy.

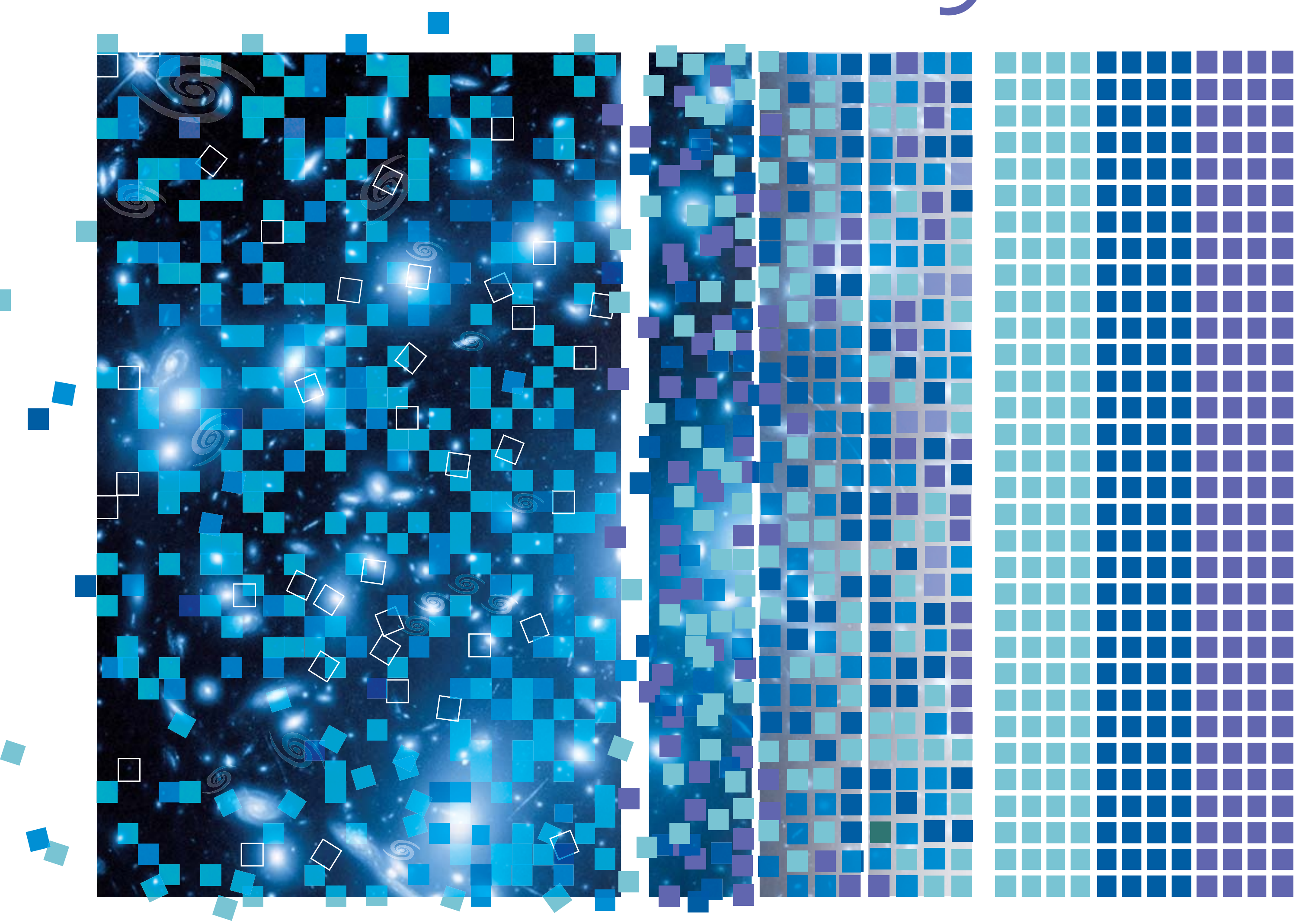


IMAGE: NASA / ESA / JENNIFER LOTZ / HFF TEAM (STSCI); PAT COPPOLA / *S&T*

You probably use artificial intelligence a dozen times a day without realizing it. If you've recently scrolled through your Facebook feed, browsed Netflix videos, used iPhone's Siri, checked a relatively spam-free inbox, or just Googled a term, you've made use of complex computer algorithms that can learn from experience.

"Artificial intelligence," though correct, may be too fanciful a term for these processes — no computer today is capable of general intelligence or autonomy. Still, what the algorithms can do is possibly paradigm-shifting. Rather than humans programming a computer explicitly, the algorithms use data to construct their *own* mathematical models — sometimes ones too complex for human understanding. This implementation of artificial intelligence is known as *machine learning*, and it can filter through vast amounts of data.

Given the data tsunami facing astronomy (*S&T:* Sept. 2016, p. 14), it should come as no surprise that machine learning has popped up in just about every part of the celestial realm over the past few years (see box on page 28). From exoplanets and variable stars to cosmology, machine learning is going to play an ever-larger role in the coming decade of astronomical research.

▲ **TO SEE CATS** Computer scientists at Google taught a powerful neural network to recognize, among other things, cat faces. The algorithm "learned" from 10 million 200×200-pixel images drawn from YouTube videos. When asked to render a cat, the algorithm produced this convincing image.

Big Data, Big Opportunity

Machine learning isn't new — pioneers of the field hail back to the 1950s. But it was long discounted as impractical, requiring too much computational power to implement. Lack of data was also a problem: Like humans, machines build their internal models based on copious observations.

It was the advent of Big Data, as well as significant advances in computing, that finally enabled machine learning to take off. In one famous example, Andrew Ng (Stanford University), who led the Google Brain project, drew from 10 million YouTube videos to teach an algorithm to recognize — what else? — cats. Fortunately, the playing field isn't limited to internet whims. In astronomy, Big Data abounds.

"We are very firmly in the era of what we call 'survey astronomy,'" says Lucianne Walkowicz (Adler Planetarium).

The Sloan Digital Sky Survey (SDSS), which has imaged a third of the sky, qualified as Big Data when it began in 2000, but new and upcoming projects are dwarfing it. The standard-bearer is the Large Synoptic Survey Telescope (LSST), scheduled to begin science operations in 2022. It will generate the equivalent of the SDSS every night, monitoring 37 billion stars and galaxies in space and time to make a decade-long movie of the southern sky.

There are others as well: The Dark Energy Survey started charting hundreds of millions of galaxies in 2013; the Gaia satellite began mapping 1 billion stars in the Milky Way in 2014; and the Zwicky Transient Facility, due to see first light in late 2017, will be scanning 3,750 square degrees every hour. That's not to mention archival data from past surveys. The bytes have become numerous enough that, even with dozens of graduate students or thousands of citizen scientists, human eyes simply can't scan all the available data.

"People don't scale," notes Joshua Bloom (University of California, Berkeley), founder of the startup Wise.io. "And especially experts don't scale."

Brian Nord (Fermilab) encountered this problem of scale when he joined the Dark Energy Survey (DES) team, where 20 scientists spent months poring over 250 square degrees' worth of images. They were looking for the warped shapes that mark *strong gravitational lenses*, where clusters or massive galaxies bend the light from background objects.

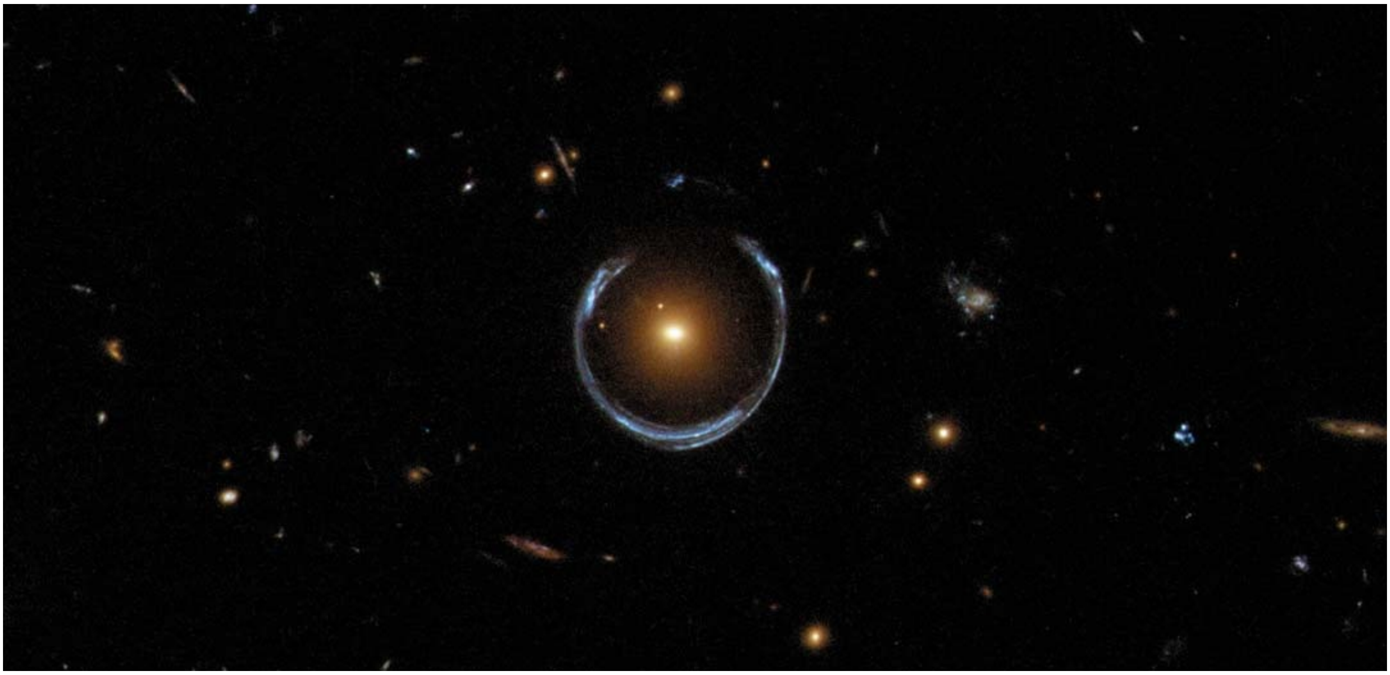
About a thousand such lenses are already known, but the full, 5,000-square-degree DES offers the potential to triple that number, and LSST might reveal an order of magnitude more. A few of these lenses could magnify exceedingly rare — and cosmologically invaluable — distant supernovae. For this reason, the researchers made sure to look at *everything* in the preliminary data set, not applying any filters that might have eased the search, in order to avoid missing legitimate sources.

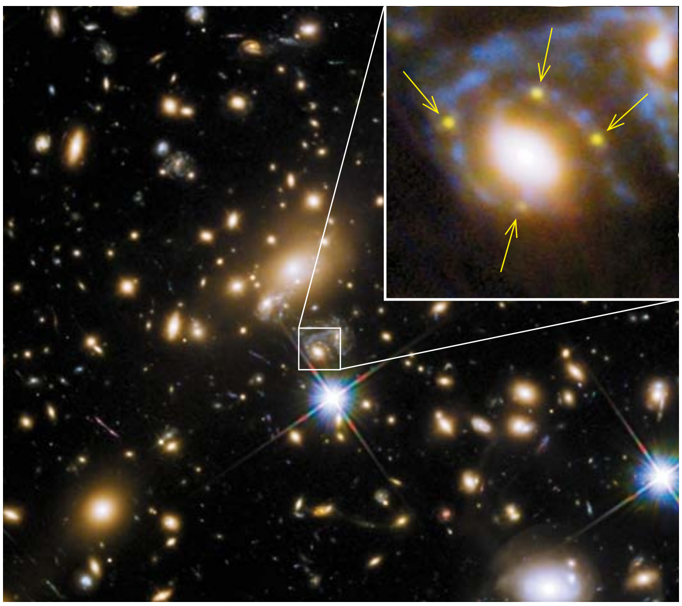
"It was a painful number of pixels to visually scan," Nord says. "I saw this, and I thought, 'Oh my God. This is so painful, there has got to be a better way.'"

MORE THAN JUST BIG

To qualify as "big" in the world of computer science, data need more than *volume*; they also need *variety* and *velocity*. Big Data is any huge amount of data that comes in a variety of formats (such as images, spectra, and times-series data) and must be dealt with in a timely manner.

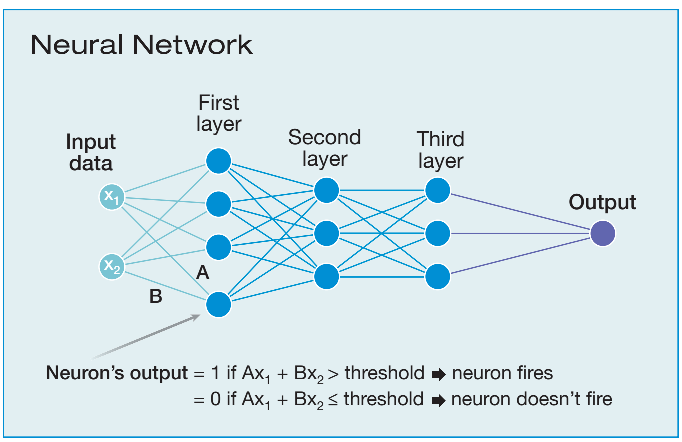
CAT: LE ET AL. / *PROCEEDINGS OF THE 29TH INTERNATIONAL CONFERENCE ON MACHINE LEARNING* 2012; NEURONS: ENOT POLOSKUN / ISTOCK / GETTY IMAGES PLUS





Nord, who says he was inspired in part by Tesla's self-driving cars, set about eliminating humans from the process. He built and trained DeepLensing, a machine-learning algorithm technically known as a *convolutional neural network*, to recognize distorted galaxy images.

As the name implies, neural networks are loosely based on the myriad connections between neurons in the brain. Each neuron in the algorithm is a simple mathematical formula. Given a certain input, it performs a calculation to decide whether, in biological terms, to "fire." During training, feedback loops within the code change a neuron's firing capabilities based on sample data. Once training is finished, those feedback loops are turned off.



▲ **LUCKY HORSESHOE** Creating strong gravitational lenses, such as the one depicted here, requires a bit of good fortune. First, two celestial objects must line up in just the right way for one to gravitationally magnify the light coming from the other behind it. Then, actually finding a lens, especially one that appears small on the sky, takes a bit of serendipity — and a lot of work if humans are the ones looking.

◀ ▲ **FOUR-LEAF CLOVER** Astronomers observing a massive galaxy cluster as part of Hubble's Frontier Fields project caught a supernova gravitationally lensed into four separate images (*inset*). A fifth image appeared several months later. Such celestial happenstances are incredibly rare and cosmologically valuable. The Dark Energy Survey could spot a few lensed supernovae over its five-year duration.

◀ **SKY NET** This schematic diagram portrays a simple neural network that starts with data, such as an image, and ends with an outcome, such as a classification. In between lie layers of neurons. The data enter every neuron in the first layer, and each neuron performs a simple calculation, weighting the data points (A and B are the weights for x_1 and x_2, respectively) to determine whether it should fire. Each neuron's decision then feeds into the next layer of neurons. The last layer of neurons then converges to produce an answer, such as "lens" or "not lens."

HORSESHOE GALAXY: ESA / HUBBLE & NASA; LENSED SUPERNOVA: NASA / ESA / STSCI / UCLA; NEURAL NET: LEAH TISCIONE / S&T

DeepLensing contains three sets of neural layers, where the output of each neuron in one layer acts as input to the neurons in the next. The layers act as filters, picking out features in the input image. For example, the first layer may separate dark regions from light ones; the next may highlight edges; the one after that may recognize shapes. Once trained, the last layer gives the final decision: lens or not lens.

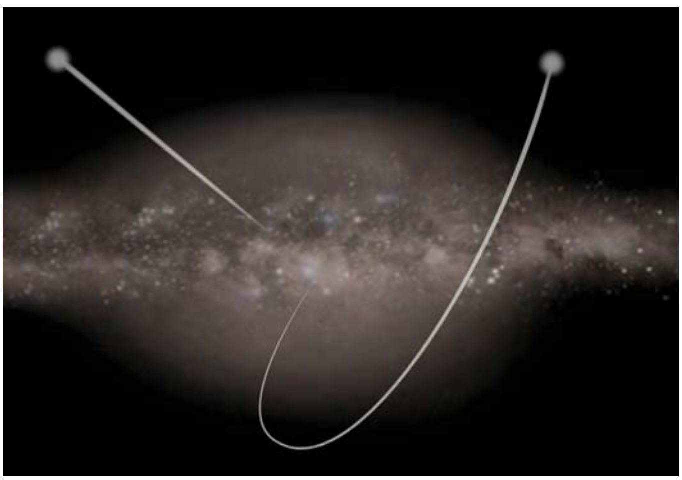
These networks are incredibly simple compared to the roughly 100 billion neurons in the human brain. In fact, it takes only a couple dozen lines of code to construct a basic neural network. Yet, mathematically, the result is linear algebra on a massive, sometimes incomprehensible scale.

Though DeepLensing is still a work in progress, it can already accomplish what other methods could not: quickly filtering thousands of input images while maintaining 90% accuracy in what it identifies as a lens in simulations. And DeepLensing isn't alone — similar, independently developed neural nets have since found and analyzed strong gravitational lenses millions of times faster than humans can.

Needles in the Haystack

Machine learning is well suited to "needle-in-a-haystack"-type searches, so it was the tool that Elena Rossi (Leiden Observatory, The Netherlands) turned to when she wanted to study exceedingly rare *hypervelocity stars*.

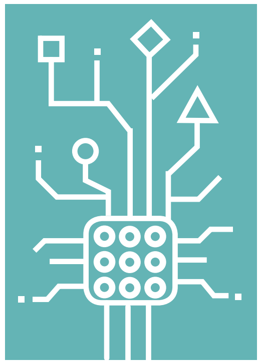
These stars speed away from the Milky Way's center, probably ejected via a gravitational slingshot interaction with our galaxy's supermassive black hole. Some of them are on a course to escape the galaxy entirely. So far astronomers have found only about 20 hypervelocity stars, but amidst the 1 billion stars that Gaia is currently monitoring, Rossi expects to find at least a hundred more. Her research has shown that that would be enough to start using their trajectories to probe the shape of the dark matter cloud surrounding the Milky Way (*S&T:* Apr. 2017, p. 22).



RUNAWAY STARS: ESA

▲ **RUNAWAY STARS** The conditions that allow a star to escape our galaxy, as pictured here in this artist's illustration, are exceedingly rare. Such *hypervelocity stars* are consequently difficult to find unless astronomers employ innovative methods.

TEST & VALIDATE



Machine-learning algorithms train on data, usually referred to as a *training set*. Once an algorithm has finished training, its accuracy is probed via a separate *validation set*. Both sets may consist of real data or, if large amounts of real data aren't available yet, simulated sources. Once the algorithm performs well on both the training and validation sets, it's ready for action.

But to map out a hypervelocity star's orbit within the dark matter halo, she first needs to know that star's motion through space. Gaia doesn't provide full, three-dimensional velocity information for every star it monitors — it only measures the motion toward or away from us, called *radial velocity*, of the very brightest stars. So not only did Rossi need to identify rare stars outnumbered a million to 1 by normal stars, she needed to do so with incomplete data.

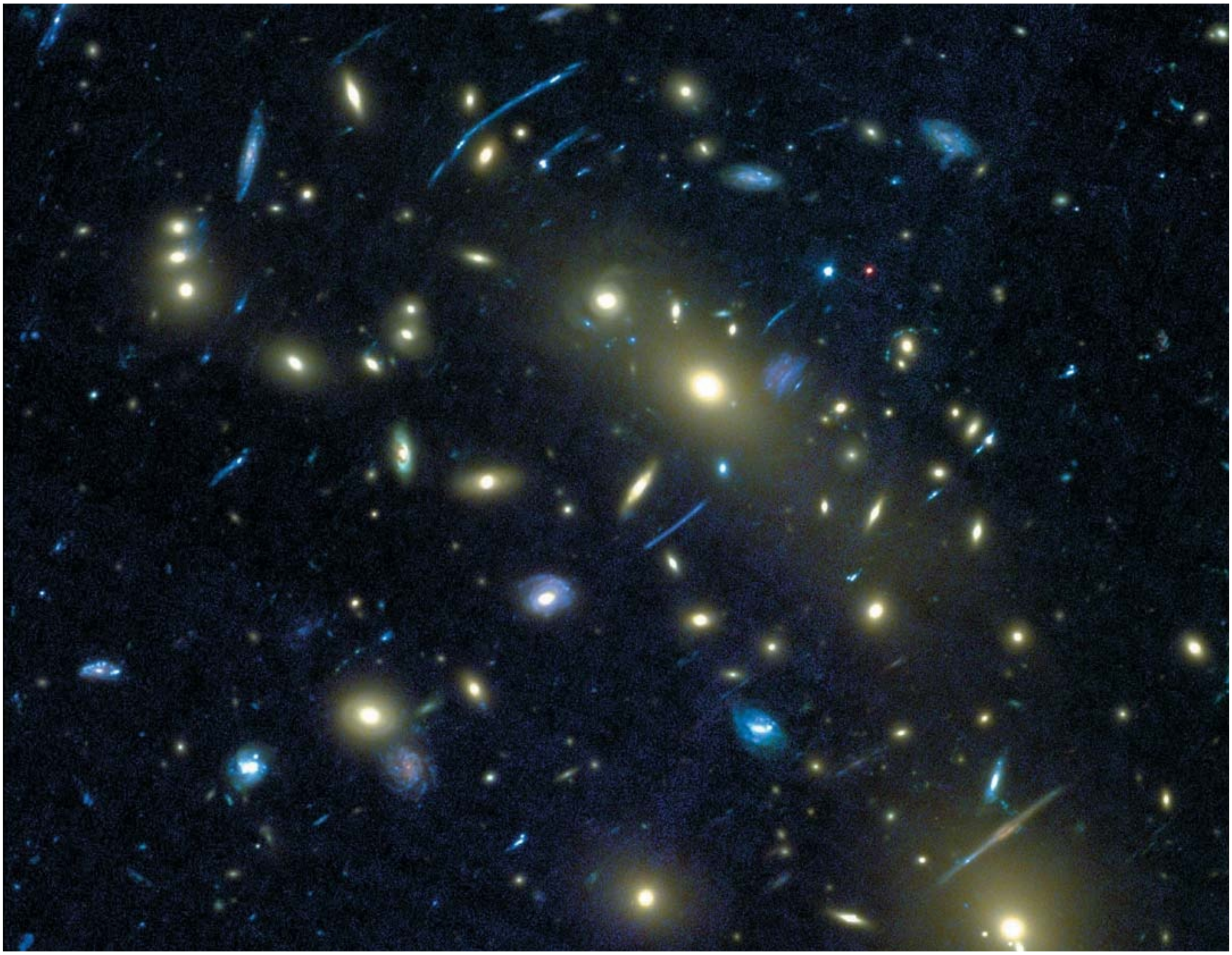
> Machines are becoming capable of "systematizing serendipity."

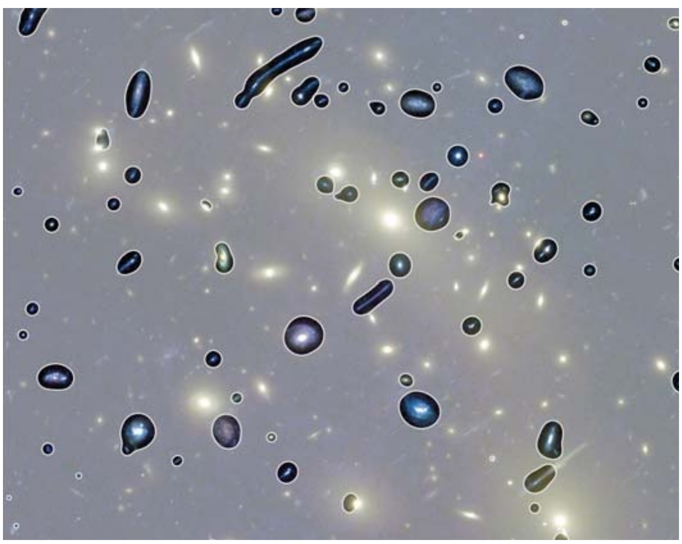
After some initial investigation, Rossi settled on a neural network of two layers with 119 and 95 neurons, respectively. The many neurons ensure that each layer is sufficiently complex to extract features from the data. Meanwhile, additional layers further filter and abstract the data, creating an increasingly flexible neural network. However, if the algorithm becomes too complex or too flexible, it begins to overfit: It tries so hard to learn from the training set that it becomes rigid, unable to generalize the lesson to other data.

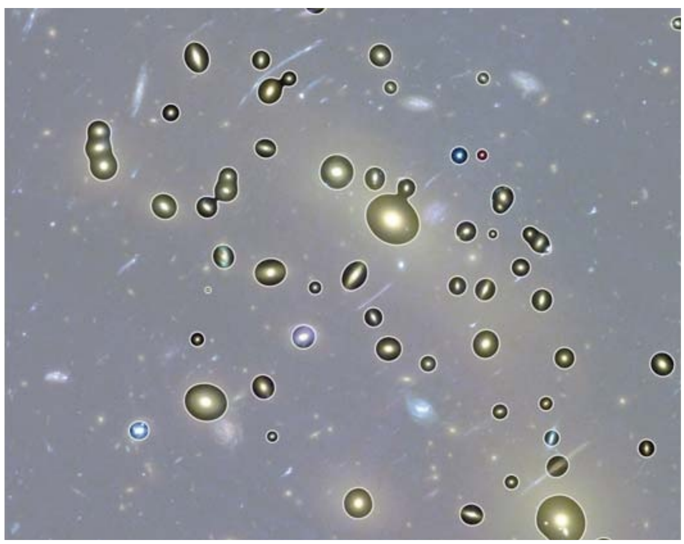
Finding the right balance is often a matter of trial and error, and Rossi and her graduate student Tommaso Marchetti put the algorithm through hoops to learn how many layers and neurons would work best. On a fundamental level, though, it isn't clear why some architectures do better than other ones.

"We're still trying to understand our tool," Rossi explains. "When I saw that our algorithm was giving us what we were looking for, at least in the right direction, I was very happy — but also surprised!"

The algorithm trawled through the first release of Gaia data, all 1 billion stars, to find 80 candidate hypervelocity stars — a reassuringly low number given the objects' rarity. Of these, 30 stars already had known radial velocities, and Rossi targeted 22 additional stars for follow-up observations. Ultimately, the team found six hypervelocity stars, a nice catch for the first go-round.







NASA / ESA / J. GEACH / A. HOCKING

▲ **COMPUTING THE GALAXY ZOO** While citizen-science projects such as Zooniverse currently enable the classification of galaxies and other objects en masse, future Big Data surveys such as LSST will provide too much data for such methods to handle. Based on a Hubble Space Telescope image of the galaxy cluster MACS0416.1–2403 (*top*), Alex Hocking (University of Hertfordshire, UK) and colleagues taught a multi-part machine-learning algorithm to automatically recognize star-forming galaxies, including lensed ones, (*bottom left*) and ellipticals (*bottom right*).

The algorithm turned up another surprise: five runaway stars *not* coming from the Milky Way's center, each traveling between 400 and 780 kilometers per second (900,000 to 1.7 million mph). These stars may once have been part of binary systems in the Milky Way's disk that were ejected when their stellar partners went supernova. But such explosions don't typically eject stars at speeds this high. "Our algorithm picked up a very special case of this mechanism," Rossi says.

Gaia's next data release, which will help validate Rossi's finds, will come in April 2018.

Astronomers have had success honing machine learning to build samples of known, rare objects. But self-taught algorithms can do more than that — they can also discover entirely new types of celestial gems.

Detecting the unexpected comes second nature to humans, who excel at pattern recognition and can therefore easily pick out rare and unusual objects. Citizen science has reams of examples: green pea galaxies, Hanny's Voorwerp, and Tabby's Star (*S&T:* June 2017, p. 16), to name a few.

Now machines are becoming capable of, as Walkowicz puts it, "systematizing serendipity." Walkowicz is working with graduate student Daniel Giles (Illinois Institute of Technology) to train an algorithm that separates Kepler-observed stars into groups and ranks them by "weirdness." Using Tabby's Star as a test subject, Walkowicz and Giles are creating the tool to pick out Tabby's Star analogs in Kepler data and, eventually, in other surveys such as LSST.

Making Connections

Some are taking these programs even further — rather than finding needles in a haystack for future study, astronomers can apply machine learning to inspect all of the hay. Self-taught algorithms can make unforeseen connections between features in the data, enabling computers to classify and characterize objects en masse.

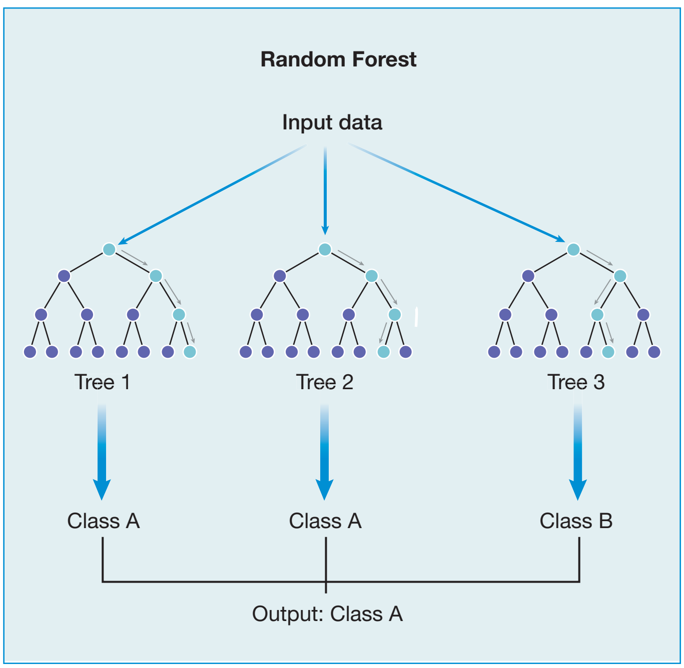
> Rather than finding needles in a haystack, astronomers are using machine learning to study all of the hay.

That ability may help solve one of the biggest problems facing the LSST. When the telescope comes online early next decade, it'll produce 15 terabytes' worth of brightness measurements every night, but it'll be missing something crucial: spectra. Spectral lines from the heavy elements that lace a star's gas reveal its physical properties, such as its surface temperature and gravity. However, follow-up spectroscopy will only be feasible for 0.1% of LSST-observed stars.

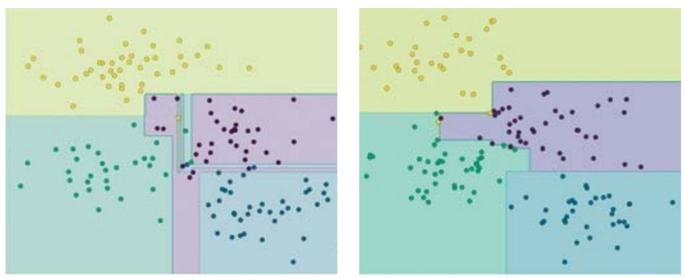
Nevertheless, astronomers can learn a lot about a star by its color, as well as by its light curve, which tracks the change in brightness over time. In 2015 Adam Miller, then a graduate student at University of California, Berkeley, and Joshua Bloom, his advisor, realized that machine learning could connect brightness measurements of variable stars to the physical properties normally gleaned from their spectra.

They conducted a proof of concept using a collection of decision trees, collectively known as a *random forest*. Each tree asks a series of questions to separate the variable stars into groups. The questions aren't programmed in; the trees decide the questions themselves based on the data they train on.

In this test case, the training set consisted of 9,000 variable stars observed in the Stripe 82 survey, a 315-square-degree field repeatedly imaged by the SDSS project. Follow-up spectroscopy came from the 6.5-meter Multiple Mirror Telescope in Arizona.



◀ **FROM TREES TO FORESTS** Random forest algorithms, such as the one shown in this simple schematic, are a collection of decision trees. Each tree is shaped slightly differently from its neighbors, asking different questions of the data and separating data points in different ways. The outputs from all the trees are averaged before providing an answer. As in neural networks, humans don't program the decision points — the trees determine what questions to ask from the data itself.



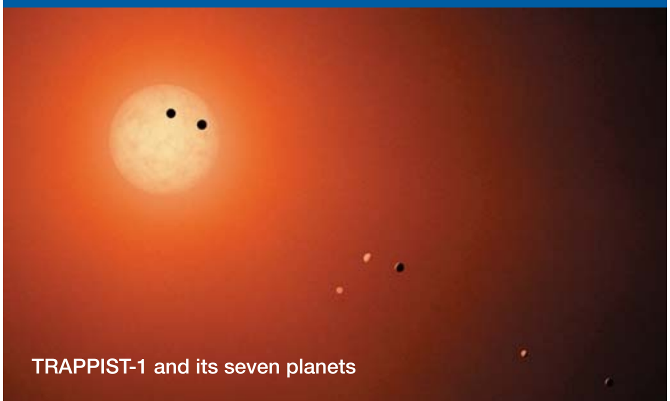
▲ **LOST IN THE WOODS** A decision tree asks questions to separate data — the more questions it asks, the more it divides the data (*left*). But a single series of decisions may miss the forest for the trees, carving up the training data so much that the algorithm is no longer useful for classifying new data sets. By averaging an ensemble of decision trees (*right*), a random forest algorithm reaches more robust conclusions.

TREES TO FOREST: LEAH TISCIONE / *S&T*; LOST IN THE WOODS: JAKE VANDERPLAS

Based solely on brightness measurements, the decision trees predicted the surface temperature, surface gravity, and abundance of heavy metals for 54,000 variable stars, achieving the same precision as low-resolution spectroscopy.

The result, which Bloom calls "sort of a weird head-scratcher," is that machine learning could transform the LSST from an instrument that measures how variable stars change over time into a sort of spectrograph, measuring the stars' spectral — and physical — properties.

AI-Aided Discoveries


TRAPPIST-1 and its seven planets

◗ Machine-learning algorithms separate true supernovae from bogus detections in the live data stream from the All-Sky Automated Survey for Supernovae (ASAS-SN). They are responsible, for example, for the detection of the most luminous supernova to date, ASASSN-15lh, which shines at 570 billion times the Sun's luminosity (*S&T:* Nov. 2015, p. 12).

◗ Machine learning helped confirm the seventh planet orbiting the cool dwarf star TRAPPIST-1. A single transit had hinted at the world's existence, but 70 days of additional Kepler observations and machine-learning analysis were crucial to verify the planet's signal (*S&T:* Sept. 2017, p. 11).

◗ A machine-learning algorithm plucked 60 non-transiting hot Jupiter candidates from Kepler data by their reflected starlight. The find was unusual, since most Kepler exoplanets reveal themselves when they pass in front of their star. These candidates now await follow-up observations to confirm their hot Jupiter status.

◗ Astronomers have built the V-FASTR classifier for the Very Large Baseline Array to distinguish new radio-wave discoveries, such as fast radio bursts, from known pulsars and human-created radio interference with more than 98% accuracy.

"It's like sitting in a room and hearing someone on the other side of the room singing," Bloom says, "and you can tell how old they are, what their gender is, and what color their hair is from how they sing."

The Black Box Problem

Despite its incredible potential, machine learning is just starting to take off in astronomy, and some of the delay is caused by sheer hesitation. "The generic problem with machine learning is that you always get an answer," Bloom cautions. "And that's really dangerous."

Because machine learning can make connections and recognize patterns better than humans do, using these algorithms carries a significant risk: The answer an astronomer receives may be an answer — maybe even a wrong one — that the astronomer can't understand.

Ashley Villar (Harvard University) ran into that complication when she was building what she calls a "home-brewed" neural network to better understand Type Ia supernovae. These are the flashes from white dwarfs that have reached their mass limit. All explode in a similar way, so they're best known for their use as standard candles in cosmology. But the bursts are not identical, and understanding their differences can improve measurements of the expanding universe.

Villar studies how different amounts of heavy elements, or *metallicities*, might alter the detonations. The conditions in which those heavy elements exist are so extreme that they can't be reproduced in the lab. So Villar is building a tiny neural network — two layers with six neurons total — to relate the heavy elements present in the star's host galaxy (which gives an idea of the metallicity of the star itself) to the explosion's spectrum.

Villar trained the algorithm and it began producing output: When she fed in a Type Ia spectrum, it reported the progenitor's metallicity. But how was it making the decision — and was it always the right one?

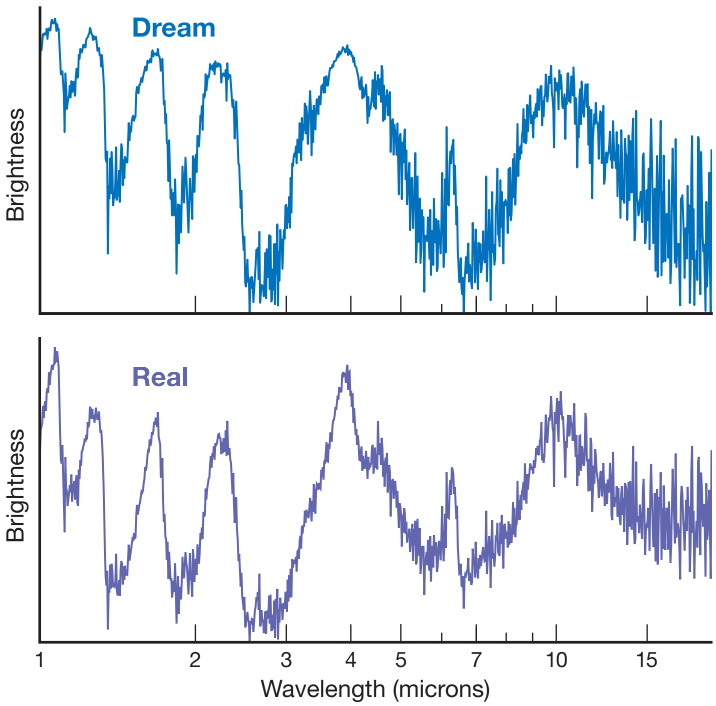
Answering that question is one of the biggest challenges facing machine learning today. "It's being talked about," Villar says, "but it's hard to quantify. And in astronomy, it hasn't been explored."

One approach, which Villar has taken, is to black out parts of the spectrum and see how the calculation of the star's metallicity reacts — basically, how wrong does the algorithm get when it's missing bits of data? The more wrong it becomes, Villar figures, the more important that section of the spectrum was in determining the answer.

There's another approach to explaining how an algorithm does what it does: letting it dream. It's actually less fantastical than it sounds. As Ingo Waldmann (University College London) puts it, "Dreaming is just working backward."

Waldmann had taught an algorithm called Robotic Exoplanet Recognition (ROBERT) to recognize molecules in an exoplanet's transmission spectrum, measured from the light that passes through the sliver of atmosphere visible whenever a planet passes in front of its star. Here, it's not the data that

NASA / JPL-CALTECH



▲ **DREAMING OF WATER** To see if ROBERT, the Robotic Exoplanet Recognition algorithm, had learned to spot the signal that water in an exoplanet atmosphere would imprint on its spectrum, Ingo Waldmann let ROBERT "dream." When fed the label "water", the algorithm came up with a depiction of a water spectrum that mimicked a real spectrum.

I. WALDMANN / *ASTROPHYSICAL JOURNAL* 2016

are complex, it's the models: A computer might peruse half a terabyte's worth of theoretical atmospheric models as it tries to match the patterns in a simple exoplanet spectrum, often taking days to reach a decision. In the coming age of dedicated exoplanet missions — including NASA's Transiting Exoplanet Survey Satellite (TESS) and the European Space Agency's Atmospheric Remote-sensing Exoplanet Large-survey (ARIEL) mission — that's not good enough.

So Waldmann built a fast, three-layer neural network to recognize the imprints molecules leave in their exoplanet's spectrum. Instead of flipping through hundreds of temperature profiles, molecular spectral lines, and cloud or haze possibilities, ROBERT simply learned the pattern that water takes in an exoplanet spectrum.

To test how the algorithm was learning that connection, Waldmann turned the algorithm around. Rather than feeding ROBERT a spectrum, he simply told it "water," then let it produce its own idea of what an exoplanet spectrum with water would look like.

"When I first built ROBERT, it was too complex," Waldmann says. "When I made it 'dream,' it had a really noisy spectrum. And then I realized . . . it was basically bored." There were so many neurons that many of them weren't activating — they were just sitting there, producing noise. When Waldmann reduced the number of layers and neurons, the algorithm's dreams crystallized, bringing forth a realistic portrayal of water's spectral lines. The dreams showed that ROBERT now "understood" molecular patterns.

Even so, there's a larger question: Does ROBERT also understand the underlying physics associated with those patterns? For example, in the process of learning the spectral lines created by water, did ROBERT also learn the temperature profiles of potentially water-carrying atmospheres?

"I think it should. There's no reason why it shouldn't," Waldmann speculates. But the point is that he isn't sure. "This is the problem with neural networks — you don't know what they know."

The trickiness of building and understanding a machine-learning algorithm and the great potential worth of its output are reflected in the response this kind of research receives. When Villar presented her supernova research at a meeting of the American Astronomical Society, she recalls, "Some people were really excited about this. They think it's the end-all be-all, it's going to solve everything. And there are definitely people who completely reject it, they think it's terrible."

Even Bloom, perhaps one of astronomy's biggest machine-learning proponents, says, "It is a whole pit of pitfalls." In fact, he adds, "I give talks to lots of different groups, and the first and last thing I say is, 'Don't use machine learning unless you have to.'" Even so, many astronomers predict that machine learning will take on an important role in the field, perhaps becoming as essential as the telescope.

> We might build algorithms that give us an answer, but it's one that we aren't capable of understanding.

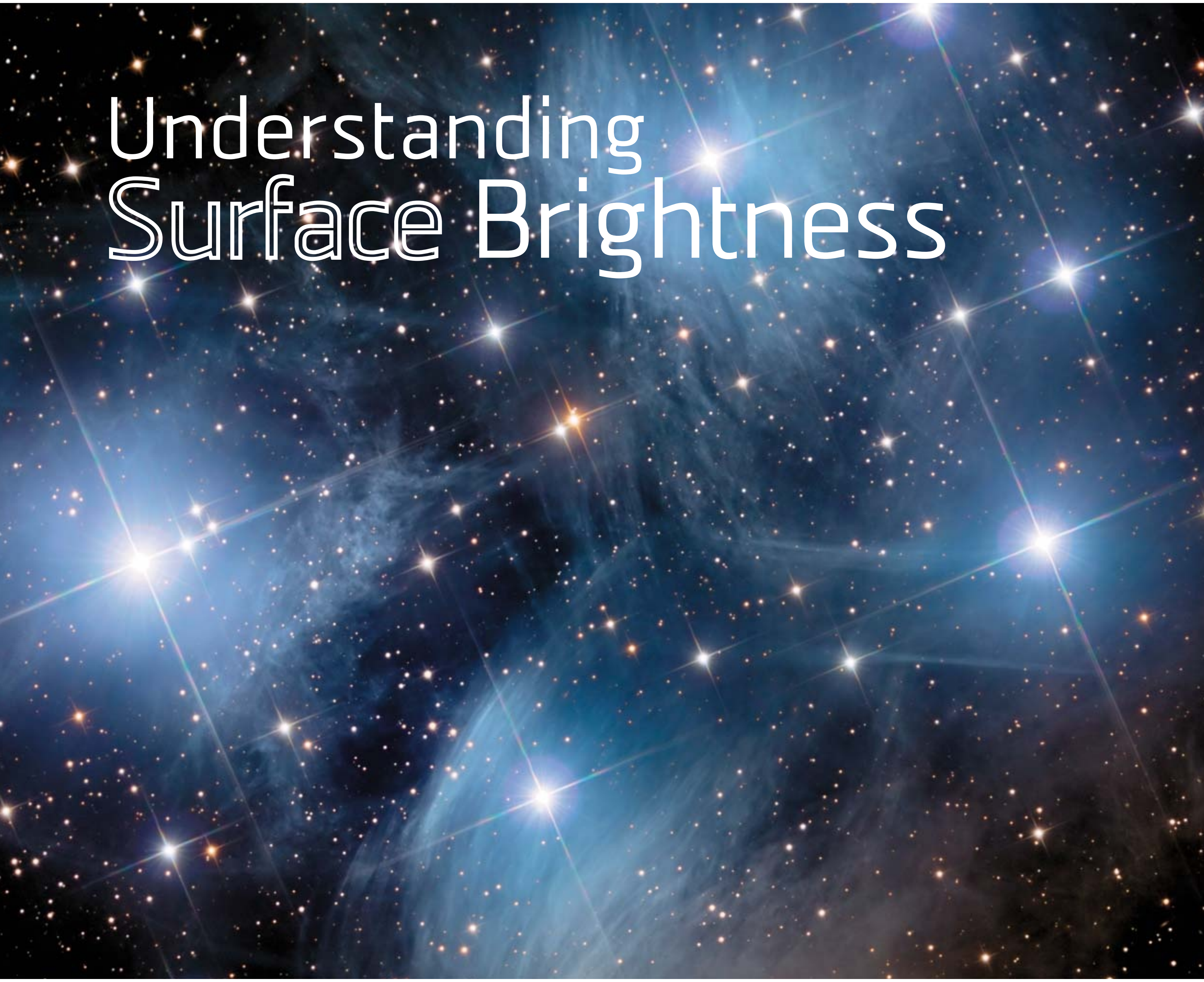
In the coming decade, machine learning will no doubt replace or supersede some traditional analysis techniques. But it's possible it could go a step further. What if the natural world is described by laws that are so complex that only machine-learning algorithms can describe the observations that future surveys obtain? We might build algorithms that give us an answer, but it's one that we aren't capable of understanding. "That's kind of a crazy thought," Bloom muses. But it's the kind of thought that comes up when working with a set of tools that's only beginning to be explored.

"From my perspective," Bloom says, "it's a little bit like being a kid in a candy store — before all the kids wake up."

■ **MONICA YOUNG**, *Sky & Telescope*'s News Editor, looks forward to peering inside the black box of artificial intelligence.

• **Try your own hand at machine learning — it's not as hard as it might seem! To start experimenting with interactive tools for various skill levels, visit https://is.gd/machinelearningastro.**

Understanding Surface Brightness



It took a while, but the light bulb finally went on above my head.

In the June 2017 Astronomer's Workbench (page 38), I wrote about building solar filters. When I showed a homemade solar filter to my astronomy club, one of the members asked me a question I couldn't answer: If the filter provides a relatively bright view when you look through it, and the light enters the telescope through the entire aperture of the filter, with it all directed to my naked eye, why doesn't the concentrated light increase the brightness to an unsafe level?

That's a very good question. I didn't have a good answer for it, so I did some research and found out why. The answer has to do with what astronomers call *surface brightness*.

As counterintuitive as it may seem, an object in a telescope can never be brighter than that same object seen by naked eye — with one exception: distant stars. Distant stars are so far away that they're essentially point sources. If you magnify a point source, it remains a point, so any increase in the amount of light that the telescope gathers will also

▲ **PARTLY CLOUDY** Because of the limitations of resolution and aperture, stars don't appear as point sources in images. The nebulosity of the Pleiades may appear brighter when viewed under magnification in the eyepiece, but it's an illusion. It's no brighter per unit area than it would be in a naked-eye view.

remain in that tiny point, making the point brighter. But any other object — a planet, a nebula, the Moon, even the Sun — has dimension to it, and that makes a world of difference.

An object with dimension gets bigger when you magnify it. And the area of that object gets bigger as the square of the magnification (area is measured in square units, after all). So if you double the size of an object, its area increases by 2^2 (2 squared), or 4 times. Triple it and its area increases by 3^2, or 9 times. And so on. At a magnification of 100×, an object's surface area is 10,000 times greater than when seen by naked eye. So the telescope gathers more light, but that light is spread out over a larger area. It cancels out.

"What's to prevent you from simply lowering the magnification?" you might ask. Get it low enough and the scope gathers more light than it spreads out. Wouldn't the surface brightness go up?

Nope, because of what's known as the *exit pupil*. The exit pupil is the diameter of the light beam that leaves the eyepiece aimed at your eye. As magnification goes down, the exit pupil gets bigger. That's what magnification is, actually: the ratio of the incoming light beam compared to the outgoing light beam. If you squeeze a 100-mm telescope aperture (about 4 inches) down to a 5-mm exit pupil, you'll have a 20× (20-power) image (100/5 = 20). You can work the math the other way, too: If you want 25× out of a 100-mm telescope, you'll have a 4-mm exit pupil (100/25 = 4).

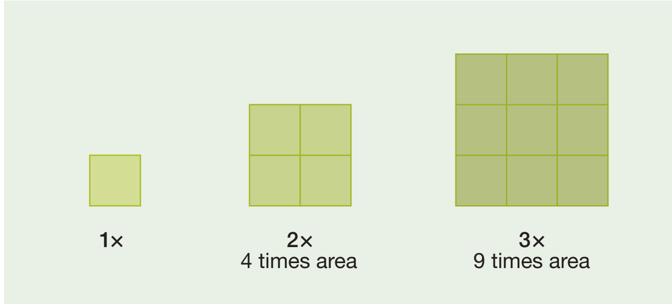
If you reduce the power down to 10×, you'd have a 10-mm exit pupil. A magnification of 5× would give you a 20-mm exit pupil. And 1× would give you a 100-mm exit pupil. In other words, at 1× the telescope wouldn't be doing anything at all. The outgoing beam of light would be the same diameter as the incoming beam.

That leads us to the next key concept: the *entrance pupil*.

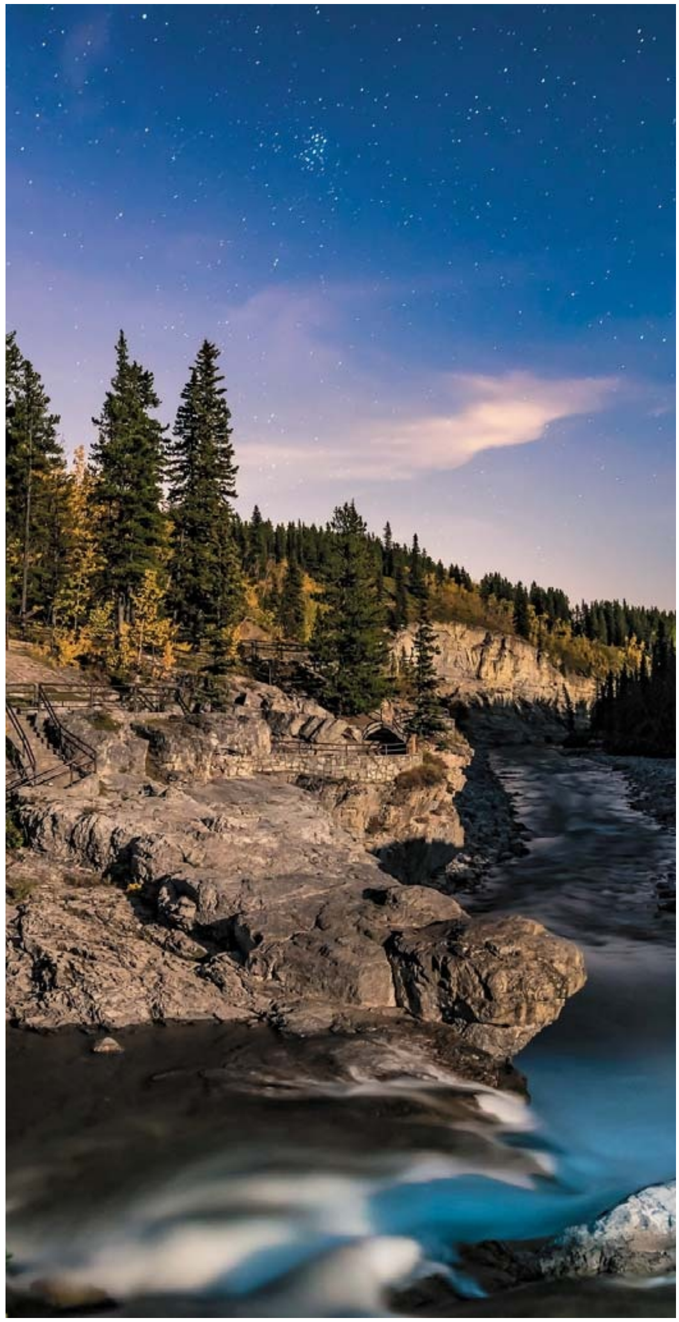
Your eye's iris will only dilate so far. For most of us, it'll open to about 6 mm when fully dark adapted. That means if you look into that 100-mm-wide beam of light coming out of a 1-power telescope, you're only going to see a 6-mm portion of that beam. Sure, the telescope is gathering a lot more light (278 times more light than an eye with a 6-mm pupil diameter), but most of that light is hitting your face. Only 6 mm worth of it is going into your eye — the same amount you'd get if you didn't look through the telescope at all.

Let's crank up the magnification just a little bit to 10×. That gives a 100-mm scope a 10-mm exit pupil (100/10 = 10). The light is definitely more concentrated now — 100 times more than when viewed by naked eye. (Compare the squares of the light beam diameters: 100^2 mm is 10,000 mm, and 10^2 mm is 100 mm. Divide 10,000 by 100 and you get 100 times the light intensity.)

That sounds pretty serious until you realize that the eye only sees 6 mm of that 10-mm beam. So it's seeing 6/10 of

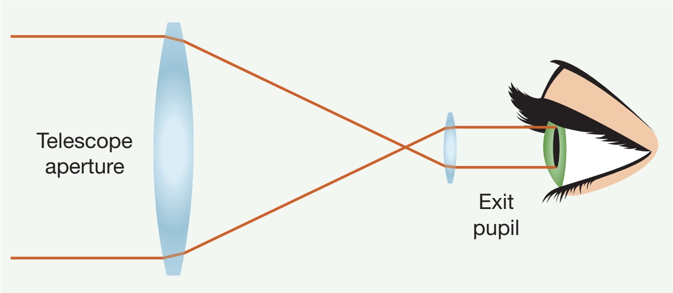


▲ **SPREADING OUT** Surface area increases with the square of magnification. The light is spread over a greater area, so the brightness per unit of area goes down by the same factor.



▶ **RISING STARS** Point sources like stars do appear brighter in the eyepiece, but it's magnification, not an increase in brightness, that makes the nebulosity more evident in a telescope.

VW PICS / ALAN DYER / GETTY IMAGES; DIAGRAM: LEAH TISCIONE / *S&T*



▲ **THE HARDER YOU SQUEEZE . . .** If the telescope squeezes the light down to 1⁄10 of its original diameter, the image will be magnified by 10×.

the beam's intensity, but we're dealing with area here, so we have to square that. Squaring 6/10 gets you 36/100, or 0.36. The eye is getting 0.36 times the 100-fold increase in light intensity, so it's only getting 36 times as much light as when you look at the same object with the naked eye.

Doesn't 36 times still sound pretty significant? That's almost 4 magnitudes. When you're looking at the Sun, couldn't that be dangerous?

Not at all. Remember surface brightness? The surface brightness goes down by the square of the magnification, so at 10× the surface brightness is 100 times dimmer. The telescope delivers 36 times as much light to your eye, but magnification spreads that light out 100 times, for a net loss of light of 36/100, or 0.36. Sound familiar? That's the proportion of the total light entering your eye, because the rest of that 10-mm-wide light beam is hitting the outside of your iris and being wasted.

The worst-case scenario would be when an entire 100-mm telescope aperture is squeezed down into a 6-mm exit pupil so all the light could enter your eye. 100^2 is 10,000, and 6^2 is 36, so you'd be getting 278 times as much light (10,000/36). But 100/6 = 16.7, so you'd need an eyepiece that delivered 16.7 power. That 16.7 power would decrease the surface brightness by 16.7^2, which is 278 times. It's a wash.

What about a teeny-tiny exit pupil? Say you squeezed all that aperture down to just 2 mm. The increase in total brightness would be 100^2 over 2^2, or 2,500 times more light (10,000/4). That sounds pretty serious! But the magnification at that exit pupil is 100/2, or 50×. The decrease in surface brightness at 50× is 50^2, or . . . wait for it . . . 2,500. Again, it's a wash.

You can never get a higher surface brightness of an extended object through the telescope than you get with your naked eye. Stars don't magnify because they're point sources, but everything else — including the Sun — has dimension, so it grows larger with magnification. And thus your eyes are safe when looking through a properly solar-filtered telescope, no matter how big the scope.

I can hear thousands of voices protesting, "But when I look at the Orion Nebula in a 20-inch scope, it's bright enough to read by! It's bright enough to trigger color vision! How can you tell me it's not any brighter than if I were to look at it by naked eye?"

Do the math. I guarantee you it's no brighter per unit of area. But the image in that 20-inch scope fills a much greater area than what you see with your naked eye. And if you're using a magnification high enough to squeeze that scope's entire aperture into your pupil (that would be 85× for a 20-inch scope and a 6-mm dilated eye), the view in your telescope is 7,225 times bigger (85^2) than the naked-eye nebula, yet every part of that huge image is just as bright as the original. Go have a look at the Sword of Orion without any optics. That middle "star" in the sword is the nebula. It's pretty bright, isn't it?

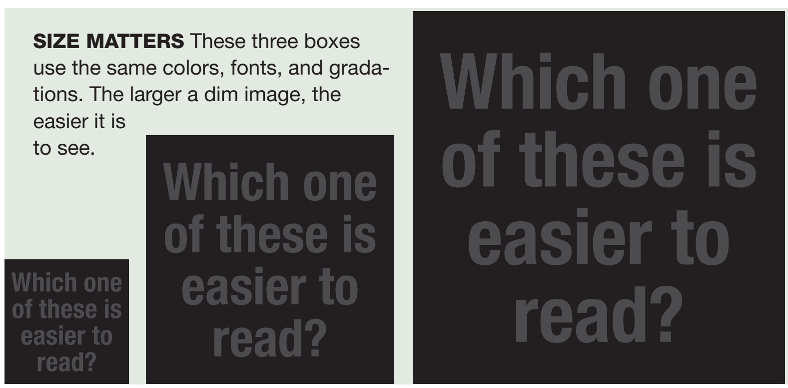
But . . . but . . . but . . . distant galaxies? My naked eye is only good to 6th or 7th magnitude at best. If the surface brightness doesn't go up in a telescope, how can I see the 13th-magnitude components of Stephan's Quintet?

That's a very good question. The answer is *magnification*.

Many people (myself included until recently) believe that magnification increases contrast. As we've just shown above, that can't be true. When you increase magnification, the background gets dimmer at exactly the same rate as the foreground object (by the square of the increase in size). So that's not why magnification helps.

The truth of the matter is, our eyes can see objects much dimmer than magnitude 6 or 7. We just can't see them if they're so small that only a handful of the several million rods and cones in our retinae receive the photons. Our retinae will only send a signal to our brains if several adjacent cells are stimulated at once, and the number of cells necessary to trigger a signal increases as the brightness goes down. To see something dim, we need to make it larger so it covers more retinal cells.

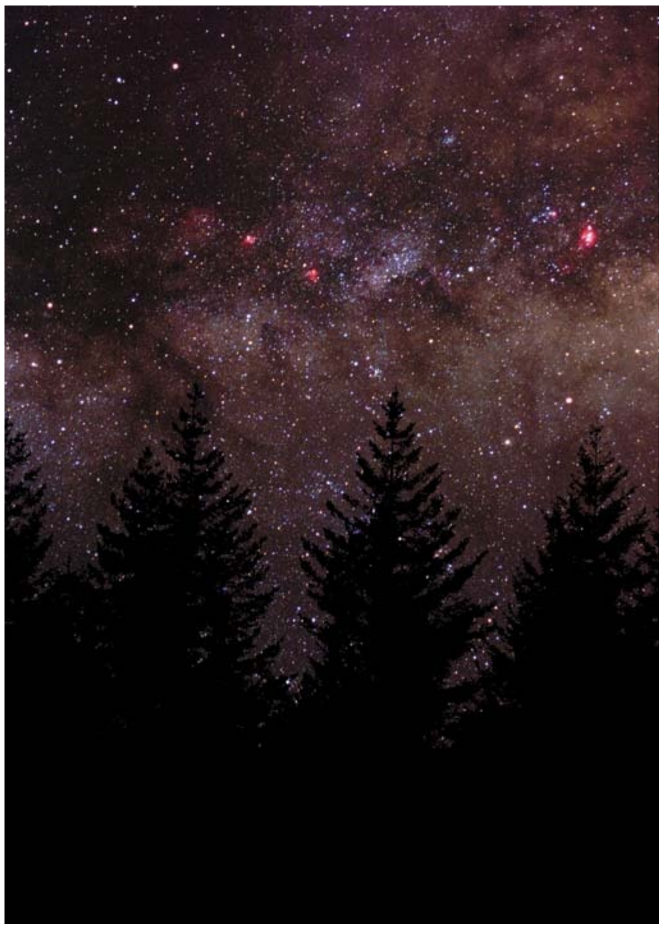
You can prove this on any clear night. Go outside and look up at the sky. If you live in town or the close suburbs, the average surface brightness of the sky will be somewhere in the range of 17–18th magnitude per square arcsecond. If you live out of town, it can get down to magnitude 21.5 or so. That's really dim, yet you can easily tell that the sky is brighter than a silhouette of a tree. More to the point: You can tell that a dark patch of sky, devoid of bright stars, is still brighter than a silhouette. The dark patch is probably as low as 22nd or



SIZE MATTERS These three boxes use the same colors, fonts, and gradations. The larger a dim image, the easier it is to see.

LEAH TISCIONE / S&T

▲ **SAME, SAME** You can never get a higher surface brightness of an extended object like the Great Orion Nebula with optical aid than you would get with your naked eye. An object's surface brightness decreases by the square of the magnification provided by your telescope and eyepiece.



▶ **DARKER THAN YOU THINK** You can see much dimmer objects than the 6th- or 7th-magnitude stars that we often consider our limit. A good dark sky is about 21 magnitudes per square arc-second, but you can easily tell it's brighter than the trees in front of it.

JERRY OLTION (3)

23rd magnitude per square arcsecond. So you can see very dim objects indeed; they just need to be big enough to trigger your retinal cells.

That's what a telescope does for you. It magnifies that tiny little galaxy until it covers a significant portion of your retina. And if you increase the aperture of the telescope, the galaxy will get brighter, right up to the point where the exit pupil matches the entrance pupil of your dilated eye. At that point you're seeing the galaxy as bright as it can get. More aperture will just spill the extra light out onto your iris — unless you reduce the exit pupil, but that raises the magnification and spreads the light out again.

That leads to one obvious last question: What's the ideal magnification for a given aperture?

That's a very good question. Get out there with your telescope and find out.

■ Thanks to aperture and magnification, Contributing Editor **JERRY OLTION** has viewed Hoag's Object, his favorite 16th-magnitude galaxy. Contact Jerry at j.oltion@gmail.com.

The Jewel in the Sword

An observer captures on a sketchpad the stunning details of one of the most wondrous objects in the night sky.

The essence of the winter sky is the Orion Nebula.

It's the most observed, photographed, and sketched object of the season simply because it's one of the most beautiful and rewarding deep-sky objects visible from the Northern Hemisphere. Look up on a dark, transparent night and there it is, glowing softly in the Sword of Orion.

Located around 1,400 light-years away, it consists of matter only about 2,000 times the mass of our Sun. It's the closest bright H II region — clouds, or nebulae, of ionized interstellar atomic hydrogen. Composed of a thin bubble of photoionized gas flowing from the much larger Orion Molecular Cloud, the Orion Nebula (M42) is roughly centered on **Theta¹ (θ¹) Orionis C**, a massive O7-type star, which, at magnitude 5.1, is the brightest member of the Trapezium multiple-star system. It's the nebula's primary source of photoionization and is mostly responsible for M42's brightness, having three to four times more photoionizing power than the next hottest star, **Theta² (θ²) Orionis A**.

The Trapezium stars have sculpted an H II canyon at the back surface of the bubble, and a much thinner layer of relatively transparent gas forms its front surface. This gas is blue-shifted, indicating that it's expanding in our direction.

The stellar nursery that produced the Trapezium stars is the Huygens region, the brightest, densest part of M42. These young stars are estimated to have a median age of only about 300,000 years. Research suggests that some of the youngest stars in this region may have ignited a mere 10,000 years ago.

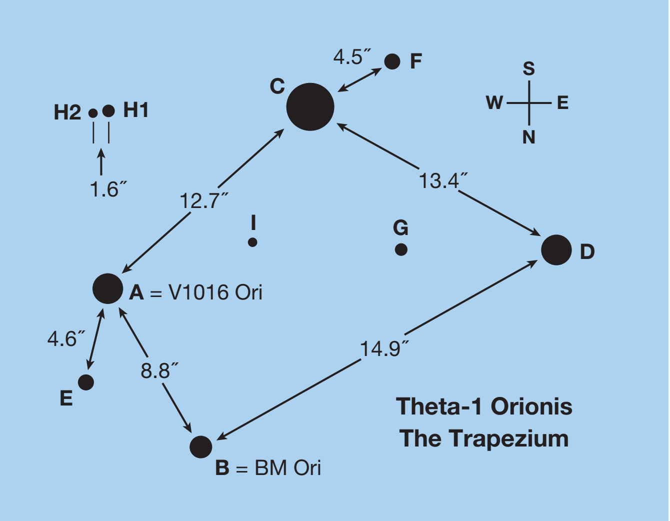
The Trapezium

Theta¹ (θ¹) Orionis — the Trapezium — is perhaps the most famous multiple-star system in the sky and is the most visible element in a still-forming star cluster. Discovered by Galileo in 1617, the Trapezium practically demands your attention. This tight knot of bright stars, all within 1.5 light-years of one another, is the unmistakable heart of M42. The compact trapezoid they form provides observers with an attractive and easy target, and the fainter companions offer challenges for scopes of all sizes and all manner of observing conditions.

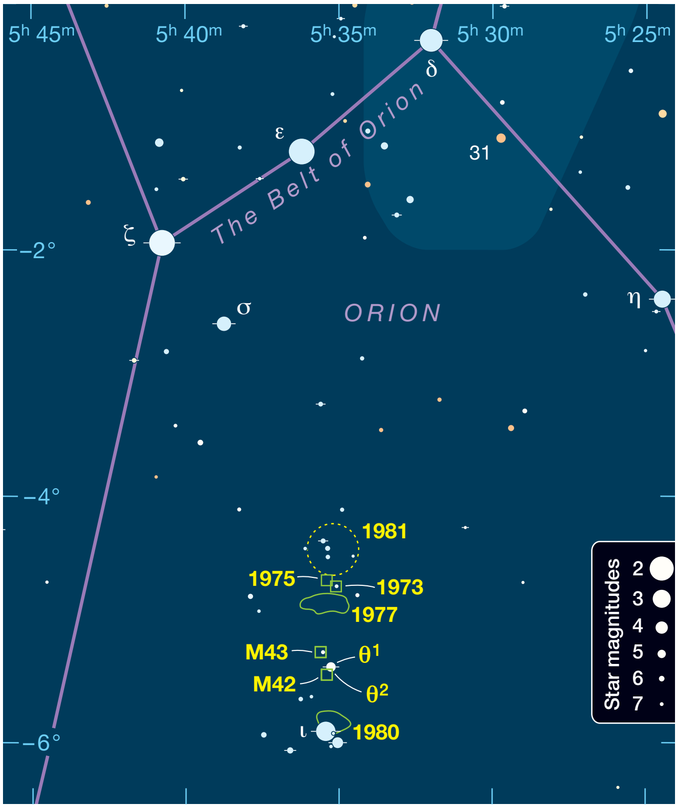
The four brightest stars are labeled **A** through **D**, with two fainter stars, **E** and **F**, hovering close by. I've observed these six stars many times throughout the years while trying to ignore the amazing nebula they illuminate.

When the seeing seemed steady enough, I've tried my luck with the much more difficult **G**, **H**, and **I** stars in and around the Trapezium, but have succeeded unambiguously only with

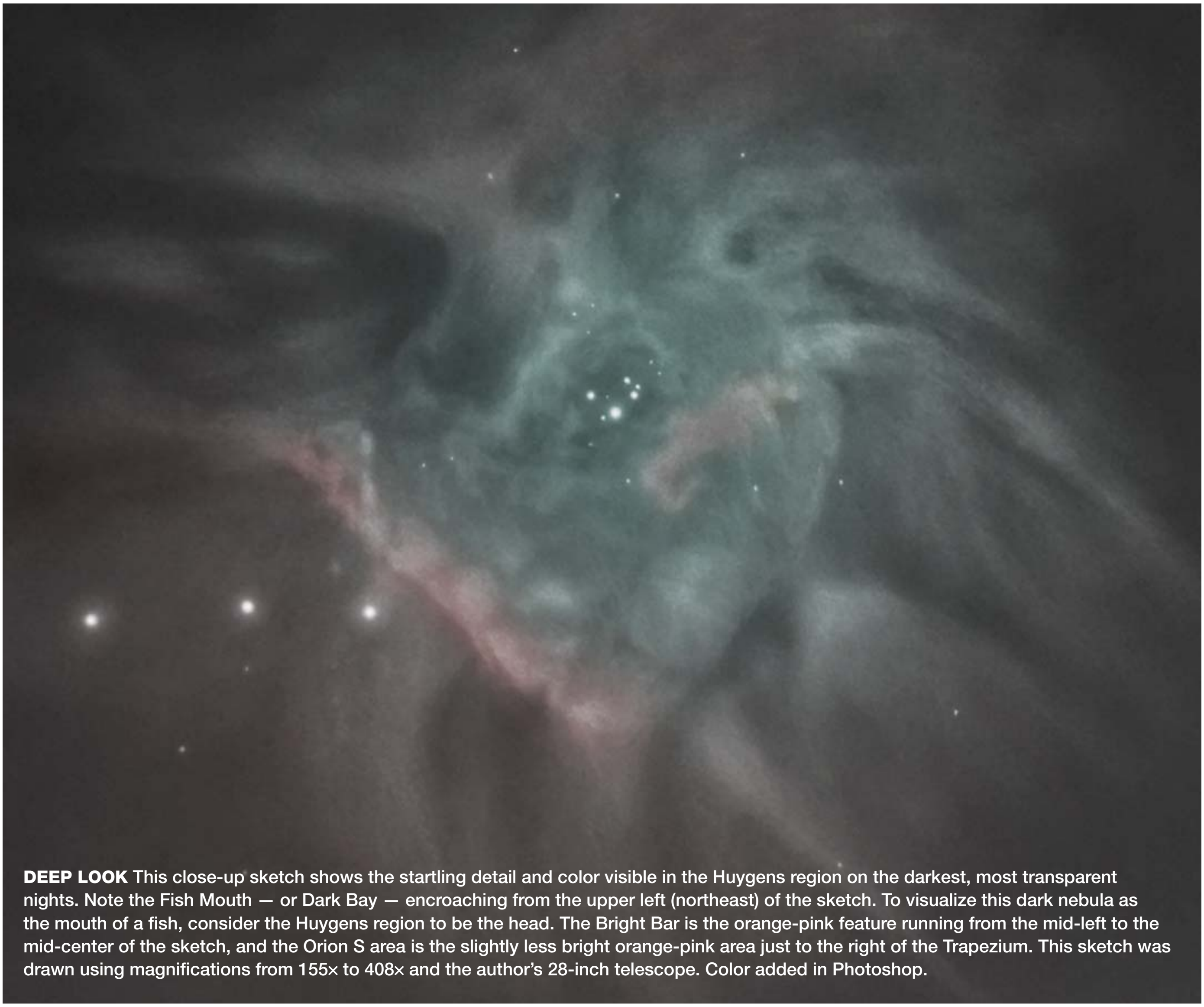
◀ **PLUSH PALETTE** This glorious Hubble Space Telescope image reveals the intense hues of the M42 and M43 nebulae.



THE TRAPEZIUM The brighter stars (A, B, C, and D) are easily observable with a 4-inch telescope, while two fainter stars (E and F) require more magnification and good seeing. The faintest stars (G, H, and I) are much more challenging.



FACING PAGE: NASA / ESA / M. ROBBERTO (STSCI / ESA) / HUBBLE SPACE TELESCOPE ORION TREASURY PROJECT TEAM; DIAGRAM: JERRY LODRIGUSS / BOB KING / LEAH TISCIONE / S&T



DEEP LOOK This close-up sketch shows the startling detail and color visible in the Huygens region on the darkest, most transparent nights. Note the Fish Mouth — or Dark Bay — encroaching from the upper left (northeast) of the sketch. To visualize this dark nebula as the mouth of a fish, consider the Huygens region to be the head. The Bright Bar is the orange-pink feature running from the mid-left to the mid-center of the sketch, and the Orion S area is the slightly less bright orange-pink area just to the right of the Trapezium. This sketch was drawn using magnifications from 155× to 408× and the author's 28-inch telescope. Color added in Photoshop.

HOWARD BANICH

the G star. The H and I stars have thus far eluded me for two reasons: I've never had the exceptionally steady seeing required while looking for them, and these faint stars exhibit precious little contrast against the Huygens region nebulosity.

Although its spectral class suggests it should look white, the 11.1-magnitude E star can appear red on a night of steady seeing, perhaps due to the dust between us and the star. You'll need a large scope to see the color well, but it can be quite striking. The A through D and F stars appear pure white.

In order to see these fainter stars, use a high enough power to eliminate as much of the surrounding nebula from the field of view as possible. In the end, however, rock-solid steady seeing is essential for success.

M42's Huygens Region

The Huygens region is essentially the bottom of the H II canyon formed by the combined stellar winds of the Trapezium stars. It has a distinct turquoise-green color. Sketching it was just as big a project as drawing the entire Orion Nebula. The challenge lay in the sheer density of details. Because everything is so tightly packed in this part of M42, it took two sketches and hours of sketching time to get the proportions correct. One of the more interesting things to look for in this area is the relatively dark void the Trapezium stars appear to float in while surrounded by bright nebulosity. This is a visual contrast effect caused by the brightness of the stars.

The ionization front known as the "Bright Bar" is the strikingly straight edge running from the northeast to the southwest border of the Huygens region. It's the most prominent edge of the H II canyon, seen edge-on. After the Trapezium stars, it's the most obvious feature of this area. Although straight overall, its border is subtly lumpy, with alternating bright and dark areas. Under specific circumstances (elaborated on below), a distinctly pinkish-orange hue can be seen along the outer edge of the Bright Bar. This color perception also holds true for **Orion South** (Orion S), a dense molecular cloud that's part of the Huygens region and lies behind the thin, relatively transparent front surface of the bubble. However, under normal observing conditions the only color I've detected in Orion S or the Bright Bar is the turquoise-green tint of the entire Huygens region.

There are several Herbig-Haro (HH) objects in the Huygens region. These are essentially newly born stars, or protostars, that exhibit jet-like features. I could make out **HH 202**, **HH 203**, **HH 204**, and **HH 524**, but I could only unambiguously identify the latter distinctly. HH 202 was an inconspicuous smudge northwest of Orion S, HH 203 appeared as a slightly brighter area of nebulosity protruding off the Bright Bar, and HH 204 was barely detectable as a faint spot. Contributing to the difficulty of observing HH 203 and HH 204 is the nearby magnitude-5.1 star Theta^2 Orionis A.

Along the northwest-to-southeast perimeter of the Huygens region are streamers of gas that appear to be flowing out of the H II canyon. The most prominent are on the northwest and west borders. Visually, they remind me of the jets produced by active comets as they approach the Sun. They're not only a fascinating detail in their own right in this rich region, but they also provide clues to the forces shaping M42.

The Fish Mouth, or Dark Bay, is the most prominent dark nebula of the Orion Nebula. Not perfectly opaque, it only partially obscures the Huygens region on the east. It has a range of subtle internal details along its length, and its borders range from sharply defined at its north edge to indistinct for much of the rest of its length.

M42's Bat Wings

Two other notable features of M42 are the Bat Wings, which extend northwest and southeast from the Huygens region. A section of the southeast feature is evocative of a bat wing, but overall the "wings" look more like flower petals to me. The inner edge of the southeast wing is clearly defined and has a unique rust-brown color. Along the wings, we're looking at the front surface of M42's bubble mostly edge-on, which means we're looking through more material in our line of sight. From the side, we'd probably see through the layers like we do the rest of the bubble's relatively transparent front surface.

The wings begin near the northeast terminus of the Huygens region. They're well-defined along much of their length, but they blend almost seamlessly with the Huygens region at their common base.

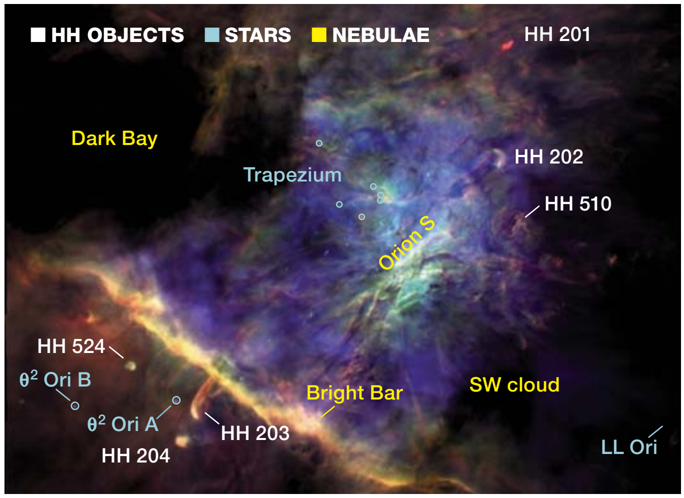
Towards the end of the southeast wing, just to the right of the bat wing feature, you'll see a much fainter appendage nearly perpendicular to the wing that looks somewhat like a tooth or a claw. Further south is a larger and fainter version. There's also a faint streamer that parallels the inner edge of the southeast wing, but it's not of the same dark rust-brown color. On a great night it has a rosy tint like much of the interior of the M42 bubble, which is best seen to the south of the Huygens region.

The northwest wing shares the dark rust-brown color of the southeast wing but isn't quite as prominent. Flowing south off the northwest tip of this wing is a series of turbulent, subtle bows and curls that delineate the inner bubble. They're difficult to see on most nights and won't be easily visible unless you have superb observing conditions.

These grayish tendrils form a delicate arch of rippling, entwined wisps and whirls that connect the tips of the northwest and southeast wings in this faintest feature of M42. Once you have seen this convoluted arch complete the full M42 bubble, you will get a sense for how large an object M42 really is, and you will get an idea of what 24 light-years looks like from 1,400 light-years away.

M43

Even though it's often overlooked, **M43** offers visual delights of its own. Through a telescope it appears to be a separate object from M42, but deep exposures show that it's clearly part of the same nebula complex.



▲ **MUSE OBSERVES HUYGENS** This Multi Unit Spectroscopic Explorer (MUSE) image of the Huygens region highlights the rich panoply of features in the Orion Nebula region.

ESO / PETER WEILBACHER ET AL.

Theta Orionis
The Trapezium Multiple Star System

Star	Mag(v)	Notes
A	6.7	Eclipsing binary in 3-star system
B	8.0	Eclipsing binary in 5-star system
C	5.1	Spectroscopic binary star
D	6.7	Double star
E	11.1	Spectroscopic binary star
F	10.1	Binary star
G	13.7	Single star

Data are taken from recent catalogs, with additions by Jerry Lodriguss.

M43 is primarily illuminated by **NU Orionis**, generally classified as a late *O*- or early *B*-type star. The area immediately surrounding the star is the brightest part of M43, which also has a comma-like shape but with two tails pointing in opposite directions. Closely examine where this area borders the north-south dark lane on its eastern side, and if the seeing is steady enough you may see a series of short, dark intrusions. I see this best at 253× and 408× in my scope. The longest of these little dark lanes shoots just north of NU Orionis, accentuating the comma-shaped area around the star.

A faint extension of M43 follows the east side of the main dark lane, flowing smoothly to the east, fading gradually. Look first for its brighter edges along the eastern border of the north-south dark lane, opposite M43. There are dark intrusions here as well, but they're less obvious than those of the west side of the main dark lane, thus making them more difficult to see. The southern part is bounded by the wide dark lane just north of M42's southeast Bat Wing that connects to the Fish Mouth. This dark lane is filled with several areas of soft, undulating nebulosity, which I saw best at 155× magnification. Look also for a faint extension off the comma's tail to the north, and note how smoothly it blends into invisibility.

Color

On a dark and transparent night far from city lights almost any scope will reveal the turquoise-green of the Huygens region. I see color throughout much of M42 using my 28-inch on a night like this, but sometimes the question, "How real is it?" comes up.

Some observers don't believe it's possible to see real color in any nebula since they're not bright enough to activate the color-sensing cones in the human eye. It's been suggested that the color photographs we're familiar with generate a strong, unconscious bias that leads us to see the same colors in the eyepiece. This is a valid point. Bias is a powerful force, especially combined with the somewhat uncertain nature of human vision at low light levels. The question remains, though, is this true for the Orion Nebula?

One school of thought suggests that the turquoise-green of the Huygens region — that some observers concede to be bright enough to see real color in — generates a contrast effect that makes the surrounding area appear to have a reddish tint. Color contrast is also a real effect, but this feels less convincing because red is the actual color of the area around the Huygens region. Even so, it's something to consider.

The special circumstance mentioned above is an observing technique I read about online that supposedly makes color temporarily more prominent. The idea is to quickly flash your observing eye with white light to momentarily push your vision back to its more normal daylight color-sensing mode.

I first tried it almost by accident on a wonderful night at Steens Mountain in October 2015. While observing M42, I decided to change the music on my iPhone. As I reached for my phone, I remembered the online tip and deliberately looked at the screen with my observing eye, then immediately went back to the eyepiece. I was shocked to see the Huygens region had sprouted two distinctly orange-pink areas that weren't there a few moments before! The rest of the Huygens nebulosity was its normal bright turquoise-green, and the orange-pink areas faded within about a minute or so as my eye became dark-adapted again. I've done this several times since then with the same result, so at least it works on this part of M42. This cool observation technique also helps convince me the orange-pink color is real, because I saw color along the outer edge of the Bright Bar ionization front and in the small patch just southwest of the Trapezium in the shrouded star-forming area, Orion S, exactly where color exists.

So if there's any H II region you can see color in — real or imagined — it's the Orion Nebula. Look for color especially in the Huygens region, and don't forget to look directly at the nebula so the color-sensing cones of your eye can best detect it.

▲ **MORE COLORS** The M43 nebula, which is illuminated by a single star, NU Orionis, also boasts vibrant and vivid colors.

NASA / ESA / M. ROBBERTO (STSCI / ESA) / HUBBLE SPACE TELESCOPE ORION TREASURY PROJECT TEAM

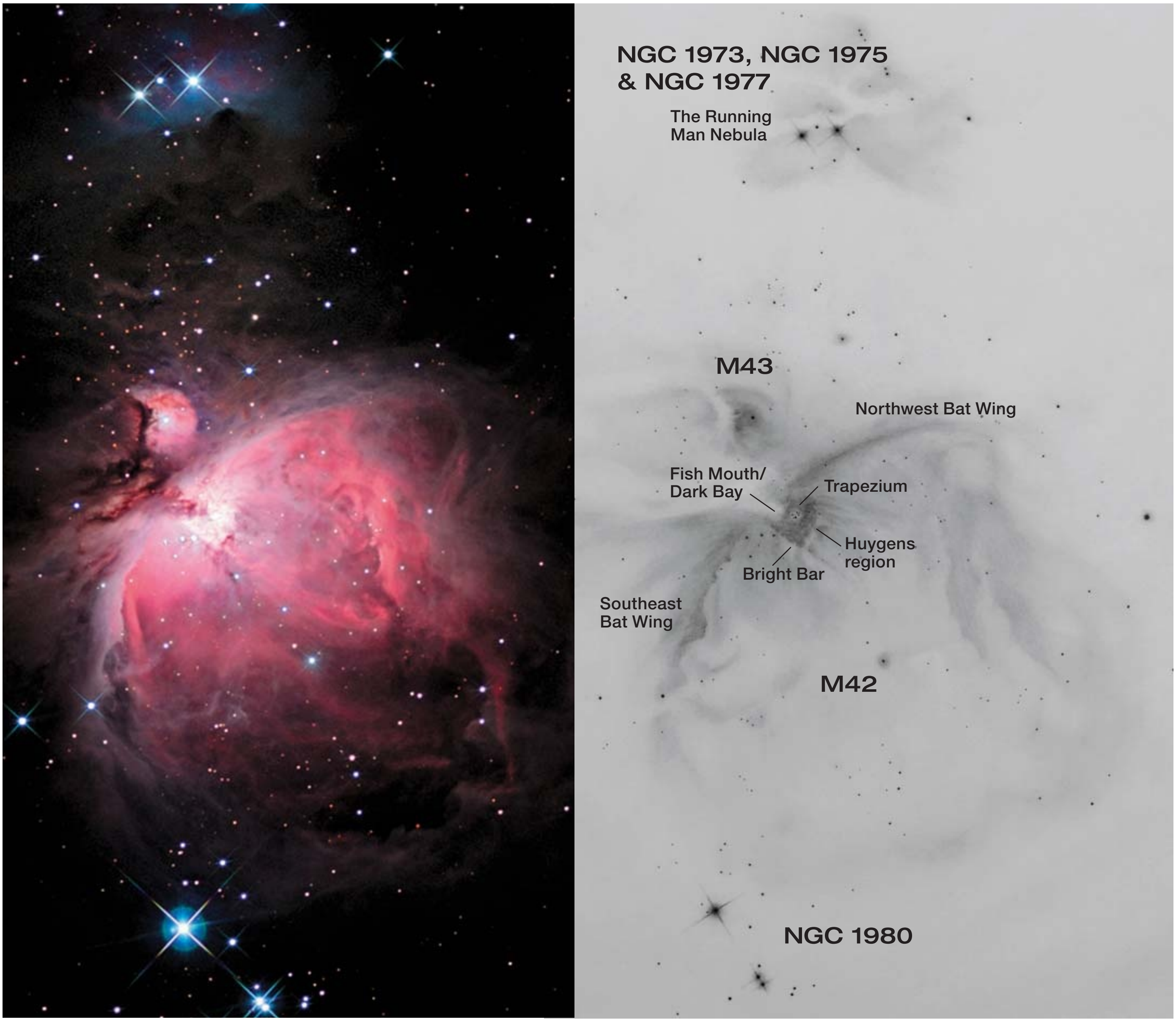
The Nebulae Next Door

The reflection nebula complexes of **NGC 1973**, **NGC 1975**, and **NGC 1977** are immediately to the north of M42 and M43 and are known collectively as the Running Man Nebula. On a good night they remind me of a time exposure of water flowing in a small stream because of their exceedingly smooth texture. They're certainly a delicate pleasure compared to the glories of M42 and M43 — if the sky isn't clear and clean, or if you observe in significant light pollution, you may not see them at all.

The Running Man shape comes from the dark nebula that divides the reflection nebulae. The figure is tricky to see visually, but the legs and arms are to the south and extend east-west, while the head is to the north. Tracing the ambigu-

SKETCH IN COLOR The author observed the Orion Nebula meticulously using a 28-inch telescope and sketched what he saw through the eyepiece over many nights at magnifications from 132× to 408×. The sketches were combined here in a finished drawing that has been inverted from its original pencil sketch and colorized in Photoshop. The colors here are only slightly more saturated than in the eyepiece.

HOWARD BANICH



▲ **THE NEBULA AND CLUSTERS** The entire region of the Orion Nebula is shown here, including the open cluster NGC 1980 just below the outer loop of M42. NGC 1981, not fully visible in the image, is above the Running Man Nebula. **Right:** The labeled version of the original pencil sketch shows the main features discussed in the text. Approximately 20 hours of eyepiece sketching time went into this and the companion close-up of the Huygens region (page 34). The magnifications ranged from 132× to 408×, and no nebular filters were used, therefore this sketch represents the natural view through the author's 28-inch telescope.

PHOTO: NOAO / AURA / NSF / A. BLOCK / R. STEINBERG; SKETCH: HOWARD BANICH

ous outlines of both the reflection and dark nebulae is an uncertain business even on the darkest and most transparent nights, so take your time.

The extended and bright open cluster **NGC 1981** lies to the north of the Running Man nebula, and the even brighter but sparse **NGC 1980** is just south of M42. Bracketing the Orion Nebula, they've already dissipated their birth nebulosity; they complete the arc of stellar birth phenomena we see in this extraordinary region.

A telescope that can produce a 2° field of view will show all of the Orion Nebula and these two clusters in relation to each other and the space around them. Perhaps you'll get a sense of how they fit in the same nebula complex, and are merely a few of the latest bright splashes produced by their much larger and darker parent, the Orion Molecular Cloud.

■ Contributing Editor **HOWARD BANICH** can't get enough of the Orion Nebula. He can be reached at **hbanich@gmail.com**.

FURTHER READING: Read more about the author's study of M42 at **https://is.gd/HBM42.** And please do yourself the favor of watching a 3D fly-through of the nebula at **https://is.gd/m42flythrough**. Your perception of its 3D shape will be profoundly changed.

Other Worlds

THE PLANET FACTORY: *Exoplanets and the Search for a Second Earth*

Elizabeth Tasker
Bloomsbury Sigma, November 2017
288 pages, ISBN 9781472917720
$27.00, hardcover.

I'LL OPEN WITH a confession: I've never been particularly interested in extrasolar planets. Or perhaps it would be more accurate to say that whatever interest I've taken in them is usually cancelled out by the (over)use of the words "habitable," "Earth-like," and "super-Earth" in discovery announcements. My interest in astronomy grew not from a desire to learn about places that are just like home, but about those that are like nothing I've yet experienced. So I initially gave *The Planet Factory: Exoplanets and the Search for a Second Earth* by astrophysicist Elizabeth Tasker (Japanese Aerospace Exploration Agency) a hard pass. A second Earth? No, thanks, I've got one already.

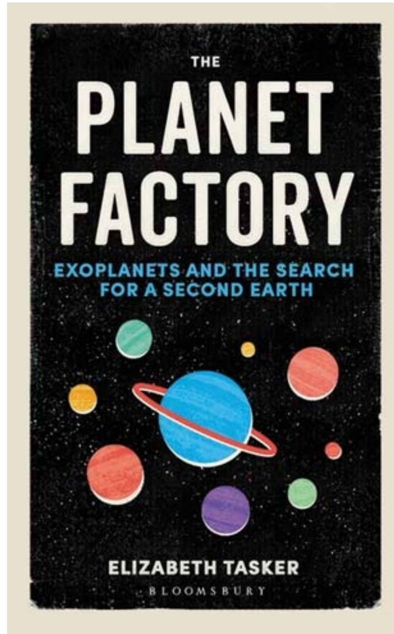
Luckily, I soon came back to see how accurately the subtitle represented the book. That was a good decision, because the story Tasker tells about exoplanets includes a much wider range of exoplanets than the cover suggests. The hunt for exoplanets may indeed be driven by a desire to find another Earth, but along the way, we've found so much more: At the time of this writing, more than 3,500 exoplanets have been confirmed, and most of them seem not only un-Earth-like, but downright weird.

> ... more than 3,500 exoplanets have been confirmed, and most of them seem not only un-Earth-like, but downright weird.

The Planet Factory is divided into three parts, plus an introduction describing exoplanet detection methods. An examination of our solar system's history comprises the first third of the book. Most of us have some basic idea of how planets form through the accretion of dust and gas affected by gravity; possibly less familiar are theories of planetary migration with elegant names like "the Nice Model" and "the Grand Tack Hypothesis" that explain how planets have moved from their original orbits (we're looking at you, Neptune and Uranus!). Reading this section carefully pays off, as many of the theories of planetary formation discussed in it reappear in later chapters.

This analysis of our solar system sets the stage for a discussion of the many types of exoplanets astronomers have discovered so far. Sure, we have super-Earths, like Gliese 876 d, a planet with a mass of about 7.5 Earth masses. But we've also got "hot Jupiters" (gas giants like 51 Pegasi b that are so close to their stars that they complete an orbit in just a few days); chthonian planets (gas giants like HD 209438b, whose atmosphere is being stripped down to expose the planet's presumably rocky core); lava-ocean worlds (like CoRoT-7b, a rocky planet so hot it's probably covered in molten lava); and diamond globes (like 55 Cancri e, an exceedingly carbon-rich lava world). We have exoplanet systems with one sun, two suns, and three suns. And we even have exoplanets with no suns. It turns out that super-Earths are a small part of an incredibly strange story.

The last third of the book indeed focuses on the hunt for the nearest Earth-like exoplanet (or moon) traveling in the so-called "habitable zone," a region around a star that receives the same amount of radiation as Earth does from the Sun. (Tasker cautions us to not consider "habitability" a firm metric; surface conditions vary widely within the zone.) Finding a candidate planet is difficult enough; once it's found, astronomers still need to interpret any markers that suggest life is possible. Spoiler alert: Oxygen isn't a great biosignature, nor is methane.



Tasker maintains a conversational, humorous tone throughout the book, making it easier to follow some very complex ideas. *The Planet Factory* is thick on data and a little thin on diagrams and other illustrative material, so I recommend downloading an exoplanet app for your preferred mobile device (I use Hanno Rein's *Exoplanet* for iPhone) to keep track of the wild things. If you've always been intrigued by extrasolar planets — or even if you haven't! — you'll want to move this book to the top of your reading list.

■ Associate Editor **S. N. JOHNSON-ROEHR** prefers her extrasolar planets to be cold, dark, and distant.

OBSERVING
December 2017

3 **MORNING:** The last full Moon of the year floats about 2° to the lower right of Aldebaran. The Moon, which is at perigee, will occult the star near dawn for Alaska and Asia. Watch out for large tides in the days that follow.

8–9 **NIGHT:** A waning gibbous Moon trails Regulus in Leo by about 5° low in the east for viewers in North America. An occultation of the star will be visible in eastern Europe and northwestern Asia.

13 **DAWN:** The thin sliver of the waning crescent Moon hovers some 4° to 5° above orange Mars low in the east-southeast.

14 **DAWN:** An even slimmer crescent slides down to about 9° below Mars and 4° above Jupiter.

13–14 **ALL NIGHT:** The Geminids, one of the most prolific meteor showers of the year, are visible from December 4–16, but peak on the night of December 13–14 (see p. 48). With the Moon a waning crescent, the shower should be quite the spectacle, provided it's a clear night.

17–18 **NIGHT:** Algol shines at minimum brightness for roughly two hours centered at 11:22 p.m. PST (2:22 a.m. EST) — see page 49.

20 **DAWN:** Look toward the southeast and you will see Jupiter rising, hand-in-hand with Alpha (α) Librae less than 1° away.

20 **EVENING:** Algol shines at minimum brightness for roughly two hours centered at 11:11 p.m. EST (8:11 p.m. PST).

21 **THE LONGEST NIGHT OF THE YEAR** in the Northern Hemisphere. Winter begins at the solstice, at 11:28 a.m. EST (8:28 a.m. PST; 16:28 UT).

30 **EVENING:** Look toward the east shortly after sunset to witness a waxing gibbous Moon whispering a mere ½° away from Aldebaran; the Moon's occultation of the star will be visible from most of North America and Europe (except the south).

▲ This image of the Orion Nebula shows Hubble optical (pink and purple, representing clouds and dust) and Chandra X-ray (blue and orange dots, which are newly formed stars) data (see page 32).

X-RAY: NASA / CXC / PENN STATE / E. FEIGELSON & K. GETMAN; OPTICAL: NASA / ESA / STSCI / M. ROBBERTO

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						

FULL MOON
December 3
15:47 UT

LAST QUARTER
December 10
7:51 UT

NEW MOON
December 18
6:30 UT

FIRST QUARTER
December 26
9:20 UT

DISTANCES

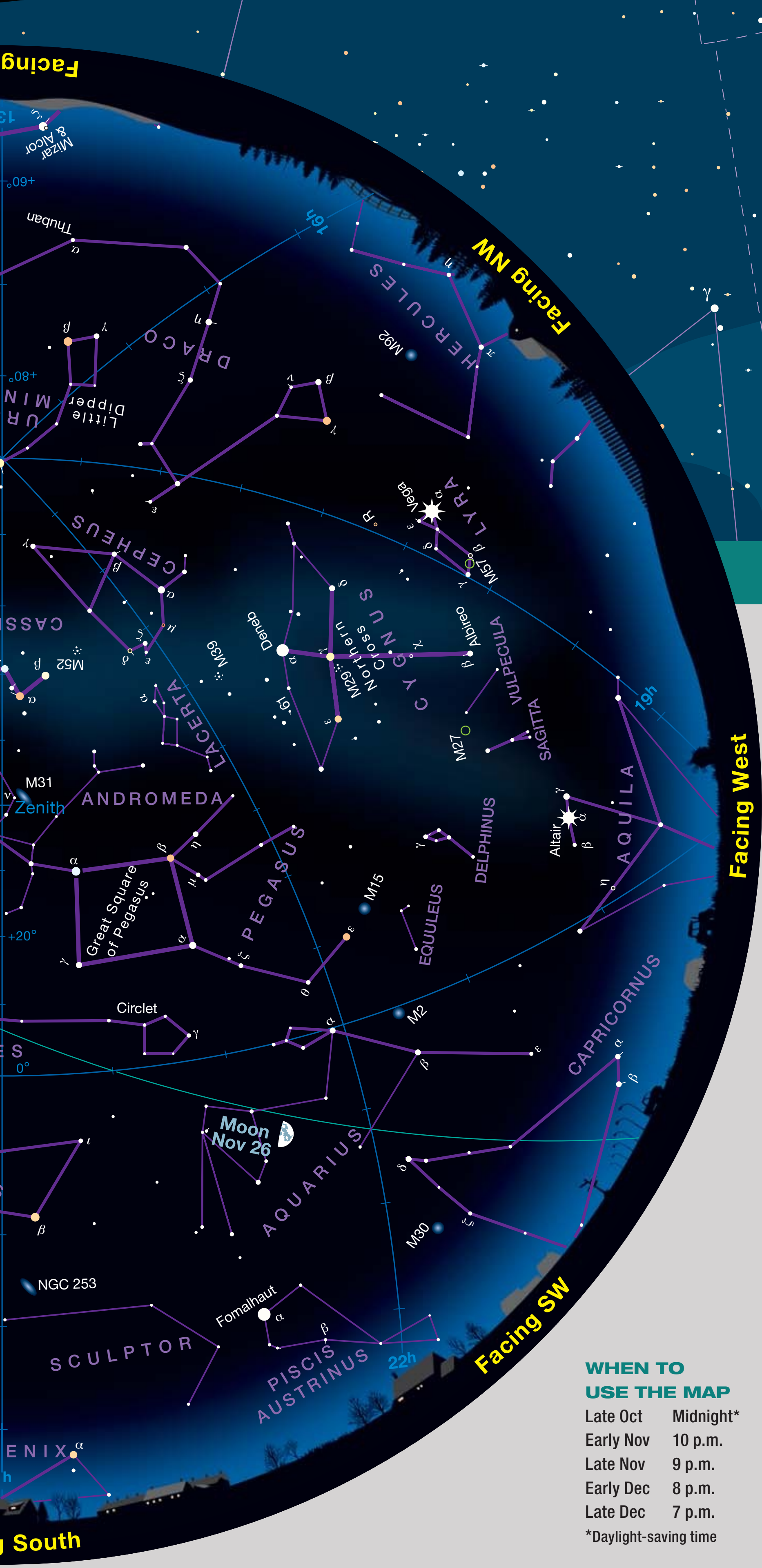
Perigee	December 4, 09^h UT
357,492 km	Diameter 33′ 26″
Apogee	December 19, 01^h UT
406,603 km	Diameter 29′ 23″

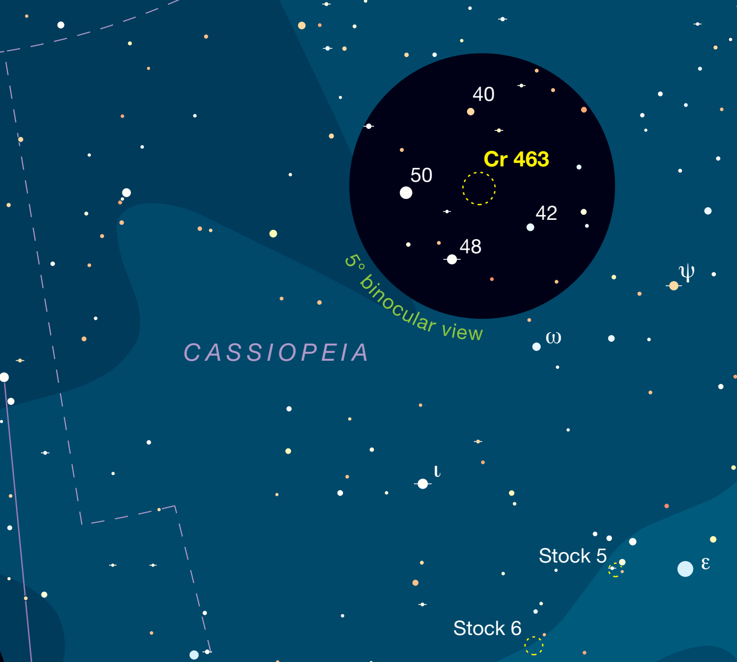
FAVORABLE LIBRATIONS

- Pythagoras Crater — December 3
- Sylvester Crater — December 4
- Petermann Crater — December 5

Planet location shown for mid-month

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





WHEN TO USE THE MAP

Late Oct	Midnight*
Early Nov	10 p.m.
Late Nov	9 p.m.
Early Dec	8 p.m.
Late Dec	7 p.m.

*Daylight-saving time

Binocular Highlight by Mathew Wedel

Big Sky Country

When I first got into amateur astronomy in the fall of 2007, Cassiopeia was my first constellation. In the era before smartphones and astronomy apps, I learned the sky the old-fashioned way, with a paper planisphere and a red flashlight. When I eventually got a telescope, Cassiopeia was usually my first stop, not only for its own celestial riches, but also as a signpost to so many others. I've started or ended countless observing sessions in Cassiopeia.

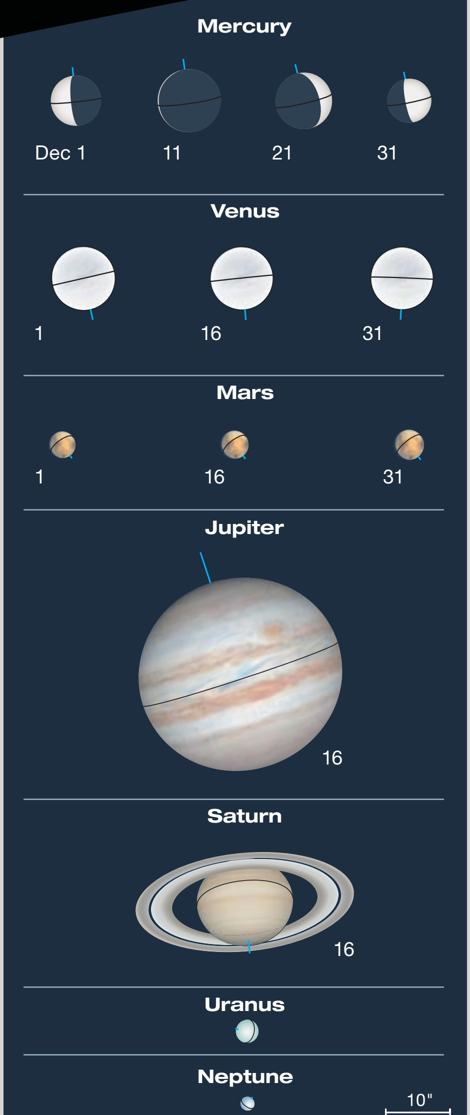
So if you'd told me a few weeks ago that there was a 5th-magnitude open cluster almost 1° across in Cassiopeia that I had never seen, I would have laughed out loud. And then I would have had to apologize, because I only recently discovered **Collinder 463**.

The astrophysical facts about Collinder 463: It's what professional astronomers call a "poor" open cluster, with 80 or so members scattered over 30-odd light-years. The cluster lies about 2,300 light-years from the Sun, on the edge of the galaxy's Orion Spur. To find it, scan 8° due north of Epsilon (ε) Cassiopeiae — or open the *Pocket Sky Atlas*, where it's just below center on the very first chart. The cluster is surrounded by a nice quadrilateral of 4th- and 5th-magnitude stars. It's big and obvious, and even 7× binos will resolve some of the brighter members, while a dense swarm of fainter suns blend into the background glow.

My first thought on observing Collinder 463 was, "How did Messier and Herschel miss this thing?" My second, more honest thought was, "How did I miss it myself, for a whole decade?"

The answer is simply this: It's a big sky. We're not going to run out of things to look at any time soon. What a wonderful truth to discover.

■ MATT WEDEL was a little unnerved about what else he might be missing out on, so he's gone to have a look.



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 dawn after the 20th, low in the southeast. **Venus:** Visible at dawn until the 12th, low in the southeast. • **Mars:** Visible before dawn all month in the southeast. • **Jupiter:** Visible low in southeast before dawn all month. • **Saturn:** Not visible this month.

December Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	$16^h\ 28.1^m$	–21° 45′	—	–26.8	32′ 26″	—	0.986
	31	$18^h\ 40.2^m$	–23° 07′	—	–26.8	32′ 32″	—	0.983
Mercury	1	$17^h\ 54.0^m$	–25° 10′	20° Ev	–0.1	7.8″	40%	0.859
	11	$17^h\ 33.2^m$	–22° 14′	5° Ev	+4.4	9.8″	2%	0.685
	21	$16^h\ 48.4^m$	–19° 25′	16° Mo	+0.8	8.8″	23%	0.764
	31	$17^h\ 03.5^m$	–20° 39′	23° Mo	–0.3	6.9″	59%	0.978
Venus	1	$15^h\ 48.9^m$	–19° 16′	9° Mo	–3.9	9.9″	99%	1.678
	11	$16^h\ 41.6^m$	–21° 51′	7° Mo	–3.9	9.9″	99%	1.692
	21	$17^h\ 35.8^m$	–23° 22′	5° Mo	–3.9	9.8″	100%	1.703
	31	$18^h\ 30.7^m$	–23° 41′	2° Mo	–4.0	9.8″	100%	1.709
Mars	1	$13^h\ 32.3^m$	–8° 31′	44° Mo	+1.7	4.2″	95%	2.208
	16	$14^h\ 08.0^m$	–11° 53′	50° Mo	+1.6	4.5″	94%	2.091
	31	$14^h\ 44.5^m$	–14° 58′	56° Mo	+1.5	4.8″	93%	1.964
Jupiter	1	$14^h\ 34.9^m$	–14° 06′	28° Mo	–1.7	31.4″	100%	6.288
	31	$14^h\ 57.5^m$	–15° 46′	53° Mo	–1.8	33.0″	99%	5.971
Saturn	1	$17^h\ 49.3^m$	–22° 29′	19° Ev	+0.5	15.1″	100%	10.993
	31	$18^h\ 04.5^m$	–22° 32′	8° Mo	+0.5	15.1″	100%	11.037
Uranus	16	$1^h\ 31.4^m$	+8° 56′	120° Ev	+5.7	3.6″	100%	19.387
Neptune	16	$22^h\ 52.7^m$	–8° 09′	77° Ev	+7.9	2.3″	100%	30.144

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-December; 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.

A Cornucopia of Celestial Curiosities

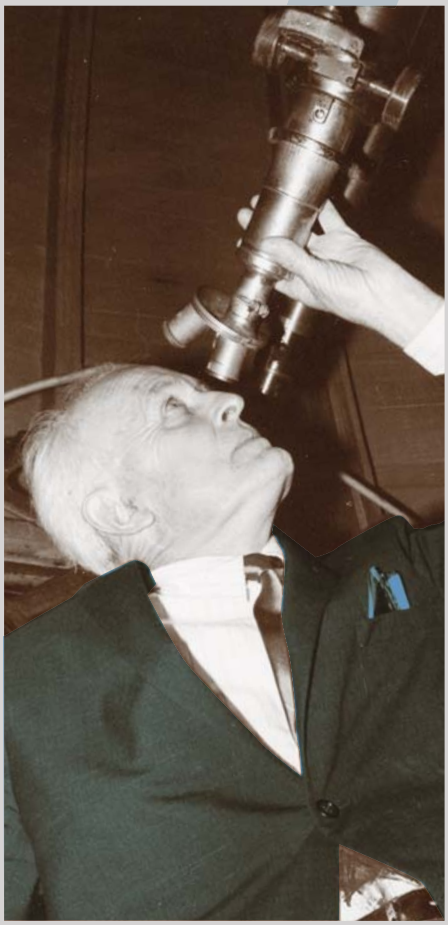
The year's end prompts reminiscences of stellar things past.

This column for the final issue of *Sky & Telescope* for 2017 is a potpourri of astronomy. In this — the year of an awesome total eclipse of the Sun — we take one last excursion into the realm of totality and into the wonders of a starry sky. We also look at three of the 20th-century's greatest amateur astronomers — variable star lovers all.

Akin to 20 miles high. I once described to my friend Steve Albers the scene in the movie *The Right Stuff* in which pilot Chuck Yeager is at almost 20 miles altitude when his jet's engine gives out. Yeager gazes longingly at a few stars shining in broad daylight before he begins his epic fall. Could he really have witnessed such a view? After a few quick calculations, Albers said that the limiting magnitude at that altitude in daylight should be about 4th magnitude. Interestingly, that's the claimed magnitude for the faintest stars seen with the naked eye during a total eclipse — provided sunglasses or an eyepatch were worn before totality in order to dark-adapt.

Fear not the stars. Back in the 1970s, at the home where I still live in New Jersey, we had pristine dark skies and no streetlights near the house. So it was with great anticipation back then that we took my very young niece, who was quite shy and not very talkative, out to look at the stars on a perfect night. We had been outside a short while when suddenly the girl insisted on going back indoors. Why? Back inside she said, "I'm afraid of the stars." But just a few seconds later she said, "I want to see the stars." And we took her back out, for it wasn't really fear she had been experiencing. It was awe.

Three greats for variable stars. Last month I profiled three classic variable stars prominently visible in fall (Delta Cephei, Mira, and Algol) and mentioned that three of the 20th-century's greatest amateur astronomers were avidly enthusiastic variable star observers. Let's take a brief look at the three: William Tyler Olcott, Leslie Peltier, and Walter Scott Houston.



▲ Leslie Peltier, discoverer of many comets and avid observer of variable stars, at his observatory in July 1968

AAVSO

Olcott helped found the American Association of Variable Star Observers, the world's premier organization dedicated to the study of variable stars, back in 1911. But he was better known for writing the most important observer's handbook of the first half of the 20th century, *Field Book of the Skies* (G.P. Putnam's Sons, 1929). I have always cherished my copy of this book, and I was fortunate enough to write the forward to Dover Publications' 21st-century reprint of Olcott's *Star Lore: Myths, Legends, and Facts* (2012).

Leslie Peltier was called the "world's greatest non-professional astronomer" by one of the world's greatest professional astronomers, Harlow Shapley. Peltier is famed for his many comet discoveries and his lovely autobiography *Starlight Nights* (1965). I stumbled upon my copy of the book while browsing through a delightfully cluttered old bookstore in Allentown, Pennsylvania, in the 1970s. But Peltier is also remembered for his exceptional lifetime tally of variable star observations — and his wistful regret at having just missed discovering the 1946 outburst of T Coronae Borealis, the "Blaze Star."

Walter Scott Houston was the father of deep-sky observing and author of the "Deep-Sky Wonders" column in this magazine spanning six decades. A book of the same name collects some of the best writing of these columns. Scotty surely loved the clusters, nebulae, and galaxies of deep-sky observing, but he was also a dedicated variable star observer. One year he even missed Stellafane, the star party to which he was so very devoted, in order to attend a meeting of variable star observers elsewhere.

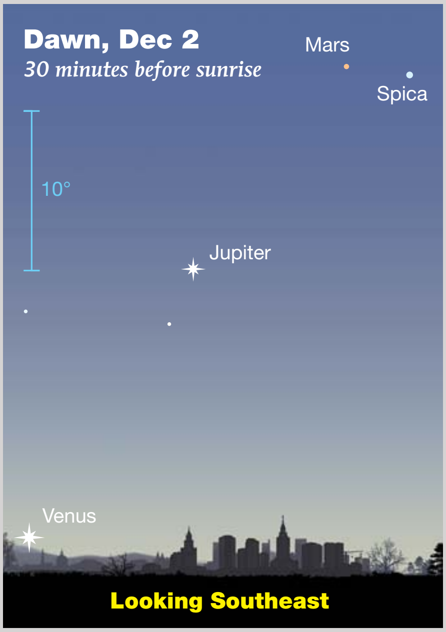
Hot and cold. You can never tell what kind of weather December will bring you. One year I watched December's great meteor shower, the Geminids, in air hovering near 0°F. The following year, I witnessed them in clear skies with the midnight temperature near 60°F.

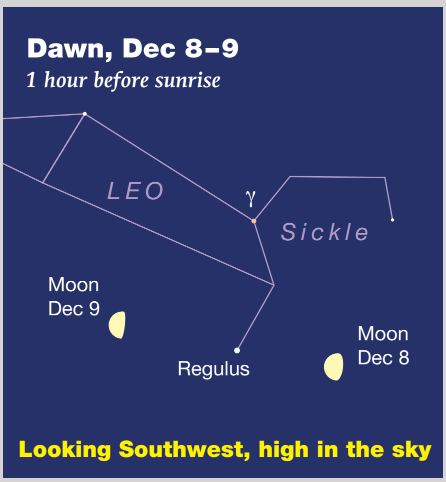
■ FRED SCHAAF is the sole author of a dozen books and co-author of one other.

December Delights

The Moon occults Aldebaran, and Mars and Jupiter dance with a star.

After Mercury and Saturn drop into the Sun's afterglow at the beginning of December, the night is devoid of bright planets. Mars appears in the pre-dawn hours all month, followed ever sooner by the rising of Jupiter. The two planets approach each other by year's end as they both pass near Alpha (α) Librae (Zubenelgenubi) in the east at dawn. Venus spends a rare month languishing too close to the Sun to observe. But Mercury pops back up in the dawn sky in the second half of December, climbing up well to the left of fainter Antares.





DUSK

Saturn is lost from evening view by the 2nd day of the month, even to observers with appropriate equipment.

After Saturn disappears, no bright planet is above the horizon for more than 9 hours. Orion the Hunter rises in evening twilight, Sirius a couple of hours later, and both constellation and brightest star march well past the meridian before Mars breaks the drought of bright planets. Ringed Saturn is in conjunction with the Sun on December 21st.

EVENING

Uranus and **Neptune** shine at only 6th and 8th magnitude, respectively, but at least provide planetary targets for a while in the evening. Neptune transits the meridian in Aquarius during evening twilight; Uranus does so about 2½ hours later in Pisces. Neptune sets before midnight, Uranus just before Mars rises. For their locations, refer to the finder charts in the October issue on pages 50–51.

PRE-DAWN

Mars rises at nearly the same time — the cold, lonely pre-dawn hours — all month, but **Jupiter** scurries to catch up with Mars as December progresses. In early December, bright Jupiter makes its appearance nearly two hours after its fellow planet, but as the month — and, in fact, the year — draw to a close, it peeks above the horizon just a few minutes after the very much dimmer Mars. Early in December, Mars gleams about 3° left or upper left of 1st-magnitude Spica.

Throughout the month, Jupiter brightens from magnitude –1.7 to –1.8, and its apparent diameter increases from 31″ to 33″. More notable is the brightening of Mars from magnitude 1.7 to 1.5, which signals the start of what will become a rapid kindling that, by next July, will have Mars shining the brightest in our skies and biggest in our telescopes it has in 15 years. For now, this December, we'll have to be content with Mars's apparent diameter merely increasing from 4.2″ to 4.8″. Even when

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

Mars has climbed to about 30° in the hour before sunrise, it looks like nothing more than a blurry orange speck in most telescopes.

The celestial background Mars and Jupiter traverse is especially interesting this month. Jupiter creeps eastward in Libra, past the wide double star Alpha Librae. Less than 1° separates the planet and star between December 18–26 for viewers at mid-northern latitudes.

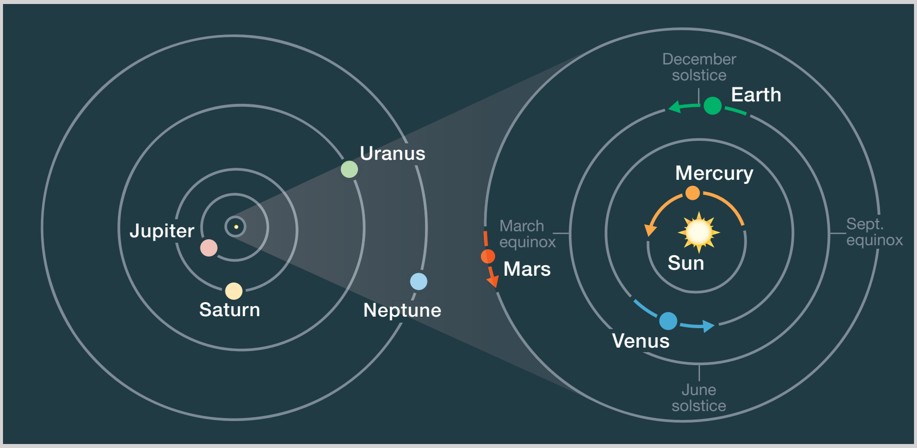
Mars crosses the boundary into Libra on December 21st. On the morning of December 31st, Mars and Jupiter hover about 1½° to either side of Alpha Librae. Keep an eye on these two planets as the New Year opens, for they will undergo an unusually close conjunction for them on January 7, 2018.

DAWN

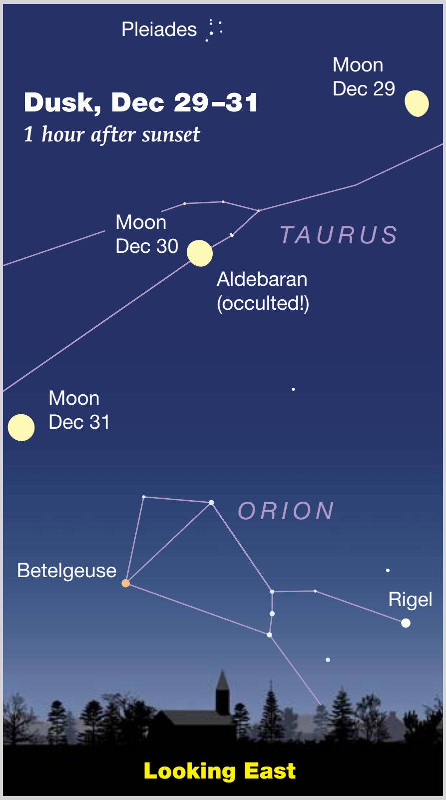
Venus rises only about 45 minutes before the Sun as December begins, but even this brightest of planets is lost from view around the 12th of the month, on its way to superior conjunction with the Sun on January 9, 2018.

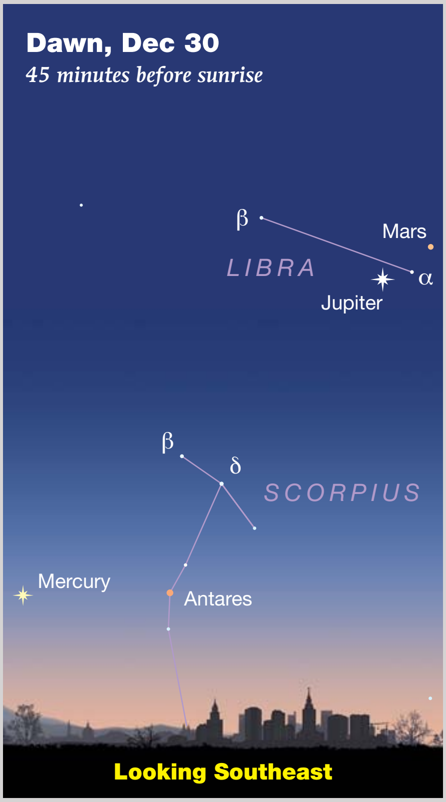
Mercury drops from evening view by the first day of December. The tiny planet goes through inferior conjunction on December 13th and reappears in the morning sky around December 20th. After that, it brightens rapidly and climbs to make one of its best appearances of the year for observers at mid-northern latitudes.

By December 23rd, Mercury rises at the start of astronomical twilight and is about 8° left of noticeably fainter Antares; bring binoculars. Around latitude 40° north, Mercury appears highest on December 29th, when it shines at magnitude –0.3. Mercury is on its way to a greatest elongation of 23° west of the Sun on January 1, 2018.



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





SUN AND MOON

The **Sun** arrives at the December solstice at 11:28 a.m. EST on December 21st, signaling the start of winter in the Northern Hemisphere and summer in the Southern Hemisphere.

The full **Moon** is near Aldebaran on the morning of December 3rd. Viewers in the far Pacific Northwest and Alaska will see the Moon occult Aldebaran that morning; see page 49.

The waning gibbous moon proudly poses on either side of Regulus before dawn on December 8th and 9th. The waning lunar crescent glows around 4° above Mars in the east-southeast on December 13th and approximately the same distance upper left of Jupiter on December 14th.

The waxing gibbous Moon occults Aldebaran late on the evening of December 30th for most of North America; see page 49.

■ FRED SCHAAF has now completed 25 years of writing the Sun, Moon & Planets column for *Sky & Telescope*.

Evening Entertainment

Go out early and stay out late to catch the best meteor shower of the year.

How bright can a Geminid get? Very!

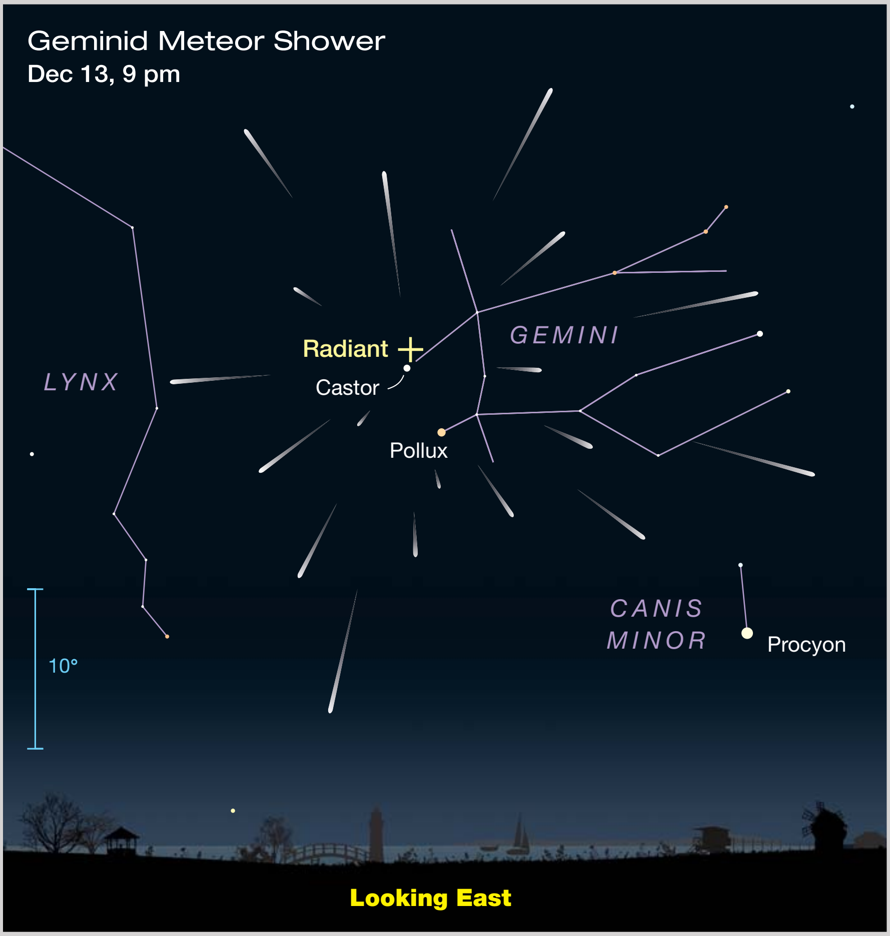
Frankie Lucena captured this image of a shower meteor over Cabo Rojo, Puerto Rico, during a full Moon on December 14, 2016.

This year Earth passes through the Geminid meteor stream under a waning crescent Moon. Peak shower activity is predicted to fall on the night of December 13–14 (6:30 UT December 14th), with the Moon well out of the way. The Moon doesn't rise until after midnight (around 3:30 a.m. EST for the East Coast, 4:00 a.m. PST for the West Coast), when it will only be 10% lit, so lunar interference will be minimal this year. This means the observing window opens at nightfall on the evening of the 13th and remains that way well into the morning hours of the 14th. The Geminids are a relatively prolific and long-lived shower, though, so it won't hurt to keep an eye out for meteors a few days in advance of the peak and a few days after, at least through new Moon (6:30 UT December 18th).

The Geminids are the only major meteor shower to provide good evening counts, thanks to the radiant's favorable position. At maximum, the radiant lies near 2nd-magnitude Alpha Geminorum (Castor), which rises or is above the eastern horizon at dusk for northern observers. Because of this, Geminids produce a high number of "Earth-grazing" meteors: often brilliant streaks of light that appear to start at or below the horizon. Look for them as soon as it grows dark. Like other meteor showers, though, the Geminids are most active when the radiant stands highest in the south, which won't happen until around 2:00 a.m. local standard time.

Geminid meteors travel at medium-to-slow speeds because they hit Earth's atmosphere at a shallow angle, often producing dramatic fireballs (meteors that blaze to magnitude –5 or brighter). These are the lights that make the evening news.

Near-peak rates for the Geminids persist for almost a day, offering such wide visibility that much of the world has a chance to enjoy the light show. The shower boasts a peak average zenithal hourly rate (ZHR) of 120 (only the Quadrantids rival



▲ This should be a good year for the Geminids. There's almost no moonlight to interfere with observing, and the shower reliably produces a high meteor count. To determine if a meteor is a Geminid, trace its path backward. If you end up at a point close to Castor, you've got yourself a winner.

GREGG DINDERMAN / S&T

it in peak activity), but it's extremely unlikely you'll see that many. You don't have to be particularly lucky to see a few Geminids if you spend even a half hour outside, however. And don't be surprised if you see a stray meteor whose origin can't be traced back to the Geminids' radiant point. It may be a sporadic, or it may come from one of the several proximately timed minor annual showers, like the Monocerotids or the Sigma Hydrids.

Geminid visibility isn't great for the Southern Hemisphere, since the radiant never climbs above the horizon, but southern observers may still see 10–20 meteors in an hour.

Minima of Algol

Nov.	UT	Dec.	UT
2	10:18	1	2:27
5	7:07	3	23:16
8	3:56	6	20:05
11	0:45	9	16:55
13	21:34	12	13:44
16	18:22	15	10:33
19	15:11	18	7:22
22	12:00	21	4:11
25	8:49	24	1:00
28	5:38	26	21:49

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

The Moon Occults Aldebaran

ON SUNDAY MORNING December 3rd for North America, the full Moon occults the brightest star in its path, Aldebaran. Only those in the far northwest of North America or in Asia will be able to catch this one, and they will be challenged by a beaming Moon and a rising Sun. Seattleites *might* see the star slip behind the Moon about 70 minutes before moonset, but the Moon will only be 10° high at that time, so there's a good chance the cloud-catching peaks of the Olympic Mountains will interfere.

Better chances are in Alaska. The Moon will be more than 20° high for Juneau at disappearance and still 15° high at reappearance: not ideal conditions, but not impossible.

For those watching close to moonset and sunrise, optical aid is required. Alaska sees both events in darkness, but a telescope or at least good binoculars will be needed to spot the star as it nestles up to the Moon's bright limb(s).

Some times: **Seattle,** *disappearance* 6:09 a.m., *reappearance* 6:56 a.m. PST; **Vancouver, BC,** *d.* 6:05 a.m., *r.* 6:46 a.m. PST; **Juneau,** *d.* 4:48 a.m., *r.* 5:39 a.m. AKST; **Fairbanks,** *d.* 4:33 a.m., *r.* 5:29 a.m. AKST; **Anchorage,** *d.* 4:38 a.m., *r.* 5:32 a.m. AKST.

Don't despair if you miss this one because of your location. The Moon-Aldebaran occultation series is winding down, but we have a few more to go before we see the last of them.

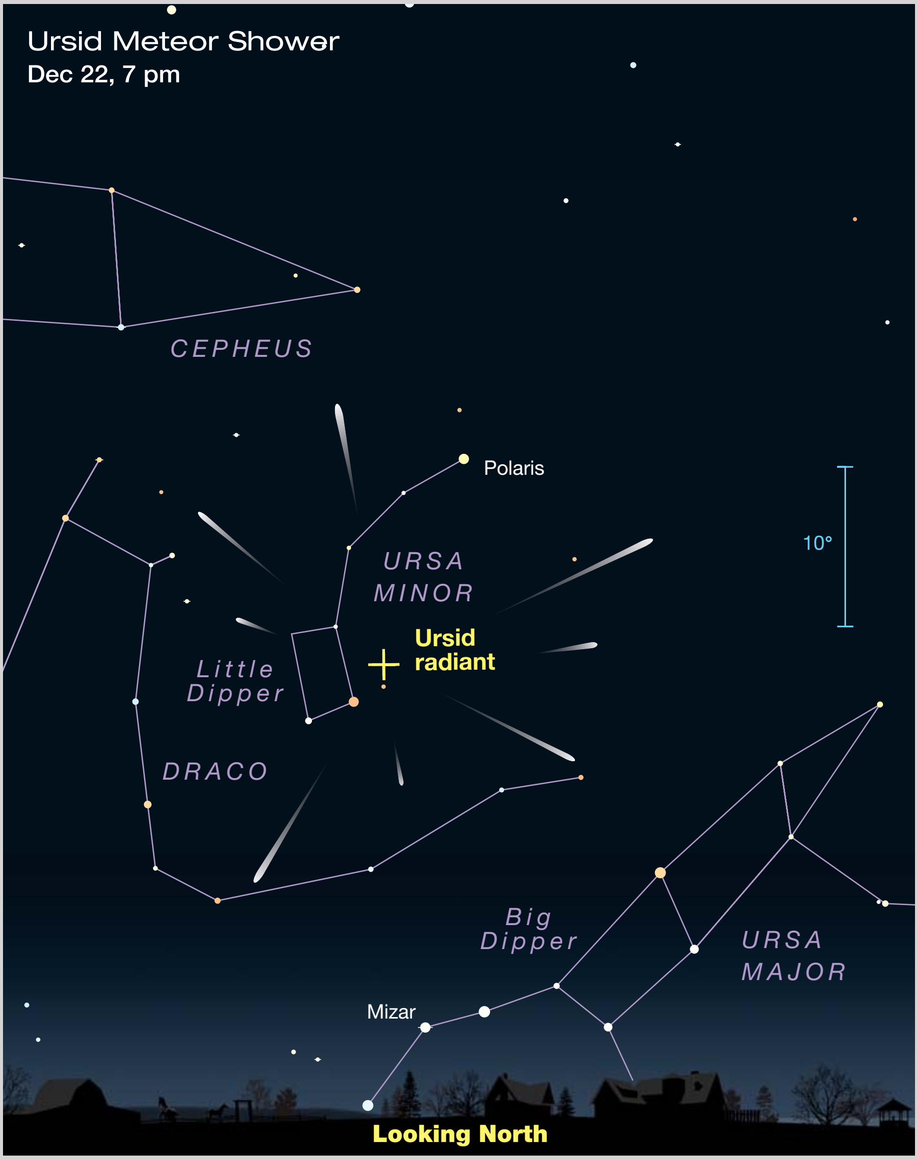
Saturday night December 30th offers a good nighttime occultation for much of eastern North America and a twilight-to-daylight occultation for western North America. The waxing gibbous Moon will be 90% lit when its leading edge slips over Aldebaran. Even though the star disappears at the dark edge, you'll need binos to combat the bright Moon. The reappearance on the bright limb, an hour or so later, will be more difficult to observe.

Some times: **Halifax,** *disappearance* 7:41 p.m., *reappearance* 8:33 p.m. AST; **Boston,** *d.* 6:29 p.m., *r.* 7:22 p.m. EST; **Montreal,** *d.* 6:28 p.m., *r.* 7:27 p.m. EST; **Washington, DC,** *d.* 6:19 p.m., *r.* 7:09 p.m. EST; **Toronto,** *d.* 6:28 p.m., *r.* 7:27 p.m. EST; **Atlanta,** *d.* 6:09 p.m., *r.* 6:52 p.m. EST; Chicago, *d.* 5:13 p.m., *r.* 6:10 p.m. CST; **Kansas City,** *d.* 5:09 p.m., *r.* 6:20 p.m. CST; **Denver,** *d.* 4:06 p.m., *r.* 5:00 p.m. MST; **Tucson,** *d.* 3:58 p.m., *r.* 4:51 p.m. MST; **Edmonton,** *d.* 4:29 p.m., *r.* 5:18 p.m. MST.

An Outburst At Last?

WHILE THE GEMINIDS remain December's premier meteor shower, it's worth directing some of your attention to the month's other major shower, the Ursa Minorids. The Ursids are predicted to peak at 15:00 UT on December 22nd (10:00 a.m. EST / 7 a.m. PST). The thin waxing crescent Moon sets early on the evening of December 21st, leaving the rest of the night and the morning hours of December 22nd free of lunar interference. Barring weather complications, observing conditions don't get much better.

The shower's radiant is near Beta Ursae Minoris (Kochab), the brightest corner star in the bowl of the Little Dipper. At just 14° from the celestial north pole, the radiant is circumpolar, so Ursids may appear even in the early evening. But as with all showers, visibility is best when the radiant is highest, which for the Ursids means just before dawn (it culminates after daybreak). How high is high? Not terribly. The radiant won't ever be overhead unless you're observing from the Arctic.



▲ For observers around latitude 40° north, the Ursid radiant remains about 30° high from nightfall to around 1 a.m. local standard time. That's not incredibly high (the best counts occur when the radiant is overhead), but you could see as many as a dozen Ursids per hour under a dark sky.

The Ursids remain one of the most under-observed showers. Maybe this has to do with the weather, or maybe they're just overshadowed by the showcase Geminids earlier in the month. The International Meteor Organization (IMO) notes an average ZHR of only 10, but outbursts with high ZHRs occurred in 1945, 1986, and 1993, and lesser outbursts may have occurred in the intervening years. It's so poorly documented, however, we really don't know. There was a predicted outburst for 2016, and radio observations did indeed suggest that the year's activity was higher than normal, but the IMO received visual counts from only 7 observers for the last shower.

There's no predicted outburst for 2017, but Earth will cross a dust trail left by the shower's parent object, Comet 8P/Tuttle, near the shower's predicted peak this year. Like other Halley-type comets, Comet 8P/Tuttle has produced a series of dust trails, each dating from a specific return. We're set to hit a dust trail ejected in AD 884 on December 22nd at 14:43 UT (9:43 a.m. EST / 6:43 a.m. PST). It probably won't bump up the meteor activity too much, but we'll never know if we don't get some data on record.

If you'd like to help solve the Case of the Unknown Ursids, go to **imo.net/visual** to learn how to carry out a rigorous, standardized visual meteor count. The American Meteor Society (**amsmeteors.org**) also offers observing strategies and forms for tracking your count.

GREGG DINDERMAN / S&T

Winter Is Coming

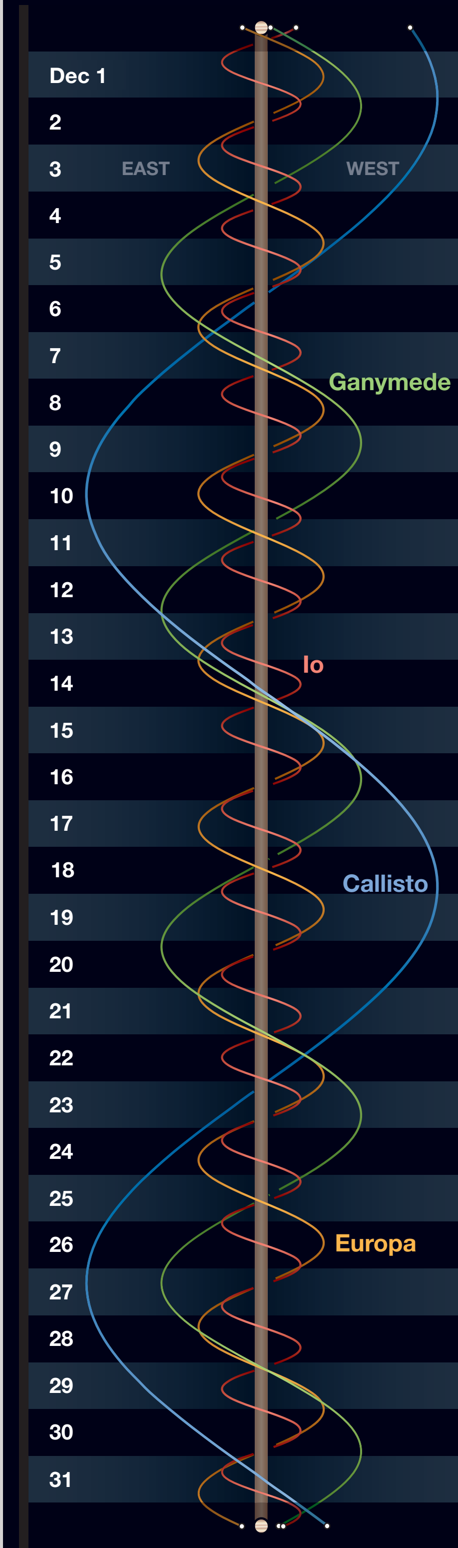
✱ The shortest day of the year in the Northern Hemisphere falls on Thursday, December 21st. Winter solstice, when the Sun hits its most southerly declination for the year of –23.4°, happens on that day at 16:28 UT (11:28 a.m. EST / 8:28 a.m. PST). The (relatively) southern city of Miami will still enjoy 10 hours and 32 minutes of sunlight on the 21st. In Kansas City, the day will be about an hour shorter (9 hours and 26 minutes), while more northerly Boston will have only 9 hours and 5 minutes of sunlight. Seattle, even farther north, will see the Sun (weather permitting) for just 8 hours and 25 minutes.

Phenomena of Jupiter's Moons, December 2017

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

Lunar Hall of Fame

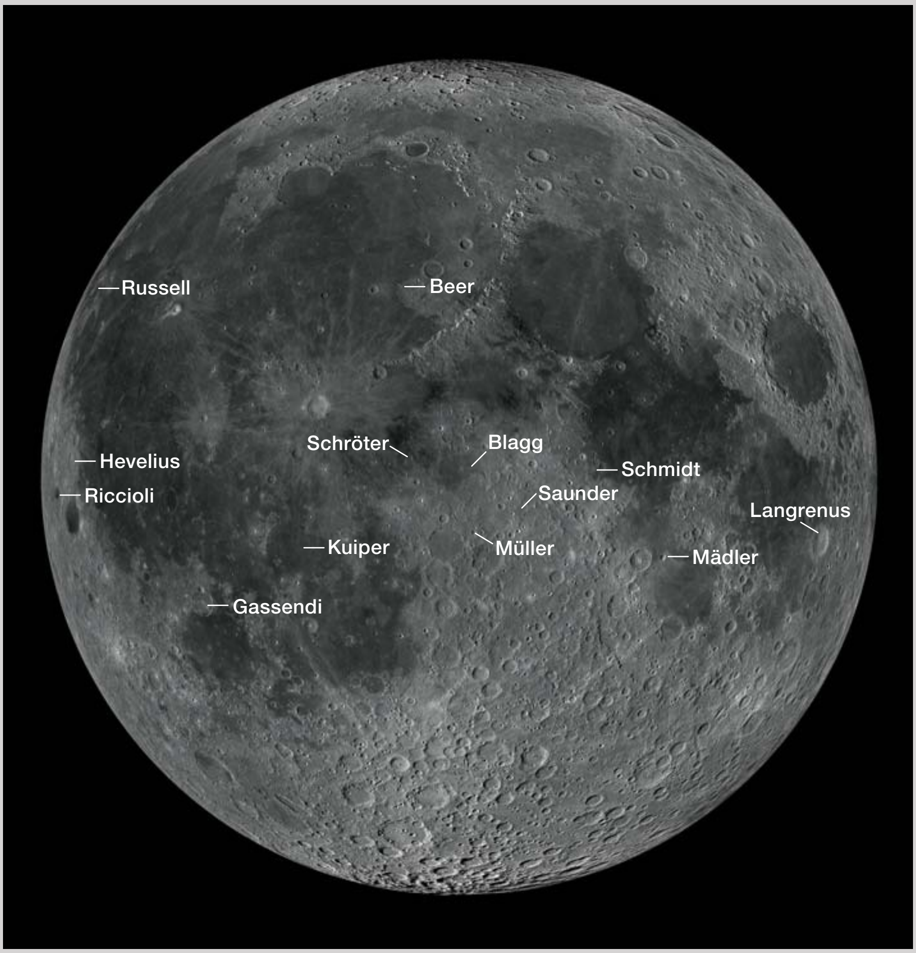
Beginning in 1645, obsessed observers drew maps of the Moon's face in ever-greater detail.

The word *lunatic* comes from Latin, meaning "moonstruck." In that context it applies to many of the observers who have devoted intense effort to studying the Moon. We commemorate their work by assigning their names to lunar craters. In this sense I think of the Moon itself as a kind of planetary pantheon — the Lunar Hall of Fame — and although its opening hours are variable throughout the month, admission is free.

So whom do I consider a lunatic? Many scholars, from Lucretius in ancient Greece to Galileo and Newton, considered the Moon in their studies — but it was not the major part of their life's work. Rather, I reason that anyone who drew a detailed map of the Moon must have spent years observing it — and thus qualifies. Here, then, are a few of the nearly two dozen craters named for passionate lunar mappers whom I particularly like because of the stories associated with them. By observing these lunatics' craters you can track the high-points of telescopic lunar exploration.

The craters named **Langrenus**, **Hevelius**, and **Riccioli** honor three pioneering lunar cartographers. Their works from 1645 to 1651 also introduced names for lunar features. Michael Florent van Langren came first, and despite the warning printed on his map not to change any of the identifications he gave "under penalty of censure," the two lunar mappers who followed him did exactly that. Langren had named most craters for Catholic royalty and saints, but Johannes Hevelius used terrestrial geographic features, and Giambattista Riccioli — despite being a priest — selected an assortment of ancient and contemporary scientists and philosophers. Riccioli's names remain (*S&T:* May 2015, p. 26), while those of his predecessors are forgotten.

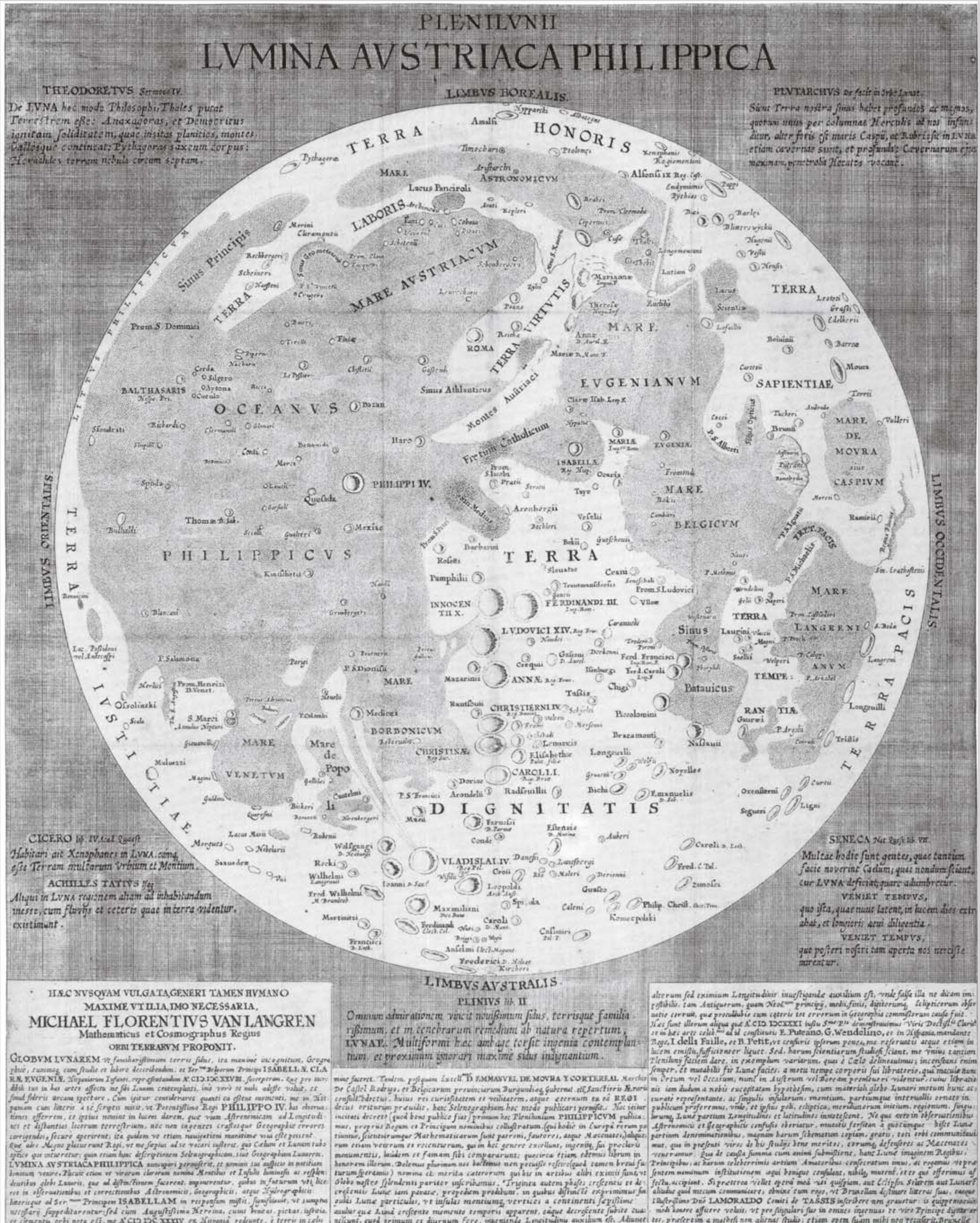
Without a doubt the most beautiful maps of the Moon were created by professional artists. First was Claude Mellan, a famous Parisian illustrator who drew two quarter-phase maps in 1635 that look nearly photographic. He combined them into a full Moon view, nudging them latitudinally to compensate for different librations. No



◀ Labels identify the famously obsessed mappers in the author's Lunar Hall of Fame.

▶ In 1645, Michael Florent van Langren published the first Moon map with names for lunar features. Two lines of Latin at the end (highlighted in yellow) state: "By royal decree, the changing of the names of this image is forbidden, under penalty of censure; also reproduction of any sort, the copy under penalty of confiscation and three florins."

NASA / LUNAR RECONNAISSANCE ORBITER

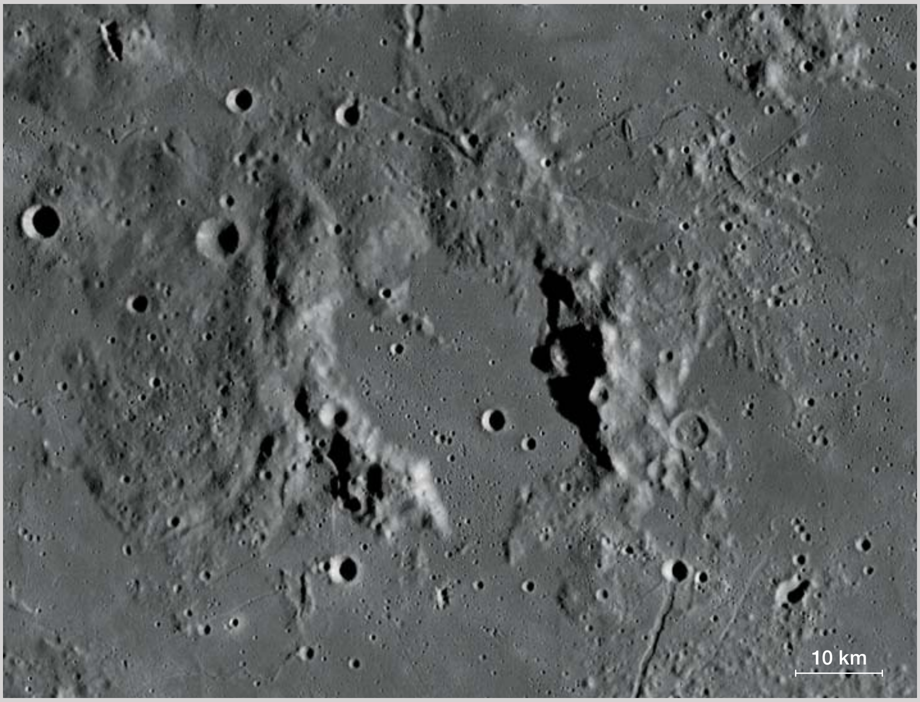


INTERNATIONAL PLANETARY CARTOGRAPHY DATABASE lunar feature commemorates Mellan, but Pierre **Gassendi**, the scientist who asked him to make the drawings, has a splendid crater.

Perhaps the most accomplished artist fascinated by the Moon was John **Russell**. Having been repulsed by the poor quality of many existing lunar drawings, he produced more than 200 sketches over 40 years, combining them into gores for a glorious lunar globe (1797) and later two maps of the Moon (1805). His works represented the lunar surface more realistically than any previous attempt.

The first astronomer to devote much of his career to the Moon was Johann Hieronymus **Schröter**, who studied Venus (*S&T:* Jan. 2017, p. 52) and other worlds, but who is most famous for his assiduous observations of the Moon over nearly 20 years. Although inelegant, his drawings initiated our modern interest in studying individual features. Schröter investigated rilles, mare ridges, and the lunar limb, and he measured elevations of mountains and craters. His results were published in two massive books titled *Selenographische Fragmente* — a recognition that he never combined his 75 detailed drawings into a complete map. The rim of Schröter's lunar crater, like his studies, is fragmentary.

▼ The rim of the lunar crater Schröter is incomplete — in keeping with its namesake's fragmentary lunar observations made over two decades.



A German duo, Wilhelm Beer and Johann Mädler, published their magisterial lunar book and map in the mid-1830s. Beer, a wealthy banker and amateur astronomer, owned the observatory that Mädler used to observe and map the Moon, completing the work in two years.

Mädler's approach and results were scientific. Based on observations, he drew many conclusions that stand today: The Moon has no atmosphere, maria are not liquid, rays have no relief, craters are much larger than terrestrial volcanoes, and rilles are unlike Earth's rivers. He also realized that some peaks at the lunar south pole are always in sunlight (*S&T:* June 2017, p. 53). Mädler famously concluded that the Moon was "no copy of the Earth."

Craters bearing the names **Beer** and **Mädler** are, appropriately, 10 km and 28 km wide, respectively. The female mathematician and astronomer Wilhelmine Witte used Mädler's map to create a lunar globe in 1838, and their meeting led to Mädler marrying her daughter. There's no lunar crater named Witte, but she's the namesake of a volcanic feature on Venus.

Julius **Schmidt**, who flourished from the 1840s through the early 1880s, is a textbook example of lunar addiction. As a young teen he obtained a copy of Mädler's map, and the Moon became his scientific focus for the rest of his life. Schmidt's obsession culminated in the publication in 1878 of the largest (77½ inches across) and most detailed map of the Moon. He compulsively counted its 32,856 craters to demonstrate his map's overwhelming superiority compared to all of its predecessors.

By the early 1900s a growing number of lunar maps carried different names for the same craters. An English woman, Mary **Blagg**, working under the guidance of Samuel A. **Saunder**, published a concordance of lunar nomenclature in 1912, and in 1935 she and Karl **Müller** published the International Astronomical Union's first catalog and map of the Moon. The catalog proved very useful; the map was ugly. Blagg, who did nearly all of the work, is remembered with a crater merely 5 km wide — while her male colleagues have craters with diameters of 22 and 44 km, respectively.

In the 1960s and early 1970s Gerard **Kuiper** and his colleagues completed the era of telescopic lunar mapping by publishing four comprehensive photographic atlases. Craters are named for Kuiper on the Moon, Mars, and Mercury. His colleague, the renowned lunar expert Ewen Whitaker, died in 2016 (see **https://is.gd/Whitaker**), and I hope his name will appear on a crater after the required three-year waiting period has passed.

■ **CHARLES WOOD**, who considers himself a certified lunatic, heads the International Astronomical Union's Lunar Nomenclature Working Group.

NASA / LUNAR RECONNAISSANCE ORBITER

HEVELIUS

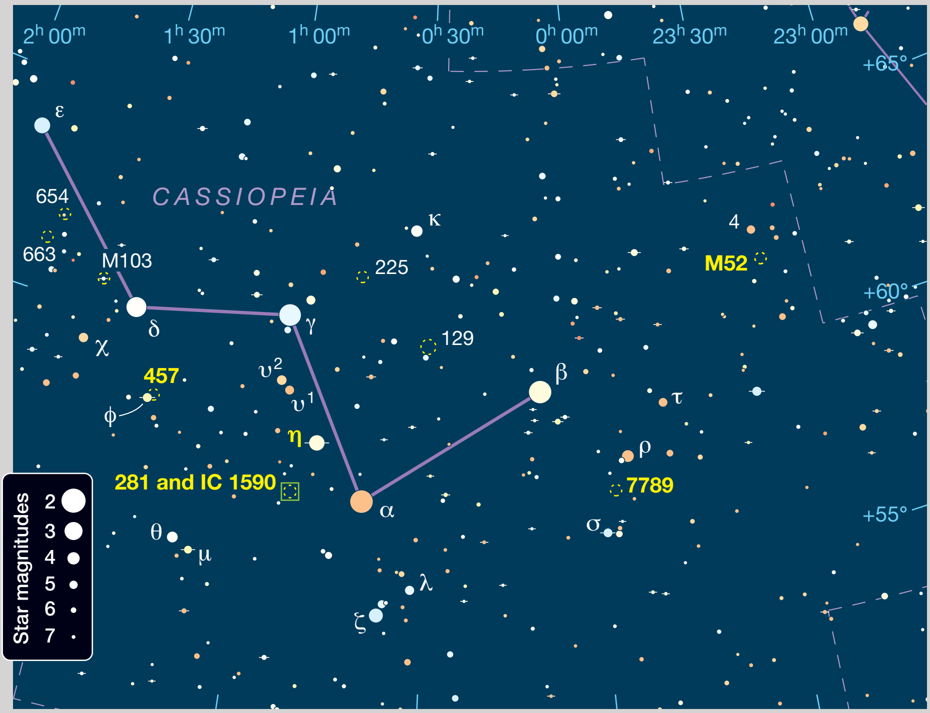
The Queen's Finest

Look to Cassiopeia for her varied collection of celestial treasure.

Next with her Cepheus Cassiopeia shines,
Her posture sad, and mourns amongst the Signs;
She sees her daughter chain'd, the rolling Tide
The Monster spout, and curses her old Pride:

She fears that Perseus will inconstant prove,
And now in Heaven forget his former Love;
But He attends, and bears the Gorgon's Head,
His Spoil, and witness of a coming aid.
—Marcus Manilius, *Astronomica*, trans. Thomas Creech (1697)

One of the most renowned Greek myths begins with Queen Cassiopeia of Ethiopia, who made the mistake of boasting that she was more beautiful than the alluring sea nymphs. The offended nymphs complained to the sea-god Poseidon, who sent the horrific sea monster Cetus to ravage her kingdom. An oracle counseled Queen Cassiopeia and King Cepheus that they could only save their realm by sacrificing their daughter, Andromeda, to the rapacious monster. So poor Andromeda was chained to a rock where she awaited her fate. Fortunately, valiant Perseus chanced upon the weeping maiden just after beheading Medusa, a hideous creature that none could behold without turning to stone. Smitten by Andromeda's beauty and moved by her plight, Perseus rushed to her aid and bade her cover her eyes. As Cetus reared up from the waves, Perseus drew Medusa's severed head from his satchel and literally petrified the fearsome beast.



From her starry perch in the heavens, Cassiopeia tenders a wealth of celestial treasure to anyone who cares to procure it, as though in payment for all the trouble she caused. Among these riches is the gem-encrusted star cluster **Messier 52**, which sparkles 41′ due south of orange, 5.0-magnitude 4 Cassiopeiae.

M52 is a moderately bright ball of mist flecked with faint stars through my 130-mm refractor at 23×. A brighter jewel at the western edge glitters yellow-orange. At 63× this starry brooch holds a clutch of 25 diamond-chip stars over dappled haze, encased in a sparser halo. In a 102× view, the cluster's densest region spans about 5½′ and is offset to the west within the halo. The 12′ halo doubles the number of stars. Through

▲ Discovered in 1774 by Charles Messier, M52 appears as a ball of fine mist, slightly concentrated toward the center, in a small scope. Increasing the magnification even a bit pops individual stars into view. Look for the burnished 8th-magnitude star embedded in the cluster's western fringe.

my 10-inch reflector at 213×, nearly 100 stars fill a 15′ cluster whose rim is frayed with scraps and strings of stars.

Star clusters often seem to be swathed in brume when many of their stars can't be individually distinguished. Charles Messier discovered M52 in 1774 and called it a "cluster of very small stars, mingled with nebulosity." With larger telescopes and higher powers, this false nebulosity resolves into stars. M52's yellow-orange star is a foreground giant with a spectral class of *F*8, implying a color index of 0.56, which goes hand-in-hand with a yellow-white star. However, the star's light is reddened by interstellar dust and has a measured color index of 1.02, consistent with a star that looks some shade of orange.

Bearing a greater hoard of tiny gemstones than M52, **NGC 7789** is a must-have on your observing list. This impressive star cluster conveniently sits about halfway between Rho (ρ) and Sigma (σ) Cassiopeiae, and through 12×36 image-stabilized binoculars, its sugar-cloud glow shares the field of view with these stars and Beta (β) Cassiopeiae.

NGC 7789 is large and gorgeous in the 130-mm scope at 102×, with densely packed core stars overlaying a fleecy haze. The teeming core covers 10′, and its straggled fringe bridges at least 15′. Together they encompass about 80 stars, 10th magnitude and fainter. NGC 7789 is stunning in the 10-inch scope at 63×. It spreads across 20′ and reveals far too many stars to count. This populous cluster is thought to weigh in at several thousand solar masses.

Caroline Herschel discovered NGC 7789 in October 1873 with a 4.2-inch Newtonian reflector made for her by her brother William. The telescope gave a magnification of 24× and a 2.2° field of view. She described the cluster as "a fine nebula, very strong." It's sometimes called Caroline's Rose, an image conjured from the whorls of stars and charcoaled voids the group presents. Under dark skies, this lovely rose blossoms even through my 105-mm refractor at 76×.

Let's mosey over to **Eta (η) Cassiopeiae**, found between the stars Alpha (α) and Gamma (γ) in Cassiopeia's iconic W shape. Eta Cas is one of my all-time favorite stars. Not only is it a pretty double, but in it we see a fascinating juxtaposition of a sunlike star with a red dwarf. Red dwarfs are so small and faint that we see few near enough to disclose their color through a small telescope, but Eta is a close neighbor, as stars go, at a distance of 19.4 light-years. My 105-mm scope at 29× nicely shows off the 3.5-magnitude, pale-yellow primary and its 7.4-magni-

The Jewels of Cassiopeia

Object	Type	Dist. (l-y)	Mag.	Size / Sep.	RA	Dec.
Messier 52	Open cluster	4,600	6.9	16′	23^h 24.9^m	+61° 36′
NGC 7789	Open cluster	7,600	6.7	25′	23^h 57.5^m	+56° 43′
Eta (η) Cas	Double star	19.4	3.5, 7.4	13.3″	00^h 49.1^m	+57° 49′
NGC 281	Emission nebula	9,200	7.8	35′ × 30′	00^h 53.0^m	+56° 38′
IC 1590	Open cluster	9,200	7.4	6′ × 4′	00^h 52.8^m	+56° 39′
NGC 457	Open cluster	7,900	6.4	20′	01^h 19.6^m	+58° 17′

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

▲ A 7th-magnitude *K*7 red dwarf lies just 13″ northwest of the 3rd-magnitude *G*0 primary star of Eta Cassiopeiae.

M52: ROBERT GENDLER / VISUALS UNLIMITED, INC. / GETTY IMAGES; SKETCH: JEREMY PEREZ

▲ Popularly known as "Caroline's Rose," NGC 7789 was discovered in 1873 by Caroline Herschel with a 4.2-inch Newtonian reflector. **Right:** Phi Cassiopeiae serves as one bright eye in the dragonfly (or owl, or E.T.) asterism drawn on the stars of the open cluster NGC 457.

▲ The curving dust cloud NGC 281, discovered by E. E. Barnard in 1881, is easily detectable in small scopes. IC 1590 nestles in the nebulosity, where it emulates the eyes of the world's most famous arcade diner, Pac-Man.

tude, deep-orange companion. Eta is a visual binary with an orbital period of 479 years. Currently the companion is 13.3″ northwest of the brighter star.

Just 1.3° south-southeast of Eta, **NGC 281** is probably Cassiopeia's easiest emission nebula to nab in a small telescope. In the *Observing Handbook and Catalogue of Deep-Sky Objects*, authors Christian Luginbuhl and Brian Skiff found it visible as a fairly low-surface-brightness glow through a 60-mm refractor. From my semirural home, it's readily visible in the 130-mm scope at 23× as a rather large, moderately faint glow in a starry field. Adding a narrowband nebula filter makes it stand out quite well as a fat comma (in my mirror-reversed view), with a fairly bright star embedded in the southern part of the comma's head. East of the comma's tail, a distinctive arc of three stars parallels the tail's curve. An O III filter makes the comma's head stand out even better.

At 164× without a filter, the embedded star becomes a quadruplet. Its 8.6-magnitude primary shows companions 1.5″ east, 3.7″ southeast, and 8.9″ south-southwest (magnitudes 9.3, 8.9, and 9.7, respectively). These stars form the core of the young cluster **IC 1590**. As of this writing, the open cluster database WEBDA assigns an age of 3.5 million years. I see perhaps five additional stars within the bounds of the cluster, but images pull out many more.

NGC 281 hovers roughly 1,000 light-years above the midplane of our galaxy's Perseus arm. It most likely formed in the galactic plane but was driven out by an expanding bubble blown by fierce stellar winds and supernova explosions. The southwestern part of the nebula is hidden by a dark cloud where star formation is ongoing. These bright and dark nebulae collude to give NGC 281 the unusual shape that spawned its nickname, the Pac-Man Nebula, for its resemblance to the critter that first appeared in the Pac-Man arcade game in 1980.

Another great favorite of mine, and a big hit at public star parties, is the open cluster **NGC 457**. It's easy to pinpoint because 5.0-magnitude Phi (φ) Cas lies within its boundaries, although it's probably a foreground star. NGC 457 is always a Dragonfly to me. In my 130-mm scope at 37×, it's a pretty thing with the two brightest stars as big, lustrous eyes, with Phi gleaming yellow. About 45 moderately faint stars make up a body and tail stretching northwest from the eyes and wings outspread to the sides. The northeastern wing is adorned with a fetching fire-opal gem.

NGC 457 inspires imaginative flights of fancy in other observers as well. In *1000+: The Amateur Astronomer's Field Guide to Deep Sky Observing*, Tom Lorenzin dubbed it the E.T. Cluster after the cute extraterrestrial in the movie E.T. The group's big, bright eyes also lead quite naturally to the nickname the Owl Cluster, which was introduced by a then teenaged David Eicher in a September 1980 *Deep Sky Monthly* article. What image do these stars suggest to you?

■ **SUE FRENCH** also enjoys the shallow sky. When reviewing this article, she was on her way to Nebraska to view last August's solar eclipse.

NGC 7789: CHAD QUANDT; NGC 281: MASIL IMAGING TEAM; PHI CASSIOPEIAE: LORAND FENYES / STOCKTREK IMAGES / GETTY IMAGES

The Star Adventurer Mini Tracker

Sky-Watcher's newest Star Adventurer merges an astronomical tracker with a time-lapse motion controller.

Sky-Watcher Star Adventurer Mini

U.S. Price: $299

skywatcherusa.com

What We Like:

One device can both track and pan cameras

Polar-alignment scope included

Wireless app allows for easy programming

Excellent battery life

What We Don't Like:

No speed-ramping option for time-lapses

Connects via WiFi (not Bluetooth LE)

Status readout requires WiFi to remain activated

Firmware updates require Windows computer

WHENEVER I PRESENT workshops on astrophotography and time-lapse imaging, I always show off an array of devices for moving the camera while it shoots. When I display one of the specialized "motion controllers" designed to pan a camera during a time-lapse, someone always asks, "Can it track the sky?" The answer is always, "No, sorry!" When I show a device that can track the sky for long exposures, the question is, "Can it also be used take time-lapses?" The answer, up to now, has been, "Sort of!"

With Sky-Watcher's new "mini" version of its Star Adventurer tracking mount, I can finally say, "Here is one

◀ The Star Adventurer Mini seen mounted to a solid tripod head for polar-aligned tracking. Its bottom plate has been removed, revealing where the polar scope installs. However, the polar scope's view is blocked when using the Ball Head Adapter.

ALL PHOTOS BY THE AUTHOR

device that can do both!" The question now becomes, how well?

To find out, I tested an early production unit, on loan from Pacific Telescope Corporation, Sky-Watcher's distributor in Canada. My test unit was finished in red, but I was assured that units sold in the United States and elsewhere with a black finish differ only in appearance.

App-Based Programming

The biggest difference between the Star Adventurer Mini, or "SAM," and other trackers is that to get it to do more than simply track the sky, you first have to program it using its free app, the *SAM Console*, available for iOS and Android devices through their respective stores.

Your device connects to SAM via an ad hoc WiFi network SAM sets up. Once the device sees SAM, the app can then connect to it to program in key parameters for motion-control time-lapses: how many shots you want, at what interval, plus the angle over which you want your camera to move, and over what time period.

Like the original Star Adventurer, SAM has a "Snap" port that connects your camera to trigger its shutter, firing your programmed number of shots at the exposure duration you want when the camera is set to Bulb. Sky-Watcher offers accessory cables for a variety of camera brands and models at additional cost. SAM also accepts every accessory available for the original Star Adventurer mount, including a Declination axis and counterweight.

As with all motion controllers made for time-lapse photography, the mount is a "shoot-move-shoot" device. It makes incremental moves only between exposures when the shutter is closed. It does not turn during the exposure, in order to keep ground detail as sharp as possible. This is a big advantage over repurposing other astronomical sky trackers to do time-lapses. Using those devices, users tip them up to aim their rotation axis at the zenith, then set them turning, usually at the standard sidereal rate. But the tracker is always moving, even during exposures, and there is little or no control over the amount of swing or speed. By contrast, SAM is a fully programmable motion controller, competing with the likes of Alpine Lab's Radian2 and SYRP's Mini Genie.

▶ The Star Adventurer Mini has two mounting surfaces, each with a ⅜-inch bolt hole. The ⅜-to-¼-inch threaded adapter ring is supplied. One surface, with a removable plate called the Tripod Connector (at left), is for mounting the Mini vertically for time-lapse shooting and panning. The other surface (on the right) is for mounting the Mini as a polar-aligned tracker.

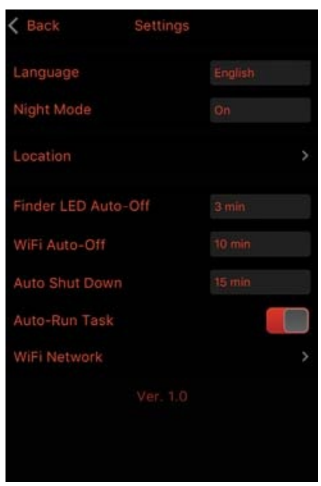
The downside of this programmability is that it complicates the more standard function of simply tracking the sky at the sidereal rate. Getting SAM to track for traditional long exposures of constellations or the Milky Way requires setting up a sequence of shots, whether or not you use SAM to actually control the camera. Out of the box, you can't just flip a switch to turn on the tracking motor and have SAM work. You always have to connect to it via WiFi to program in what you want it to do that night: pan or track?

However, the app allows you to program in a number of preset routines and then have SAM automatically start your sequence when it's powered up. What I often did was save a preset and load it with SAM set to "auto-run." When powering up next time, SAM would start the sequence without any need to connect via WiFi. So, if you have several nights of tracking shots planned, that's a convenient way to get SAM going without needing to program it each night.

Connection and Powering

Connecting my iOS devices to SAM's WiFi took a few seconds but always worked fine. But it does mean disconnecting the device from your normal network, if only temporarily. To conserve battery power, SAM can be told to shut off its WiFi once a sequence is running.

While the app can keep track of the sequence, telling you how many frames have been shot and the time remaining, this "Status" is available only if SAM's WiFi remains on and connected. I would like to see a free-running display of a sequence's progress.



◀◀ SAM broadcasts an ad-hoc WiFi network. Other than an on-off switch, the unit has no hardware controls. Settings can be applied only through the free *SAM Console* mobile app once a phone or tablet is connected to its WiFi.

◀ The tracker can be instructed to turn off its WiFi once a sequence is running, to conserve battery power. The "Auto-Run" option also tells SAM to start the last programmed sequence automatically on power up.

▲ The included polar scope clicks into the polar axis with a solid assurance. A separate illuminator clips onto the front to illuminate the field. A "Snap" port controls the camera shutter. A micro USB port is for applying firmware updates or powering the tracker with an external 5-volt source.

With the WiFi set to turn off, I found the two internal AA batteries provide several hours of tracking or panning, more than enough for 3 or 4 nights' work on warm summer evenings. Alternatively, SAM can be powered from an external 5-volt power pack, such as used to charge phones, through a micro USB port. Users need to supply their own micro USB cable.

While the WiFi connection worked reliably, I would have preferred if SAM connected via Bluetooth LE, as is the case with many other motion controllers. Connecting via Bluetooth LE is easy, takes less power, doesn't require switching away from your normal WiFi network, and allows for convenient over-the-air updates to firmware using the mobile device itself, as it can remain connected to the internet and to the controller at the same time.

As it is, updating Sky-Watcher's mount firmware currently requires using a Windows-only application, leaving MacOS users out of luck.

Tracking Functions

When set up as a star-tracker, the included polar-alignment scope inserts into the polar axis. The scope comes with a separate bright-field illuminator and an excellent reticle suitable for both the northern and southern hemispheres. The app also displays the same reticle and the current positions of Polaris or Sigma Octantis.

The SAM gets its location from your mobile device, so there is no hardware N-S motor direction switch on the device. If it detects you are south of the equator, it turns the motor in the opposite direction to what's needed up north. I tested SAM only from home in Canada.

There are software options for setting the tracking rate to Sidereal, Solar, or Lunar, and for having SAM turn at 2× or 0.5× sidereal rate, the latter useful for some nightscape images.

I set up several exposure sequence tests that would fire the shutter while it tracked over several hours. As a star-tracker, the SAM worked great. It was easy to polar align and tracked well when using wide-angle lenses.

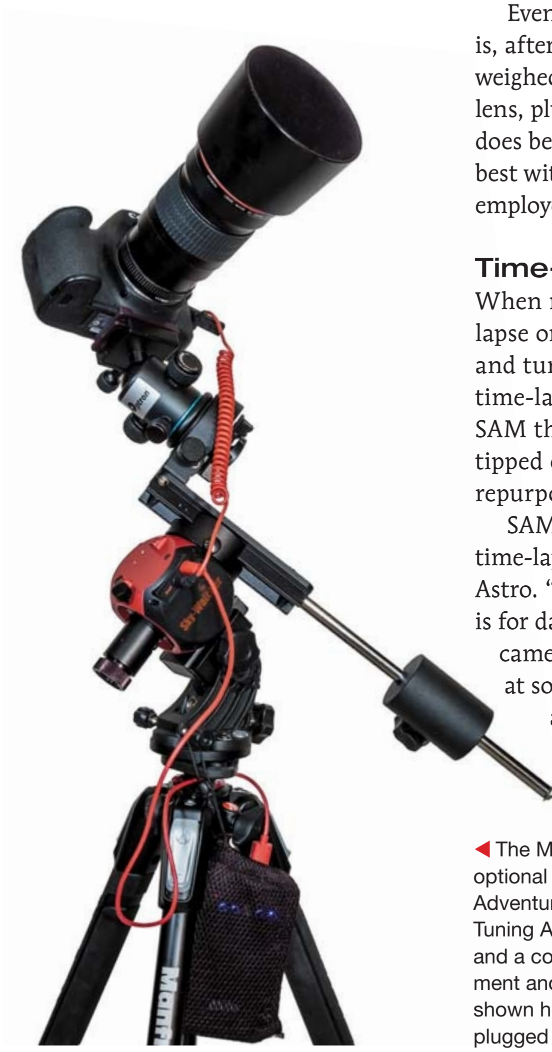
Images through a 200-mm telephoto did show some trailing, with about 60% of 1- to 2-minute exposures displaying trailed stars. Unlike the larger Star Adventurer, SAM has no autoguider interface. While an optional declination axis and counterweight are offered, I didn't see any improvement in tracking accuracy when using them to balance a telephoto lens. However, this wasn't surprising; I found the Mini's tracking accuracy to be typical of small drives in the $300 price class. When shooting with focal lengths over 50 mm, it's best to shoot lots of frames so you can pick out the best and toss the rest later.

Even so, I would emphasize that SAM is, after all, a "mini" mount. When weighed down with a heavy camera and lens, plus the optional counterweight, it does become bouncy. I feel the unit works best with the wide-angle lenses typically employed in nightscape imaging.

Time-Lapse Functions

When mounted to a tripod in its time-lapse orientation, SAM stands vertically and turns left/right in azimuth for time-lapses panning along the horizon. SAM then remains in balance, and not tipped over precariously as when using repurposed star-trackers.

SAM offers three modes for taking time-lapses: Regular, Long Exposure, and Astro. "Regular-Exposure Time-Lapse" is for day or twilight shots where the camera operates on auto-exposure or at some pre-determined shutter speed, and at an interval (what the app calls "Frame Period") you set. SAM then just sends a fixed



◀ The Mini is compatible with the same optional accessories offered for the larger Star Adventurer: the Equatorial Wedge, the Fine-Tuning Assembly for declination slow motion, and a counterweight. These aid polar alignment and shooting with heavier lenses. SAM is shown here powered by a user-supplied battery plugged into the USB port.

▲ This image of Cygnus is a stack of eight 2-minute exposures taken with SAM and the 200-mm f/2.8 telephoto lens shown on the facing page. Telephoto shots require taking many more exposures than needed to allow picking just the frames least affected by the slight tracking error exhibited by SAM (and most other low-cost trackers).

0.5-second pulse to trigger the shutter.

In "Long-Exposure Time-Lapse" mode, SAM controls the exposure time, opening the shutter for as long as you want, with the camera on Bulb. This is for night time-lapses.

In both modes you have full control over the number of frames you want to shoot, the angle over which SAM will turn, and the time it will take to perform the complete move. SAM can also turn clockwise or counter clockwise, and even be set to bounce back and forth if you want.

By setting parameters to give a speed of 15° per hour (for example, setting up a turn of 45° that will take three hours to execute), SAM will nicely follow the equatorial sky as it moves from east to west over a landscape.

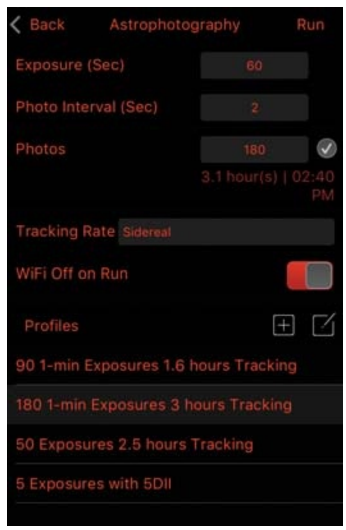
These functions worked reliably, firing off exactly the number of shots I wanted over the angle I had programmed.

One deficiency, when compared to other dedicated motion controllers, is SAM's lack of any option for speed ramping. This would allow SAM to ramp up and down in speed at the start and end of sequences. This adds a cinematic touch to final time-lapse movies.

In addition, there is no way to set absolute start and end "keyframe" positions. Instead, SAM offers a manual speed control for panning back and forth, to help plan how many degrees the unit needs to turn to end a move at a desired point, perhaps aimed at a scenic feature. It works but is very slow. I never used it, relying on the degree scale on my ball head to estimate the angle of move I needed for a time-lapse.

Astro Time-Lapses

By contrast to these deficiencies, SAM has one function no other motion controller offers, what it calls "Astro Time-



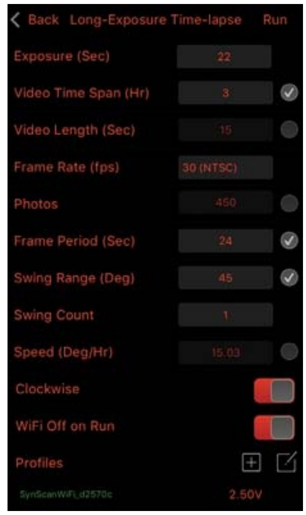
▲ Providing several hours of continuous tracking requires programming in a preset sequence such as the one seen here. Or SAM can be told to fire the shutter for several multi-minute exposures. However, once a sequence ends, the tracking motor stops and SAM powers down.

Lapse." In this mode, you set up SAM as a polar-aligned sky tracker. You then frame the landscape scene and program in the exposure time and number of shots you want, or the span of time you wish to shoot over.

SAM then tracks the sky for the duration of each exposure. When the shutter closes, SAM "rewinds" back to the starting position then begins another exposure with the tracking motor turned back on. No other time-lapse controller can do this.

This mode is great for time-lapses of the Milky Way under dark sky conditions using exposures long enough to really show the Milky Way well but without the stars trailing in the shots, or excessive noise. Of course, the ground will be blurred due to tracking the sky. But as it would be dark, any loss of detail in the ground might not be objectionable.

► In "Regular-Exposure Time-Lapse" mode, SAM sends just a short trigger pulse to the shutter. The exposure time is set on the camera, as is needed for daytime and twilight shots.



►► In "Long-Exposure Time-Lapse" mode SAM controls the length of exposure, with the camera set to Bulb mode. This is for night time-lapses. Here SAM is set to turn 45° over three hours, taking 22-second-long exposures, firing the shutter every 24 seconds, for a total of 450 frames separated by a gap of two seconds.

Astro Time-Lapse worked amazingly well. I did not detect any frame-to-frame jitter in resulting time-lapses. The device reset precisely and quickly in just a second or so.

▲ **Left:** When mounted for time-lapse shooting, the drive remains balanced over the tripod, and can now turn in azimuth for panning along the horizon. Here, SAM is mounted to a standard tripod head. While the adapter plate is supplied, users must supply their own ball head.
Right: For sequences in its unique "Astro Time-Lapse" mode, SAM must be set up as a polar-aligned tracker, but with the camera now framing a horizon scene, for tracked time-lapses of the moving Milky Way or bright comet over a fixed landscape.

The Astro Time-Lapse mode is best reserved for sequences needing exposures over 30 seconds. But that means long shoots. For example, using 60-second exposures will yield rich Milky Way images but will demand shooting for five hours (!) to acquire the 300 frames typical of most time-lapses.

Then, when played back at the usual rate of 30 frames a second, the sky will appear to turn at a pretty high speed. Sequences with a more graceful sky motion require more frames shot over a shorter time span, which means shorter exposures, likely at a high ISO. That combination doesn't need "Astro Time-Lapse" tracking and its required polar alignment. Nevertheless, Astro Time-Lapse is a great tool to have for some Milky Way time-lapses.

In all, SAM is a compact and affordable option for anyone wanting to get into both tracked wide-field shooting of the Milky Way, and time-lapses of the sky turning over landscapes. With the caveats stated, the Star Adventurer Mini from Sky-Watcher can do it all, at a price comparable to other single-purpose trackers and motion controllers.

A four-minute video collage of time-lapse movies taken by the author with the Star Adventurer Mini can be viewed at **https://is.gd/SAM_demo**.

■ Pick up Contributing Editor **ALAN DYER**'s ebook *How to Photograph & Process NightScapes and TimeLapses* at amazingsky.com/nightscapesbook.html.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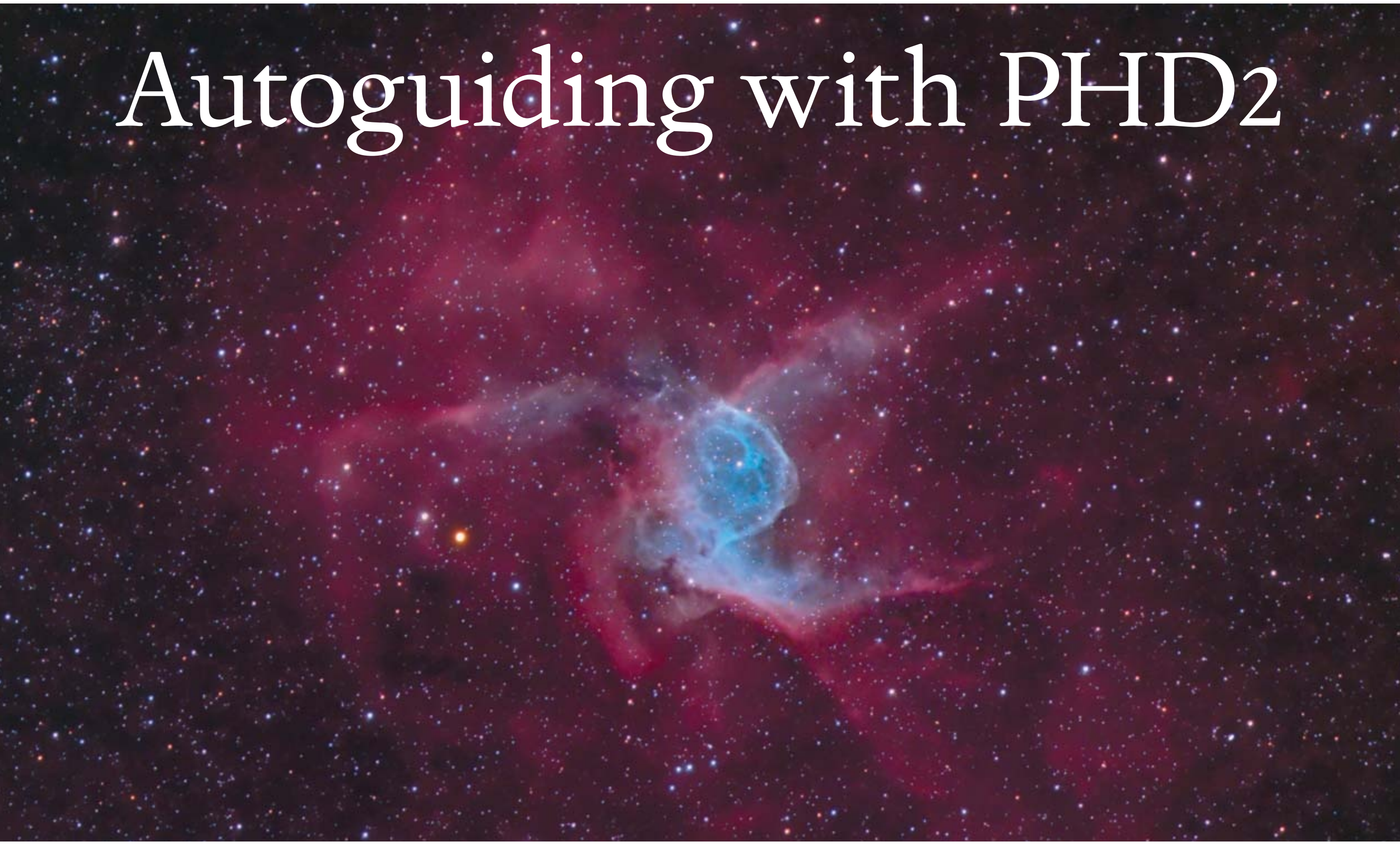
Autoguiding with PHD2



This open-source freeware can help you get perfectly tracked astrophotos.

In the good old days last millennium, serious astrophotographers hand-guided film astrophotos to ensure a sharp result. They spent countless hours monitoring a single star in a reticle eyepiece to ensure a perfectly tracked photograph. Otherwise, small-scale details in images were lost to blurring in the final result. Thankfully, those days are history. The advent of computer-controlled autoguider cameras has opened up deep-sky astrophotography to more amateurs than ever before. While autoguiding support is built into many high-end imaging programs, there's only one standalone program that does it for free.

PHD stands for "Push Here Dummy," a humorous, self-deprecating name for the highly regarded autoguiding program originally written by Craig Stark (available to download at **openphdguiding.org**). Stark literally made autoguiding as simple as pushing a couple of software buttons.

The latest version of the program, *PHD2*, works on Macs and PCs and includes some nifty new features. Multi-threading, new visualization tools, an improved drift alignment tool, and declination compensation have been added to eliminate the need for recalibration when switching targets. Here's how to use it.

First Things First

Before you get started autoguiding with *PHD2*, you first have to address all of the mechanical issues with your equipment that let you achieve accurate guiding. Here are some important things to consider:

• When using inexpensive mounts, limit the weight of your gear to half of the mount's stated payload capacity.

• Make sure to polar align your equatorial mount accurately, because a typical 2- or 3-star Go To alignment routine

▲ **PERFECT GUIDING** Unless you use an extremely high-end telescope mount, you'll need to autoguide every deep-sky astrophoto to ensure round stars in your images. This deep exposure of Thor's Helmet (NGC 2359) is made up of more than 7 hours of exposures guided using *PHD2*. **Facing Page:** *PHD2* includes several ways to monitor your guiding. The main image from your autoguider is seen at top left of this screen, with the chosen guide star marked with a green box. Additional windows monitor the profile of the guide star, guiding statistics, and the History graph that shows what corrections have been made in both axes. The toolbar is visible below the guide image.

ALL IMAGES COURTESY OF THE AUTHOR

merely improves your mount's pointing model, but does not improve its polar alignment.

• Don't try to guide a large reflector or catadioptric telescope with a piggyback guidescope — use an off-axis (or on-axis) guider whenever possible.

• Minimize differential flexure between the guidescope and imaging scope. Pay special attention to the guidescope's focuser and its mounting rings.

• Always use guidescope rings with at least two alignment screws spaced 120° apart. Tubes in single set screws can pivot.

• Secure all dangling cables. They can subtly drag on your scope, sway in the wind, and ruin your exposures.

• Slightly offset the balance of your mount in right ascension so that it's *lifting* the weight on the east side of the meridian. This ensures the gear is always engaged. Be sure to rebalance after a meridian flip.

Getting Started with *PHD2*

Be sure to install any drivers required to operate your mount and autoguiding camera. Set your mount to a 1× guide rate.

Once you've installed and open *PHD2* for the first time, a "first light" wizard opens. This guides you through selecting your guide camera and inputting other equipment details, particularly how the program will communicate with your mount. Once that's completed, the program opens a History graph as well as a toolbar along the bottom of the window.

The toolbar contains icons to connect equipment, loop exposures (for calibrating and focusing), begin guiding, stop guiding, and change the camera settings. There's also a drop-down menu to change the autoguider exposure and a slider to change the brightness of the image display.

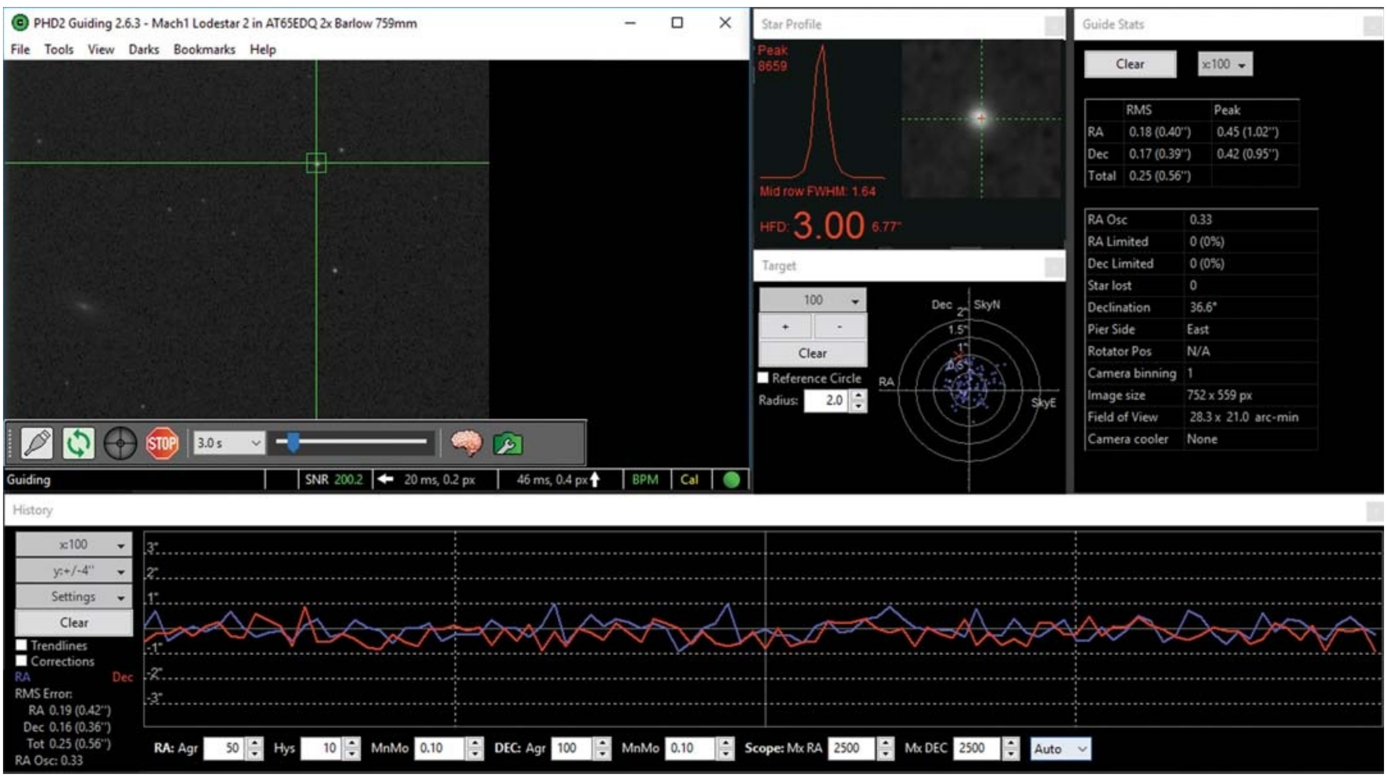
Many additional settings are located under the menus at the top of the main window as well as under the advanced settings "brain" icon in the toolbar. Most of these settings can be left on their defaults.

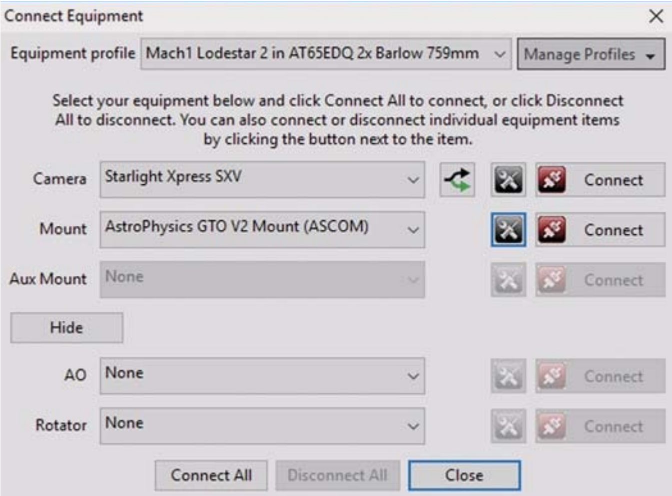
Start by clicking on the Tools menu at the top of the screen and select Enable Star Image Logging. This can help you diagnose most guiding problems later.

Clicking on the brain icon in the toolbar opens the Advanced setup window, where you can change all of the settings made when first opening the program. You can also enable advanced features such as dithering (or offsetting) the guide star between exposures.

Once you've plugged in all your gear and are ready to begin, click the Connect Equipment icon and press the Connect button to the right of the camera and mount dialogs. When both have successfully activated, press the Loop icon to start an exposure cycle, using between 1- to 3-second exposures. Focus your guidescope or off-axis guider and then lock everything down.

Next, simply click on a star in the display window, and hold down Shift and click the Begin Guiding icon to calibrate the program to your equipment. The calibration routine will issue a series of move commands in right ascension and declination and then re-center the guide star. This will tell *PHD2* how much the mount will actually move for a given amount of time. When calibration is finished successfully, *PHD2* will start guiding automatically.





▲ **CONNECTING EQUIPMENT** Clicking on the USB icon in the toolbar opens a window where you connect your autoguider camera, mount, and auxiliary mount. Additional connections for camera rotators and AO devices are available when clicking the More Equipment button.

At this point, open the Guiding Assistant from the pull-down Tools menu. When launched, this will turn off guiding and monitor the guide star for a few minutes, then report back useful information such as your polar-alignment accuracy. It will then offer recommendations for how long your guide exposure should be, as well as minimum motions and backlash settings. These should then be automatically input in the Advanced Setup dialog.

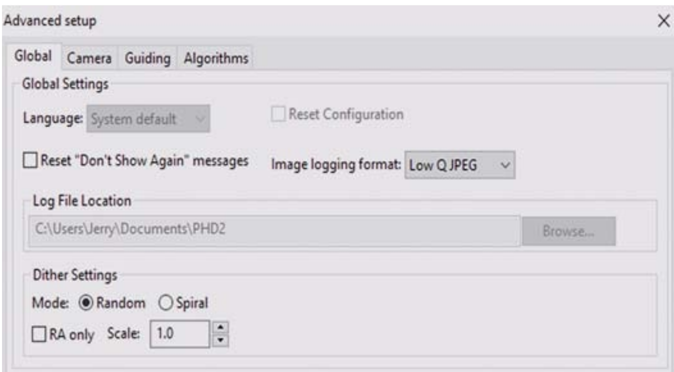
Additional Tips to Improve Guiding

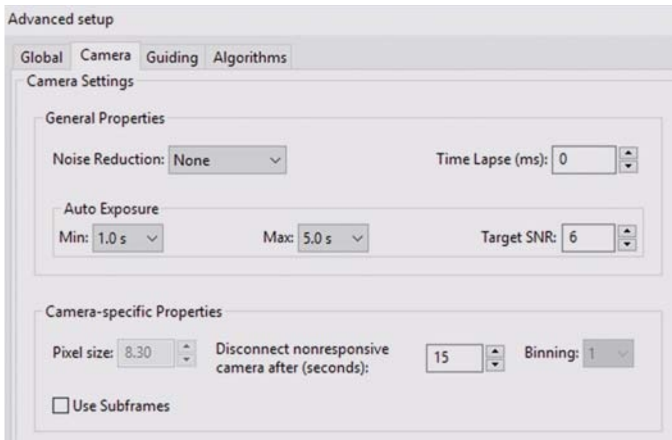
Now that you're autoguiding, here are some valuable suggestions to get the most out of your nights.

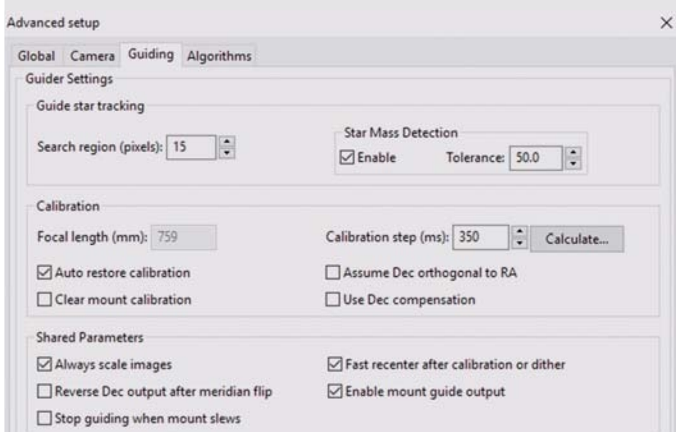
Don't chase the seeing! When imaging in unstable seeing conditions, set the guide exposure to around 3 to 5 seconds. This will produce a better average of the guide star's location. Also try reducing the right ascension aggressiveness settings in the Advanced Setup window, located in the Algorithms tab.

Disable unnecessary declination corrections. Some of the biggest guiding problems come from backlash in the declination gear, producing overshoot and oscillations, especially with inexpensive mounts. You can determine which way your guide star is drifting by simply turning off declination guiding altogether at the bottom right of the History graph for a couple of minutes and observing the drift direction. Then enable declination corrections only in the direction needed to correct for this drift.

Turn down the aggressiveness setting in right ascension in the Advanced Setup / Algorithms tab. This is often set too high, especially in poor seeing conditions. Adjust it until your right-ascension oscillation readout is between about 0.5 and 0.3 in







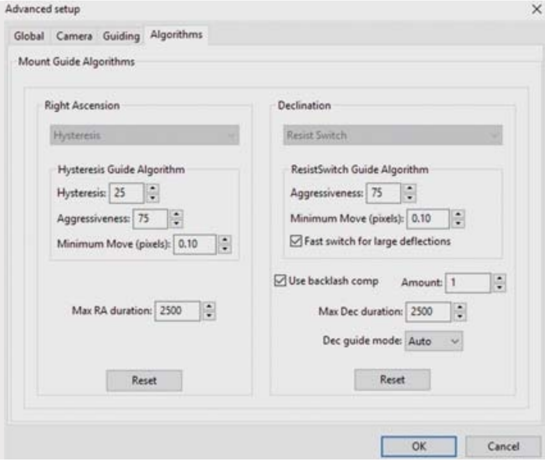
▲ **DITHERED GUIDING** Clicking on the "brain" icon opens the advanced setup dialog. The Global tab includes an option to do "dither" (or offset) guiding, which improves the overall signal of images when shooting multiple exposures.

▶ ▲ **CAMERA SETTINGS** The Camera tab allows you to change exposure settings if necessary. These should be set automatically when choosing your camera during initial setup.

▶ **GUIDING** Make advanced adjustments of the program's guiding parameters using the Advanced Setup Guiding tab. Input the focal length of your guide scope (or off-axis guider) and click the Calculate button to access the Calibration Step Calculator.

• For more helpful astrophotography tips, visit Jerry's website at astropix.com.

◀ CALIBRATION CALCULATOR This advanced tool computes how much *PHD2* moves your mount in both axes to make corrections, training the program to get the best results from your telescope mount.



◀ GUIDING ALGORITHMS The Algorithms tab in the Advanced Setup window lets you change the mode that *PHD2* uses, though the default settings work well. Here is where you can adjust the aggressiveness values when imaging under unstable seeing conditions.

the Guide Stats window. A readout of 1 means the program is changing directions after every exposure, so reduce the aggressiveness. A readout below 0.3 means you're not making enough corrections, requiring you to increase the aggressiveness.

Choose a guide star with the correct brightness. One that's too bright might saturate, leading to less accurate centroid calculations. Too dim, and it might disappear if conditions deteriorate. Select View > Display Star Profile from the pull-down menu. If the top of the peak is flat, then the star is being overexposed. Correctly set the calibration step size. During calibration, *PHD2* will issue a move command in milliseconds in right ascension and declination to see how far the star moves. It will do this a number of times to get a good average. If you have the calibration step size set too low, it will take a long time to calibrate. Set it too large and it might not make enough steps to get accurate calibration data. Aim for about 10 to 15 steps. If you correctly input your guidescope focal length and autoguider camera pixel size, *PHD2* will automatically calculate a recommended step size with which to start.

Change the minimum move parameters. The minimum move (MnMo) setting tells *PHD2* how far a star is allowed to move before a correction is issued. If this is set too small, it will try to chase the seeing. Too large a value, and the software might not make needed corrections. Remember, the MnMo readout is for the guidescope camera but needs to be configured in relation to the resolution of your imaging scope and camera. If you're shooting with a longer focal length than your guidescope's, the MnMo needs to be set to a smaller number.

Recalibrate only if necessary. If your mount reports the declination, you don't need to recalibrate when you move to a new target. If your setup is permanent, or the same every time out, and you orient the guide camera reasonably close to the last time you calibrated, you can save the calibration and use it again — you don't need to calibrate initially or recalibrate for a new target or after a meridian flip.

Accurately input your camera and guidescope parameters. Be sure of the focal length and guide-camera pixel size. This will give you a tremendous amount of feedback as to how well your setup is guiding. Note that you can set the History graph to measure corrections in either pixels or arcseconds. Setting this to arcseconds makes the graph readout appear much worse than if set to pixels, even though the guiding is exactly the same. Set it to arcseconds so you can see how you are really doing in relation to your imaging rig's resolution.

Align your autoguiding camera. While *PHD2* doesn't need the autoguider camera aligned with right ascension and declination axes to do its job, it does help you when diagnosing problems after a night of imaging. If stars are trailed east-west, there is a problem in right ascension. If stars are elongated north-south, the issue is in your declination guiding. Aligning your guide camera makes it easy to determine where the problem resides.

Interpreting the readouts. RMS (root mean square) is a mathematical average of the guiding accuracy that gives you an indication of how well the guiding is performing. You can judge it in relation to the seeing. For high-resolution work under excellent seeing with top-end equipment, your RMS should be about ¼ of the FWHM (full-width, half-maximum) you hope to achieve. When imaging with the shorter focal lengths found on camera lenses, guiding requirements are much more lax.

In Closing

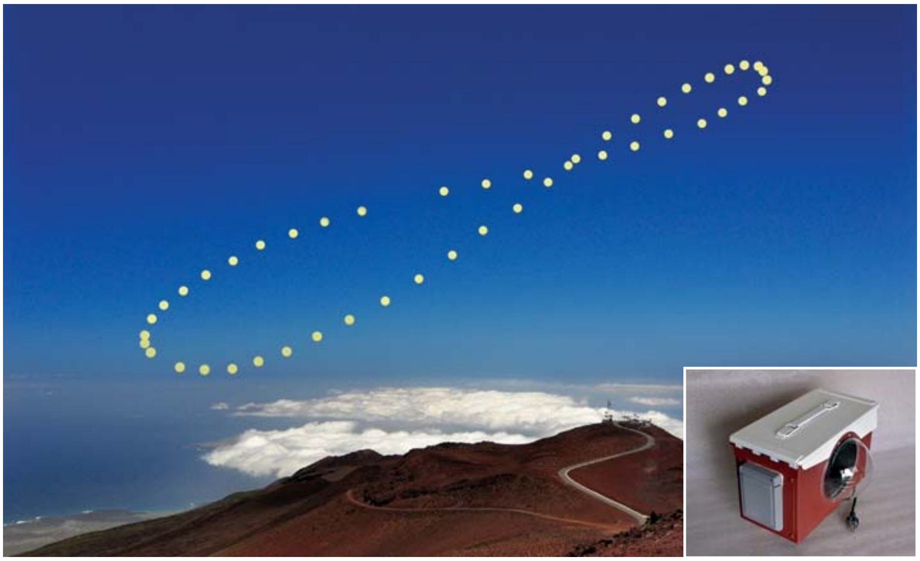
Autoguiding can significantly improve your astrophotos by allowing you to shoot longer untrailed images — and more of them — to achieve a much better signal-to-noise ratio. Autoguiding with *PHD2* frees you from the tedious chore of having to do it manually.

Remember, however, that the map is not the territory. The ultimate judge of your guiding should be the size and shape of the stars in your images. It doesn't matter if you have 0.25 arcsecond of total RMS guiding error if your stars aren't round in your light frames. Likewise, if your stars are tight and round in your lights, and the history chart looks like a foreboding mountain range, don't obsess about this. Simply tell your scope to push here, dummy!

■ Contributing Editor **JERRY LODRIGUSS** has been photographing the night sky for more than four decades.

A Foolproof Analemma Box

This project practically guarantees good results.



▲ Rob Ratkowski's first analemma shot over Haleakala Observatory on the island of Maui. Even there, clouds blocked two key images. *Inset*: The camera box sealed up and ready to go.

IN DECEMBER it's traditional to look back over the year and consider what you've accomplished. Amateur astronomer Rob Ratkowski of Maui, Hawaií, will have little trouble doing that. He has photographic evidence of a year-long project: shooting an analemma.

An analemma is the figure-eight pattern that the Sun makes in the sky when photographed at the same time periodically throughout an entire year. It's a visual representation of the way the Earth's axial tilt and orbital eccentricity interact during a trip around the Sun. It's also very difficult to photograph.

To get a pleasant spacing between Sun images, you need to take a photo at least once a week. That's more than 50 shots, and every one of them has to be just right. For starters, you need to aim the camera at *exactly* the same spot in the sky for every shot. That means either building a dependable mount where you can set the camera each time and know it's pointing at precisely the same place, or mounting the camera permanently for the entire project.

You also need to take your photographs within a minute or so of the same time of day or the images will be out of place. This requires being very punctual or using a timer to take the photos for you.

Rob chose the latter option in both cases. He explains his reasoning: "In my case easy access was the issue. The camera is a 45-minute drive up Haleakala from my home, but by having it automated I just download every couple months and then composite the files. Having a location nearby and a place to bring your camera and have it be exactly aimed for a year is convenient if you can do it, but it takes planning."

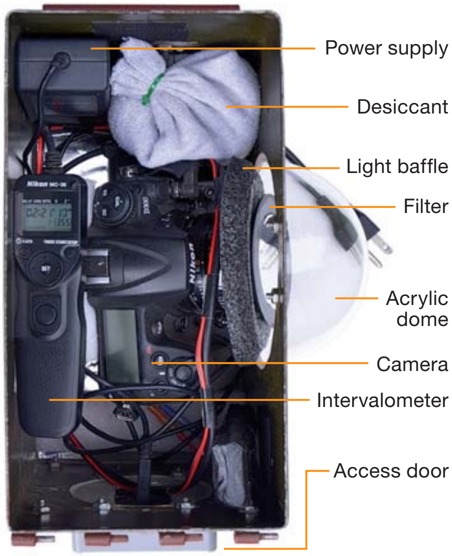
Not surprisingly, aim is at least as vital as timing. An analemma is 47° long (twice the Earth's 23.5° tilt) and 7.7° wide, so you need to make sure the whole thing will fit in your frame. You also need to decide what time of day to trigger the shutter. Early morning or late afternoon analemmas will be reclining on the horizon. A noon composition will stand up straight like a bowling pin. Rob says, "It's mostly planning and knowing where to aim the camera. The aim is critical for a nicely framed image."

The foreground image is arguably just as important as the analemma itself. You don't want just a swirl of spots in a blue sky; you want it over something cool. Rob works as a laser range safety officer at Maui's Haleakala Observatory, so the choice for him was obvious. He was able to place his camera on the roof of a satellite ranging trailer looking westward. His 5:10 p.m. exposure time places the analemma right over a secondary peak of the volcano.

To protect the camera — a Nikon D300 with a 20-mm f/2.8 lens — for an entire year, Rob placed it inside an ammunition box with an acrylic bubble in the side for the lens to look through. The box also contains the power sup-

▲ Rob with his analemma camera box

ALL IMAGES BY ROB RATKOWSKI



▲ Here's everything needed to shoot an analemma undisturbed for months on end.

ply to keep the camera running for an entire year, an intervalometer to trigger the shutter at the correct times, insulation, desiccant, and a USB cable to download the images.

Rob discovered early on that his intervalometer was running fast. That would have distorted his analemma into a Spirograph section, not joining up again at the end of the year, so he had to reset the intervalometer every two months, which he says was "a real PITA to do."

Also, he learned that opening the case to hook up the USB cable when he downloaded images risked disturbing the camera's aim, so his later camera emplacements use an external weatherproof USB port.

Later emplacements? Oh, yeah. Analemmas are like just about any other aspect of amateur astronomy: Once you start in, you're hooked. Rob has a second camera going on a Kihei rooftop, and a third overlooking Haleakala Crater. And he already has this one, his first, as not just a proof of concept but a beautiful image in its own right.

For more information on the analemma camera box, contact Rob at **ratkwski@gmail.com**.

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

"No photo I have ever seen compares to the spectacle of seeing the diamond ring with the naked eye or through binoculars. It was beyond magnificent!"
— Richard Friedman, West Orange, New Jersey

◁◁ PORTUGAL SUNSET
Tom Zaranek
"While vacationing in Alvor, Portugal, I took this partial solar eclipse just before sunset." *Canon EOS Rebel T3i, ISO 320, 55-mm lens, f/5.6, 1⁄800 second.*

△ DIAMOND RING
Rion Kussow
Partial cloud adds to the drama of totality's end as seen from Franklin, North Carolina. *Nikon D3000, ISO 400, 300-mm lens, f/4, 1⁄80 second.*

◁ PICTURE PERFECT
Tom Wachs
A large tree provides dramatic foreground during totality from Seneca, South Carolina. *Nikon D610, ISO 200, 18-mm lens, f/8, 1⁄10 second. (Partial phases: 85-mm lens, f/8, DayStar filter, 1⁄500 second every 4 minutes.)*

"Once totality began I was overwhelmed and just forgot about the camera in my trembling hands. The coolness of the air, the sound of the cicadas, and nighttime in the middle of the day were just awesome!"

— Debra Williams Spegal, Humboldt, Tennessee

△ CHALLENGING WEATHER

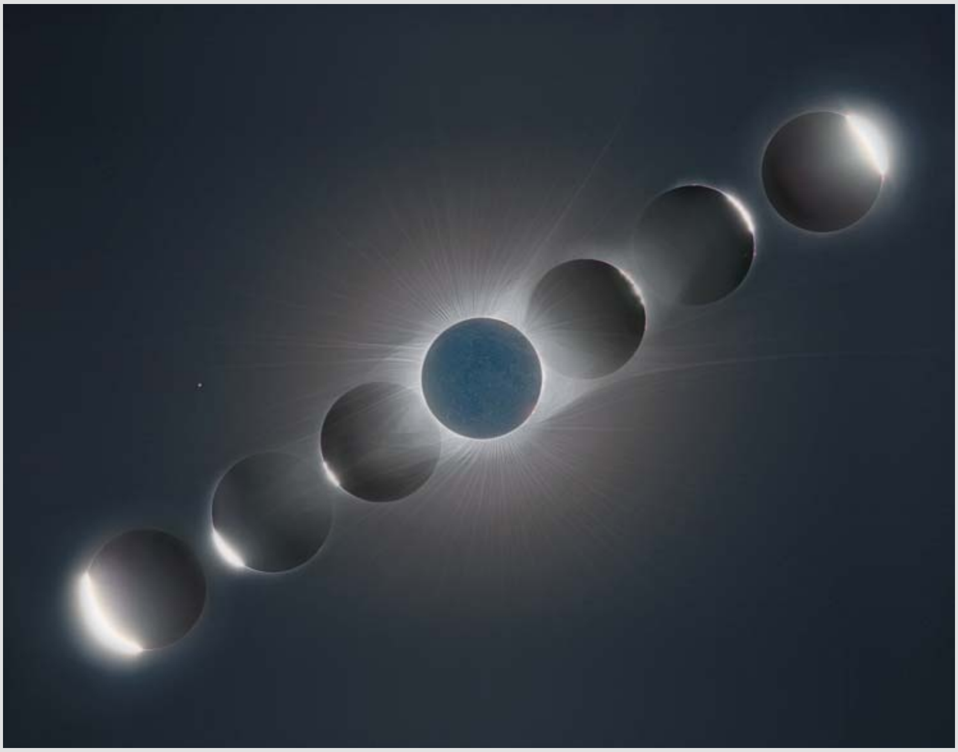
Jim Schaff

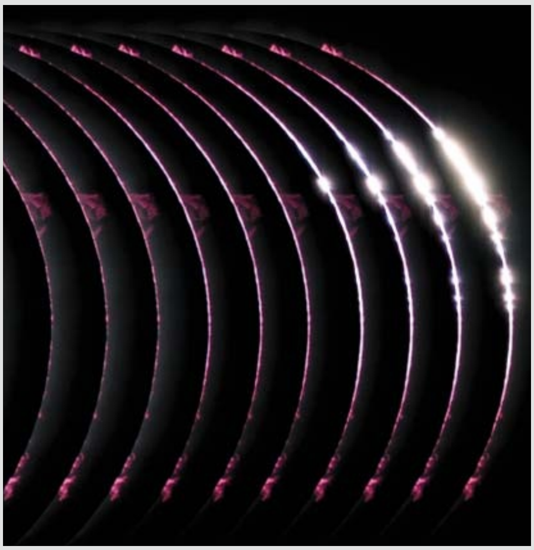
A lucky break appeared in the clouds during totality just west of Wilber, Nebraska. *Canon EOS 5D Mark IV, ISO 400, 16-mm lens, f/2.8, 1/100 second.*

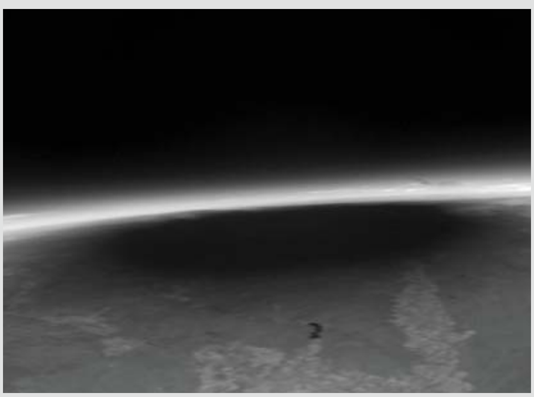
▷ CRESCENT-DAPPLED GROUND

Pardner Wynn

Leaves in a tree-filled yard acted like thousands of pinholes, yielding a plethora of crescent Suns on the ground below. *iPhone 6s Plus, ISO 50, 4.2-mm lens, f/2.2, 1/15 second.*







△ 5 MINUTES OF MAGIC

Damian Peach

Hodges, South Carolina, was the location for this exquisite composite from near second contact (at left) through third. *Canon EOS 6D, ISO 100, TMB 80-mm apo refractor, f/6, 1/4,000 to 5 seconds.*

◁ BEADS & PROMINENCES

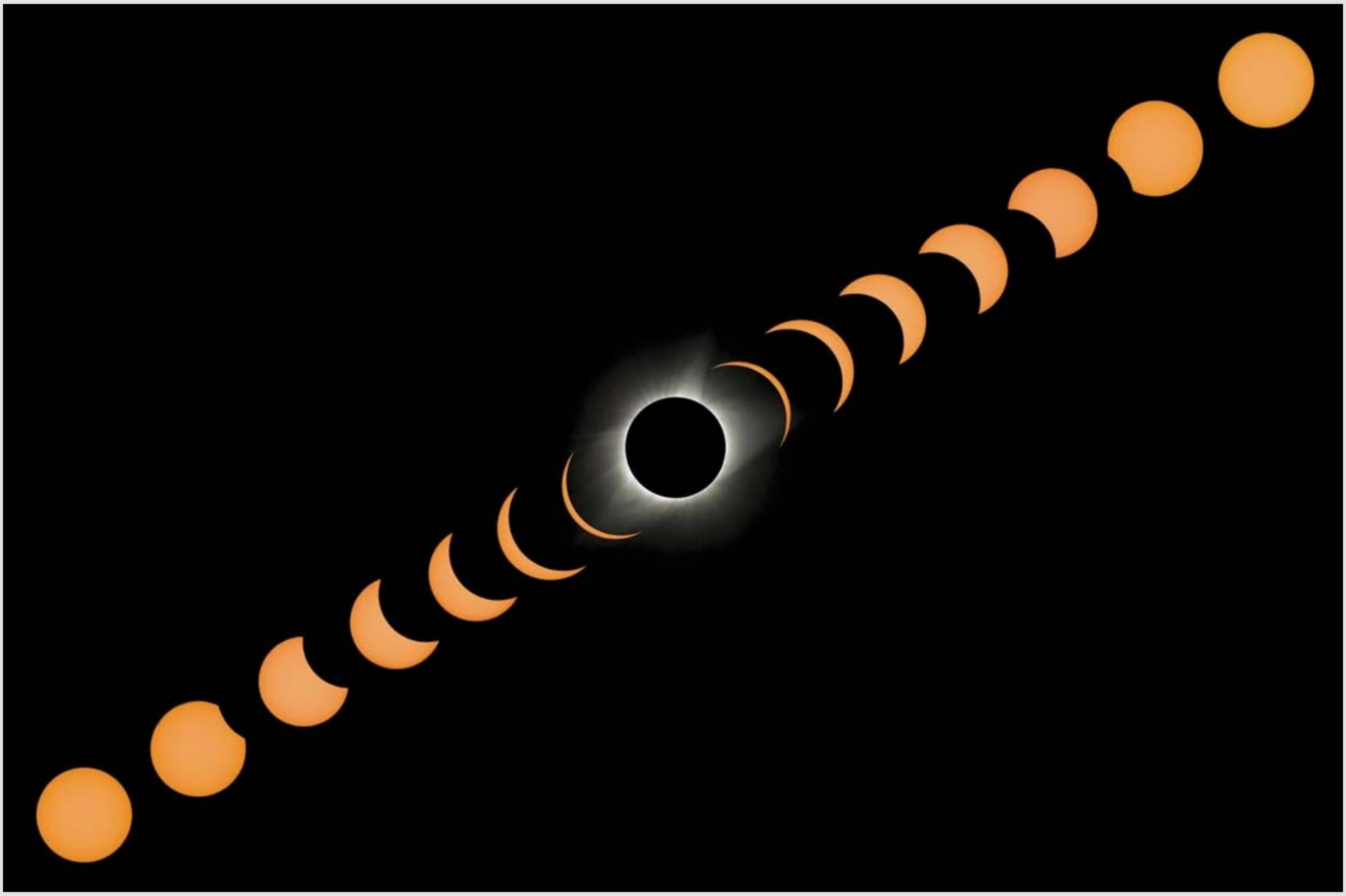
Philipp Salzgeber

Dramatic prominences, crimson chromosphere, and Baily's beads all vie for attention during this sequence shot at third contact. *Nikon D750, ISO 400, 300-mm lens with 2× teleconverter, f/8, 1/2,500 second, 1 second apart.*

◁ VIEW FROM ON HIGH

L. Paul Verhage

A balloon-borne camera captured the Moon's shadow from an altitude of 45,000 feet above the Oregon-Idaho border. *Mobius ActionCam, ISO 145, 2.5-mm lens, f/1.8, 1/30 second.*



△SOUP-TO-NUTS SEQUENCE

Ron Phillips

Clear skies prevailed in Old Hickory, Tennessee, for this 3-hour-long series from first to fourth contact. *Nikon D3, ISO 400, 200-mm (zoom) lens with 1.7× teleconverter, f/8, 1⁄10 (totality) and 1⁄400 second (partial phases, Thousand Oaks filter).*

◁FEAST FOR THE EYES

Chris Cook

Long streamers enriched the corona's naked-eye appearance, which this image from Madras, Oregon, comes close to matching. *Canon EOS 6D, ISO 200, 600-mm (zoom) lens, f/6.3, ¼ second.*

◁GETTING IT ALL

Alson Wong

An high-dynamic-range (HDR) composite reveals exquisite detail in the corona's complex array of streamers and the Moon's face aglow with earthshine. *Nikon D7500, ISO 100 and 200, Borg 77-mm apo refractor, f/6.5, 1⁄1,000 to 2 seconds.*

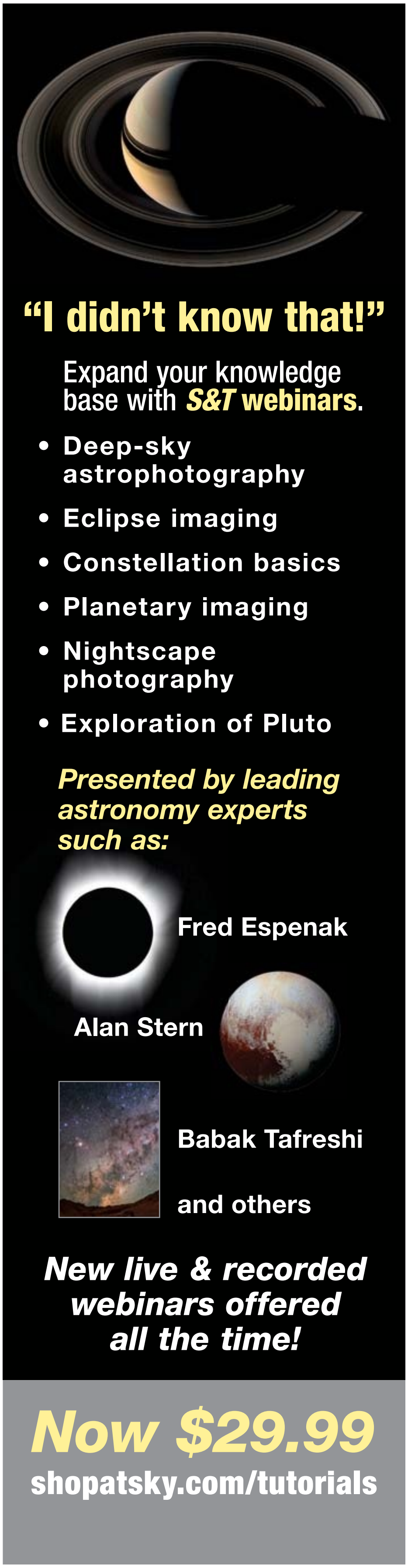
Gallery showcases the finest astronomical images submitted to us by our readers. Send your best shots to gallery@skyandtelescope.com.

△ 360° OF MIDDAY "TWILIGHT"
Ryan Guzy
The relatively narrow path of totality created dramatic lighting all around the horizon and a planet-studded sky overhead that wasn't especially dark. *Ricoh Theta S camera, ISO 1000, f/2, 360° panorama of 1⁄30-second exposures.*

"An epic 12-day trip of 2,930 km, two Canadian provinces, three American states, and a broken refrigerator, all in the pursuit of the Moon's shadow at Madras, Oregon."

— Andrew & Blythe Lowe, Calgary, Alberta

• Visit **skyandtelescope.com/online-gallery/solar-eclipse-2017-pictures** for more of our readers' eclipse photos.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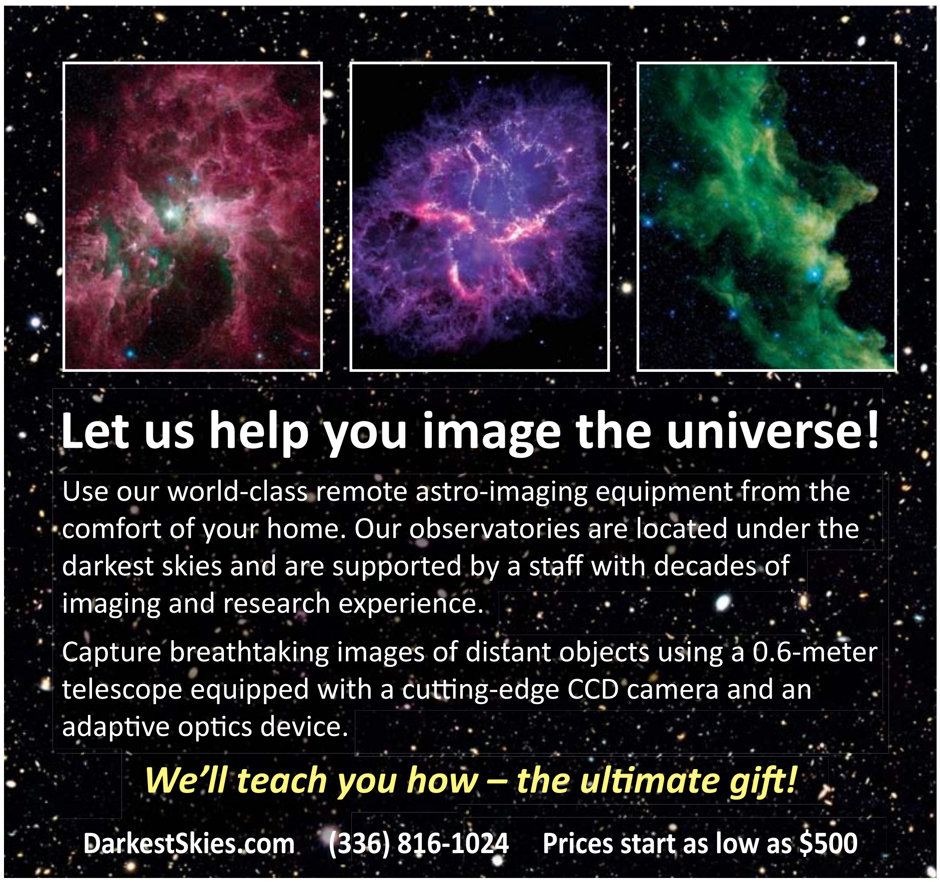
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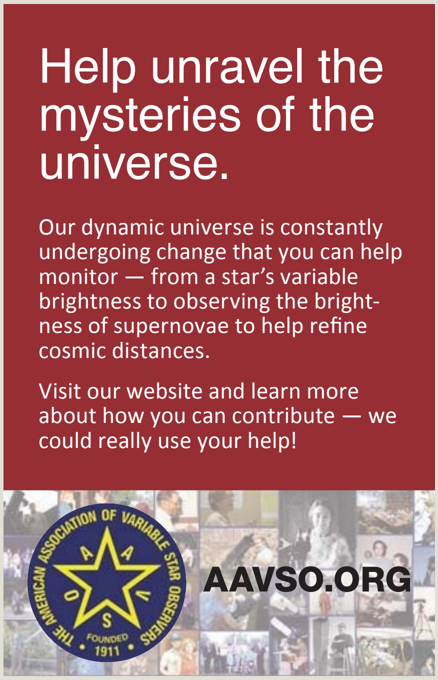

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The Family Telescope

Even though I'd conceived of and built it, who was I to consider it my instrument?

IN THE EARLY 1960S, when I was about 12 or 13 years old, my older brother brought home a book that described the amazing things one could see with a telescope. This slim volume included instructions for building a 6-inch reflector, which would show such wonders as the moons of Jupiter and the rings of Saturn. Ordinary people with ordinary tools could create it, the book promised.

I'd thought telescopes were constructed by experts and sold for a mint, so I was fascinated by the idea of crafting one myself on the cheap. Together with the Edmund Scientific catalog, this little book was all I needed to do some serious dreaming.

My first telescope comprised a 25-mm objective lens, an eyepiece, and a tube made of black construction paper. I fashioned a beautiful mount with my Erector Set. This little scope provided fine views of the Moon and the Pleiades, and it gave me a yearning for something bigger and better. Aperture creep, anyone?

I wasn't adventurous enough to grind my own mirror, so I started saving my paper-route earnings in order to buy a ready-made one. By downsizing the 6-inch mirror to a 4¼-inch, the parts became affordable. I purchased the mirror, along with a very simple focuser, a secondary mirror, a finder mount, and two eyepieces from Edmund Scientific. The tube was a stovepipe, and for the azimuth bearing I co-opted a pair of pipe fittings. Everything else was made from recycled wood and hardware-store items.

Without my dad's help, the project wouldn't have gone far. He devoted numerous Saturdays to assisting me. My father had a keen sense for cost-cutting. As a mechanical engineer, he knew that a $2.50 cast-iron pipe flange would work just as well as the $15 brass flange the plans recommended. The blueprints called for hardwood legs for the tripod; we used softwood left over from other projects. To make the mount, we cut up a leaf from an old oak table.

My enthusiasm for astronomy must have rubbed off on other people. I took the pipe fittings to a machine shop to get them drilled and tapped. I expected to pay a dollar for the work, but for his efforts the machinist wanted only a copy of the plans!

When we finally began using the telescope, it performed very well. My parents and four siblings enjoyed looking at the Moon, the planets, and the Pleiades. For my part, I loved to aim at a random area in the Milky Way and slowly move through the star field.

After the initial excitement wore off, my family rarely came out to look through the telescope. I misunderstood this to mean they didn't care about it. Years later, they were horrified to learn that I'd given it to a friend. They considered it to be theirs as much as it was mine. This, I realized, is why they'd always referred to it not as "John's telescope" but rather as simply "the telescope," meaning the *family* telescope.

I knew I had to do the unthinkable and ask for it back. Fortunately, my friend was more than happy to return it, and I felt that I was back in good graces with my loved ones.

On a recent Christmas, we had a pleasant day with our children, who are now adults with little ones of their own. After dinner, the weather was mild and the Moon full — a perfect moment to introduce a new generation to . . . the family telescope.

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