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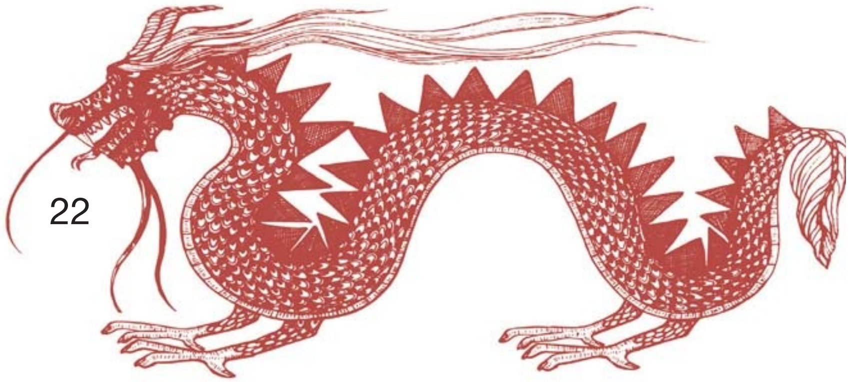

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VOL. 134, NO. 2

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Eclipse Day's Big Unknown

AS WITH SO MANY celestial events, the degree to which we know *precisely* what will happen when the Moon covers the Sun on August 21st is noteworthy.

We're certain of just how long the Moon's shadow will drape across our planet's surface, from its initial touchdown in the North Pacific to the time it lifts off and returns to space not far from West Africa: 3 hours, 13 minutes. When the umbra, or that part of the shadow within which one would see a total eclipse, first hits the Oregon coast — at more than three times the speed of sound, mind you — the local time will be 10:16 a.m. At the moment it leaves South Carolina behind, accurate clocks in that state will read 2:49 p.m.

Detailed maps and tables reveal how long totality will last at any given spot along the umbra's path — to within a fraction of a second. Want to pinpoint the very acreage from which you'd experience *greatest duration* (longest-lasting totality) or *greatest eclipse* (where the axis of the Moon's shadow slices closest to Earth's center)? Sure thing. You'll find the first about 10 km (6 miles) from Carbondale, Illinois, the second 144.4 km southeast of there near Hopkinsville, Kentucky.

In short, we grasp the particulars of this imminent spectacle inside and out.

Yet there's one salient datum that no one can calculate ahead of time: the total number of people who will turn out for this rare happening.

The Moon on the U.S. Postal Service's new eclipse stamp appears from the black disk (left) when touched by the heat of a fingertip.

Will highways into and out of the path of totality clog with traffic, or will they be largely open in case eclipse chasers need to sprint toward an opening in the clouds? Just how jazzed will the millions of folks be who are not in the path of totality but who will still see a deep partial event?

The press has tirelessly publicized this total eclipse, the first to cross the contiguous U.S. in a century. We ourselves have published multiple articles, including several in this issue; a web portal with links to dozens of eclipse resources (**skyandtelescope.com/2017-eclipse**); and our special publication, *America's 2017 Eclipse*, which you can find now on newsstands and in **shopatsky.com**. But despite all the hoopla, we just won't know how fired up the American populace is until the big day itself.

Meantime, you can help get the word out. Tell your family and friends, members of your community, anyone who will listen. Naturally, none of us wants to be stuck in gridlock on August 21st. But with careful planning, we can all relish what those who've witnessed a total eclipse would swear is the most astonishing celestial event visible with the naked eye.

Peter
Editor in Chief

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Dark Matter Matters

Monica Young's "Spirits of Our Galaxy's Past" (*S&T:* April 2017, p. 22) clarified for me the point that dark matter actually exists as clouds of gravitationally condensed concentrations rather than as diffuse clouds of evenly distributed matter surrounding galaxies. So, assuming that baryonic dark matter interacts with normal matter through gravity, wouldn't these concentrations interact with light the same way that normal matter does, basically acting as gravitational lenses? If so, what wavelengths would be ideal for its detection, and could a survey determine dark matter's distribution around either our galaxy or more distant ones?

David Britz
Rumson, New Jersey

Monica Young replies: *I agree that gravitational lensing should be a great way to detect dark matter clumps. So I checked with Frank van den Bosch, a dark matter substructure expert at Yale University. Here's his response (in part):*

"Detecting substructure via gravitational lensing occurring in the Milky Way will be extremely hard. Typically you want your 'lens' (in this case the substructure) to be roughly halfway between the observer (us) and the distant 'source' galaxy that is being lensed. Since most galaxies are much farther away from us than any substructure in the Milky Way, we wouldn't expect the latter to cause any measurable lensing of background galaxies."

That said, we could try to detect substructures around other galaxies. So far observers have only detected large structures, and as far as I (and van den Bosch) know, none of these are totally dark matter. However, a small number of dwarf galaxies have been found by their image distortions. But if the technique can be refined, then it's only a matter of time before we start probing smaller masses and finding substructures that have no stars and only dark matter.

In Defense of Science

I feel compelled to express my sincere gratitude for Peter Tyson's timely and inspirational essay "This Is, and No Mistake" (*S&T:* May 2017, p. 4). As a longtime reader, I understand and appreciate that *Sky & Telescope* is an educational and scientific publication that is and always has been apolitical. Its occasional forays into the world of politics are never to promote any one political agenda. The only goal is to inform the readership as to policies that affect the future of astronomy and all its allied scientific disciplines. Your detailed explanation of the tenets and processes behind the scientific method — and how adhering to these disciplines has allowed us to discover not only a useful body of knowledge but also certain "incontrovertible truths" — touched just the right nerve at just the right time.

Michael Swanson
Houston, Texas

Given your readership, I was kind of expecting an editorial like yours. Thanks for that. It means a lot to me.

Marcello Rasparini
Mol, Belgium

I thought I detected a whiff of politics, a mention of "fake news," in the editorial of May's issue. If *Sky & Telescope* goes political, this 30-year subscriber will drop you like a hot potato. It is that simple. I used to subscribe to both *S&T* and *Astronomy* magazines. But when *Astronomy* got snarky and political back in the '90s, I canceled my subscription and haven't looked back. Mr. Tyson should keep his opinions to himself. Stay focused on astronomy, okay?

Darrell Mason
Colorado Springs, Colorado

While I always enjoy reading Peter Tyson's monthly editorials, the one about fake news and the scientific method was spot on. I was mesmerized by it. You expressed thoughts that Wendee and I have been thinking for well over a year now. And you even managed to include an appropriate comment by Thoreau, one of my favorite writers. So keep it going. *S&T* has made great leaps forward with you as its editor.

David H. Levy
Vail, Arizona

The truth, the whole truth, and nothing but the truth is a noble aspiration. But your publication is far from living up to it, and you could start improving by looking in the mirror. Your pages repeatedly assert that astronomers have

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"deduced" what goes on inside peculiar stars, black holes, Martian history, and so on, whereas in fact they have come up with explanations that are consistent with most of the observed facts and appear superior to competing explanations. But who's to say that a better explanation might not come along, or that further observations might support conflicting theories?

Astronomers rarely deduce or produce anything incontrovertible. Dark matter and dark energy are not incontrovertible truths. They are ad hoc explanations designed to cover up holes in modern cosmology big enough to drive a galaxy through. Yet for some reason your pages have never pointed that out. You can do better.

Jesse Hobbs
Murfreesboro, Tennessee

Monica Young replies: *Multiple, independent lines of evidence point to the existence of dark matter, and these have led scientists to take it very seriously since the 1970s — seriously enough to spend millions (if not billions) of funding dollars on researching its nature. That said, science doesn't prove ideas true — it can only prove ideas false. And any cosmologist worth his or her salt would agree that dark matter might yet be proven false. In these pages, we attempt to present research in such terms, noting when particular searches have failed and therefore to what extent they have narrowed the parameter space for dark matter's existence.*

Eclipse-Day Finderscope Fix

Looking forward to August's eclipse, I purchased a solar filter for my 90-mm refractor but wanted one for my finderscope as well. So I made one very cheaply, and it works great. All you need is a small length of PVC pipe (available at any hardware store) slightly wider than the diameter of the finderscope. I cut the length so that it barely extends past my mounted finderscope. I made a shim out of electrical tape and glued it to the inside of the pipe so that it could sit flush on the finderscope's front end. Then I taped on a solar filter cut from a pair of eclipse glasses. Now my finderscope solar filter is ready to go!

▲ With a short length of PVC pipe and some "eclipse glasses," you can quickly make a solar filter (seen finished at left) for your finderscope.

CURT BOUDREAU

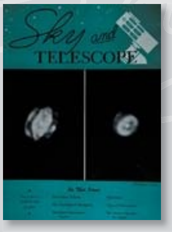
Curt Boudreau
Huntsville, Alabama

FOR THE RECORD

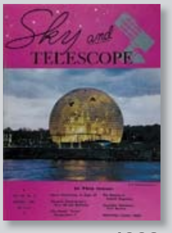
● The front page of the *New York Times* (*S&T:* Jan. 2017, p. 70) is from January 25, 1925 (not October 25th).

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

1942



1967



1992

August 1942

Shadow Bands "[A] peculiar phenomenon seen at an eclipse are shadow bands. These are wavy rippling lines that flit across the landscape at the beginning and end of totality. No doubt they are atmospheric, but the matter is still one under a great deal of discussion. They were noticed as early as 1820 by [Hermann] Goldschmidt. So far they have defied photography [since there] is no emulsion of sufficiently high speed and high contrast to catch them. . . ."

Apart from a poor 1925 image, by the 1970s better film emulsions did on occasion record shadow bands. Today's digital cameras are much better than film at discriminating low-contrast bands on a smooth white screen — a project worth considering on August 21st, when the first total-solar-eclipse track in 99 years sweeps the contiguous U.S. coast to coast.

August 1967

Southern Telescopes "The dream of many astronomers for really large optical telescopes in the Southern Hemisphere moved much closer to reality this spring with the near-simultaneous announcements that 150-inch reflectors will be erected in Chile and New South Wales.

"On April 13th, while he was in South America, President Lyndon B. Johnson announced jointly with President Eduardo Frei of Chile that a 150-inch reflector will be built at the Cerro Tololo Inter-american Observatory near La Serena. . . .

"The second 150-inch reflector [will] be built by the Australian and British governments for an estimated $11,760,000 . . . at Siding Spring Observatory near Coonabarabran in New South Wales."

Back then, the largest telescopes south of the equator were 74-inch (1.9-meter) reflectors at Radcliffe Observatory in South Africa and at Mount Stromlo in Australia. Today no fewer than eight southern instruments probe the sky with apertures from 6.5 to 9.2 meters.

August 1992

Mystery Solved "Jules P. Halpern (Columbia University) and Stephen S. Holt (NASA-Goddard Space Flight Center) have detected pulsed X-ray emissions from Geminga, a point source of high-energy gamma rays that has defied explanation for 20 years. . . . The discovery of a 0.237-second periodicity . . . suggests that Geminga is a pulsar, or rapidly rotating neutron star. . . .

"David L. Bertsch and his colleagues looked for the same periodicity in data from the Compton Gamma Ray Observatory. They found it, clinching the source's identification as a pulsar similar to the ones in the Crab and Vela supernova remnants."

With Geminga's basic nature settled, astronomers still puzzle over its unusual lack of radio emission.

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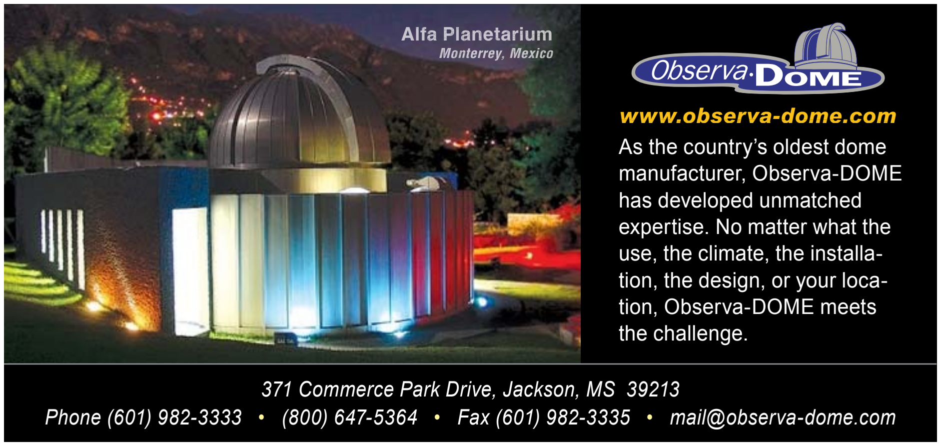

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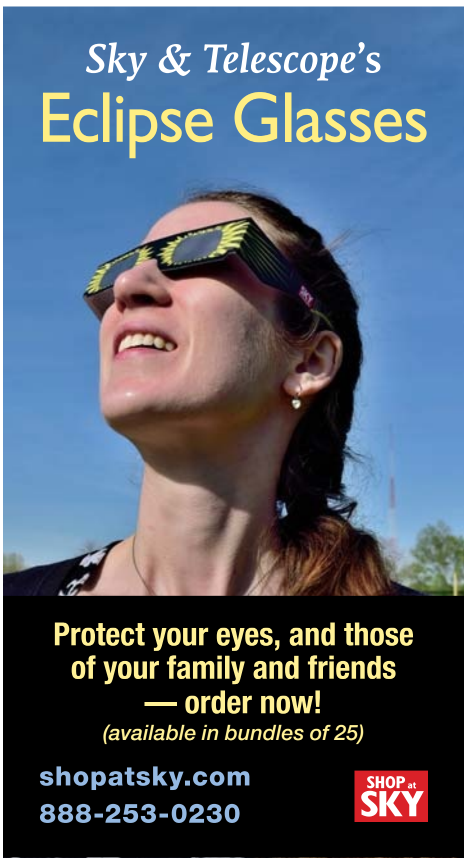

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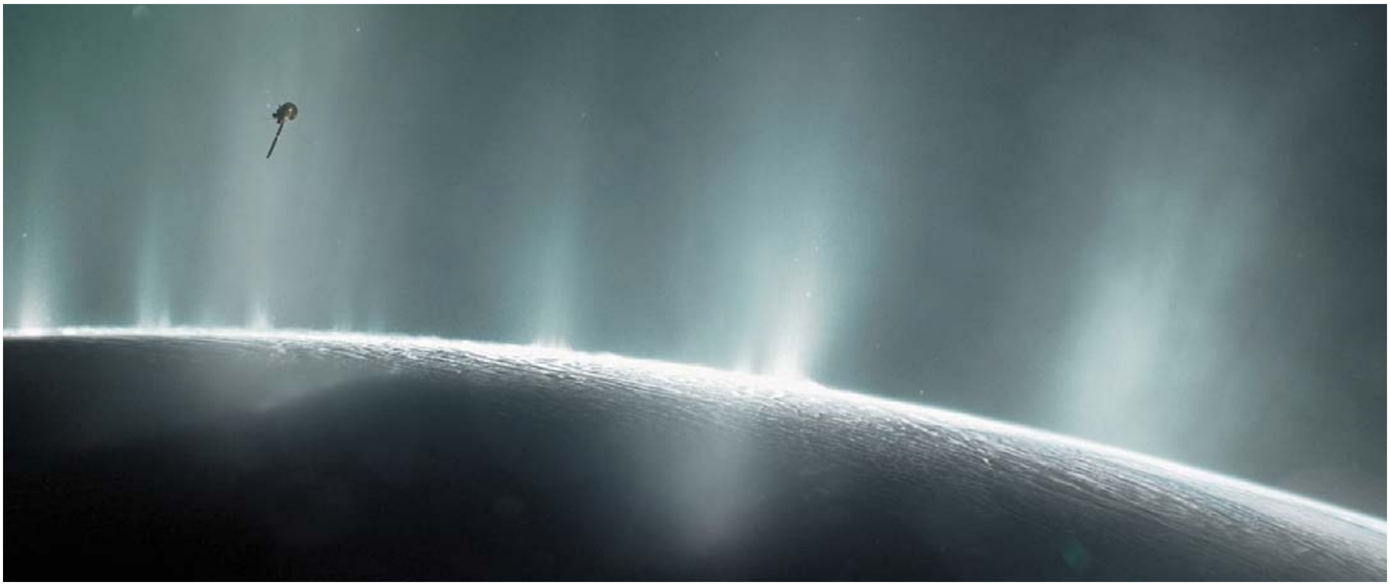

SOLAR SYSTEM

Enceladus's Hydrothermal Heating, Europa's Leaks

▲ This artist's illustration depicts Cassini diving through geyser plumes over Enceladus.

ASTRONOMERS HAVE more evidence that the hidden ocean inside Saturn's moon Enceladus is heated by hydrothermal activity.

The Cassini spacecraft detected geysers spouting from Enceladus's south pole soon after its arrival in the Saturnian system in 2004. Subsequent work showed that these are probably high-pressure leaks from a global subsurface ocean. Chemically speaking, the water in the plumes is tainted from being around rocks. There's ample evidence that this taint is hydrothermally produced, from the salt in the water to silica nanoparticles coughed out by the moon, the latter of which would have precipitated out of hot, rock-interacting water when it cooled.

One of the chemical fingerprints scientists have been hoping to find is molecular hydrogen. Rocks in a hydrothermal environment will leach oxygen from water, producing hydrogen.

In October 2016, Cassini scientists did their penultimate flyby of the moon with the specific goal of finding this hydrogen. Reporting in the April 14th *Science*, J. Hunter Waite (Southwest Research Institute, San Antonio) and colleagues confirm they've succeeded.

The heat in Enceladus's ocean exists because of Saturn. The giant planet tidally wrenches the little moon, and this tidal energy warms and cracks the moon's rocky core. Seawater flows into these cracks, heats up, and comes back out. The inferred temperature is high enough that the process might drive large-scale convection within the ocean.

This new result has crucial implications for astrobiology. Molecular hydrogen's production creates a chemical imbalance in the surrounding seawater, because the hydrogen "wants" to react with other things. Some of the most ancient forms of life on Earth exploit this imbalance by eating hydrogen and metabolizing it, living off the chemical energy and making methane. (Cassini has previously detected methane, CH_4, but don't get too excited: The methane could be produced abiotically, no microbes required.) The new result will help astrobiologists understand the energy available to any potential organisms inside the moon.

Among those speculating about the implications for life, astrobiologist Mary Voytek (NASA) says that the abundant hydrogen and carbon dioxide Cassini sees from Enceladus actually *disfavor* the presence of life in her mind. "If there is life, it's not very active," she surmised in an April 13th press conference. Think of hydrogen like pizza. "When you have stacks of pizza, much like in a graduate school department, it disappears. So we have this buildup of food that's not being used."

In tandem with Cassini's Enceladus result, astronomers also announced news about a second icy moon: Jupiter's Europa. The Hubble Space Telescope had previously detected a hint of geyser activity from this moon, too (*S&T:* Feb. 2017, p. 14). Reporting in the April 20th *Astrophysical Journal Letters*, William Sparks (Space Telescope Science Institute) and colleagues say they've now also seen a possible plume in 2016 data, in the same place as one detected in 2014 — *and* where the Galileo orbiter saw a "heat anomaly" way back in 1999.

The detection is at the limit of what Hubble can record, so it's not unequivocal, Sparks cautions. But like Enceladus, Europa is tidally squeezed due to its parent planet. Maybe that creates some sort of pseudo-plate tectonics, explaining the moon's young-looking surface.

■ CAMILLE M. CARLISLE

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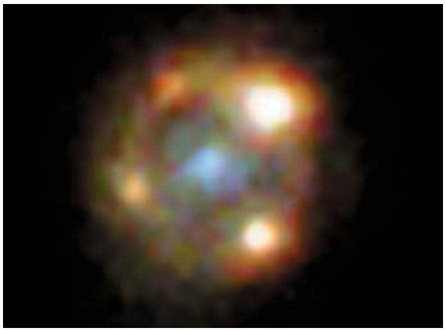
SUPERNOVAE

Cosmic Lens Provides Unique View



▲ Gravitationally lensed SN 2016geu

ASTRONOMERS HAVE discovered a gravitationally lensed Type Ia supernova that will hopefully give them a new measure of the universe's expansion.

Type Ia supernovae are *standard candles*, events with known intrinsic luminosities from which observers can calculate their distances. But initial images of SN 2016geu didn't seem to follow the rules. "I was baffled," Mansi Kasliwal (Caltech) says of her first impression of the supernova. "It was much brighter than it should have been given its distance from us."

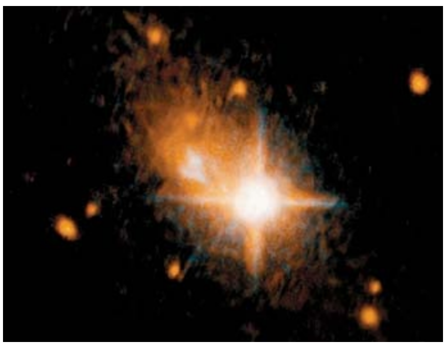
Follow-up space- and ground-based observations revealed three identical supernovae near the first one. Turns out a foreground galaxy's gravity bent and focused the light of SN 2016geu during its 4.3-billion-year journey toward Earth, dialing up its brightness by a factor of 52 and splitting its light into four images just 0.3 arcsecond apart. The result is a classic Einstein Cross (shown), the first ever for a Type Ia supernova.

As Ariel Goobar (Stockholm University, Sweden), Kasliwal, and their colleagues report in the April 21st *Science*, the object could help resolve a debate in cosmology about how quickly the universe is expanding. Researchers using supernovae in the local universe calculate a different rate than those looking at the cosmic microwave background. Since the light from SN 2016geu was split into four images, each of those images took a slightly different path to Earth. The team is now using the delays between the arrival times of the different images to calculate the rate of cosmic expansion: Since the astronomers didn't need to assume any cosmological model to measure the supernova's distance, luminosity, or amount of magnification, they can use that information and the time delays to calculate the expansion rate, instead of vice versa. "It would be neat if we could contribute to resolving that quest," Goobar says.

■ MONICA YOUNG

BLACK HOLES

Gravitational Waves Dethrone Supermassive Black Hole



▲ The starlike quasar 3C 186. Its former host galaxy is the faint, extended object behind it.

ASTRONOMERS HAVE discovered a supermassive black hole not sitting in its customary seat at the center of its galaxy. Gravitational waves from a recent merger might have ejected the object, Marco Chiaberge (Space Telescope Science Institute) and colleagues suggest in the April 2017 *Astronomy & Astrophysics*.

The black hole powers the quasar 3C 186, a brilliant beacon of light emitted by gas that's plummeting down into the black hole. But new Hubble Space Telescope images reveal that the quasar's location is offset from its galaxy's center by about 35,000 light-years, farther than the Sun lies from our galaxy's center. The galaxy itself looks like it's been distorted by a merger.

The team also analyzed the quasar's visible-light spectrum and found that the black hole that powers it is flying away from the galaxy's core at 2,140 km/s (4.8 million mph).

Together, the quasar's incredible speed and its offset from the galaxy's center point to one likely conclusion, the team says: This black hole is the product of two unequal black holes, whose lopsided merger emitted asymmetric gravitational waves that kicked the resulting object out of its galactic home. This isn't the first such candidate discovered, but it's the first to have two signatures of gravitational-wave recoil — previous candidates have shown spatial offset or incredible speed but not both.

There is a chance that the quasar lies in a second, less luminous galaxy that's behind the galaxy that Hubble imaged. Chiaberge's team is pursuing follow-up observations to rule out this alternative.

■ MONICA YOUNG

IN BRIEF

Supernova Discovered in "Fireworks Galaxy"

On May 13th, Utah amateur Patrick Wiggins discovered a core-collapse (Type IIP) supernova in the spiral galaxy NGC 6946 in Cygnus. The explosion, designated SN 2017eaw, is the 10th supernova found in this galaxy in the past century, reaffirming its reputation for fireworks of the grandest kind.

Pegged at magnitude 12.8 at its discovery, SN 2017eaw is located at right ascension 20h 34m 44.24s, declination +60° 11′ 35.9″, which is 61″ west and 143″ north of the galaxy's nucleus and not far from two stars of similar brightness. The galaxy lies on the border of Cygnus and Cepheus, within a degree of the open cluster NGC 6939. It is approximately 15 million light-years away.

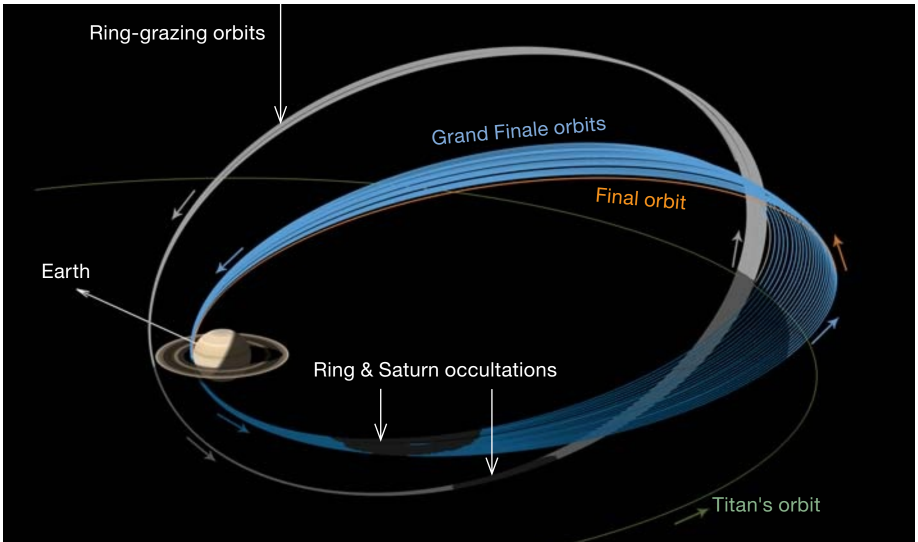
Wiggins found the supernova by comparing a CCD image made on May 14th UT through his 0.35-m f/5.5 reflector with one taken several years ago and another from May 12th. In fact, SN 2017eaw marks his third supernova. The explosion hit peak brightness around May 19th, reaching magnitude 12.6 or 12.7.

■ BOB KING

SUPERNOVA: ESA / HUBBLE / NASA; BLACK HOLES: NASA / ESA / M. CHIABERGE (STSCI / ESA)

MISSIONS

Cassini Finds Empty Space on First Finale Pass



Cassini's Grand Finale orbits (blue) versus previous ring-grazing orbits (gray). The final orbit is in orange. The spacecraft will plunge into the planet on September 15th.

NASA'S CASSINI spacecraft has found less than expected in the gap between Saturn and its rings, a span only 2,000 km (1,200 miles) wide. The craft made the first of 21 daring passes through the gap on April 26th, sailing through at 34 km/s (77,000 mph) with nary a hit from big dust particles.

"The region between the rings and Saturn is 'the big empty,' apparently," Earl Maize (Jet Propulsion Laboratory) said in a press release.

During the dive, the mission team had pointed Cassini's 4-meter (13-foot) main dish forward to act as a debris shield and protect the spacecraft's main structure. Two instruments extended out beyond the dish's edge: its magnetometer and the Radio and Plasma Wave Science (RPWS) detector. Although the RPWS detected hundreds of hits from smoke-sized particles during earlier ring-grazing orbits (see diagram), it only registered a few pings as the spacecraft crossed the ring plane on this first Grand Finale pass, all from particles on the order of a micron across or smaller. These strikes, when converted to an audio format, sound like pops and cracks scattered among the instrument's plasma-wave data.

Although the absence of threatening debris came as a relief for engineers, it was a surprise for planetary scientists.

"It was a bit disorienting — we weren't hearing what we expected to hear," William Kurth (University of Iowa) said in the same release. "I can probably count on my hands the number of dust particle impacts that I hear."

Because of the low debris level, engineers didn't have to keep the main dish rotated forward on subsequent passes through the ring plane, enabling the other science instruments to collect data.

Cassini is now on a looping elliptical orbit around Saturn once every week, which will continue until the mission ends in September. On its following dives it has also sampled Saturn's tenuous outer atmosphere and ring dust and done a series of radio-occultation experiments as the rings crossed the craft's line of sight with Earth. In addition, scientists hope to map out Saturn's gravitational field and thereby probe the planet's deep interior.

■ DAVID DICKINSON

• Listen to the debris Cassini encountered at https://is.gd/grandfinale1.

EXOPLANETS

LHS 1140b: A Super-Earth in the Habitable Zone

The MEarth-South array in Chile

THE MEARTH EXOPLANET survey has nabbed a rocky super-Earth transiting a red dwarf star just 41 light-years away from Earth. The 14th-magnitude star, LHS 1140, is located near right ascension $0^h\ 45^m$, declination −15° 14′ in the constellation Cetus, the Whale.

This is the third exoplanet spotted by the MEarth Project (pronounced "mirth"). MEarth hunts for planets around nearby *M*-dwarf stars using two arrays of eight 16-inch telescopes, one in Chile and the other in Arizona.

The new exoplanet, LHS 1140b, is a tantalizing find. Its star has only 15% the mass of our Sun, and the world passes in front of it once every 25 days as seen from here. Combining MEarth's transit data with radial-velocity measurements from the HARPS survey, Jason Dittmann (Harvard-Smithsonian Center for Astrophysics) and colleagues calculated the planet's characteristics.

The super-Earth orbits a mere 0.09 astronomical unit from its star, less than a quarter the average distance between the Sun and Mercury, yet it receives about half as much radiation as our planet does. With a mass between 4.8 and 8.5 times Earth's and a diam-

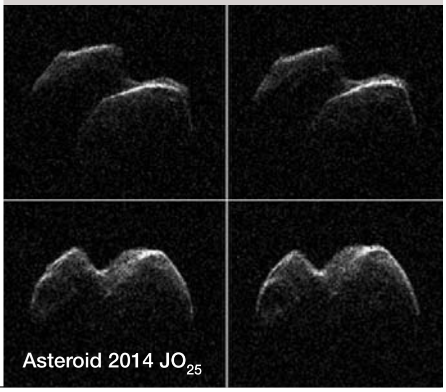
MISSIONS: NASA / JPL-CALTECH; EXOPLANETS: JONATHAN IRWIN

SOLAR SYSTEM

Two-Lobed Asteroid Flies Close by Earth

Asteroid 2014 JO_{25} passed 1.8 million km (1.1 million miles) from Earth on April 19, 2017. This was 4.6 times the Earth-Moon distance, the closest an asteroid 600 meters (2,000 ft) wide or larger has come since 2004. Prior to this, observations from the NEOWISE spacecraft had suggested the asteroid's albedo was 25% — about twice the Moon's average — and thus that it had a diameter of 650 m. But radar images from April's pass (shown below) reveal that, while the object is indeed about 600 m across its short axis, the longest part of 2014 JO_{25} spans a full kilometer. It turns out that the asteroid is twin-lobed, much like the contact-binary nucleus of Comet 67P/Churyumov-Gerasimenko (*S&T:* May 2017, p. 14). Planetary scientists have found about 50 contact-binary near-Earth asteroids with radar, and about 15% of all NEAs bigger than 150 m probably have this shape, notes Shantanu Naidu (Jet Propulsion Laboratory).

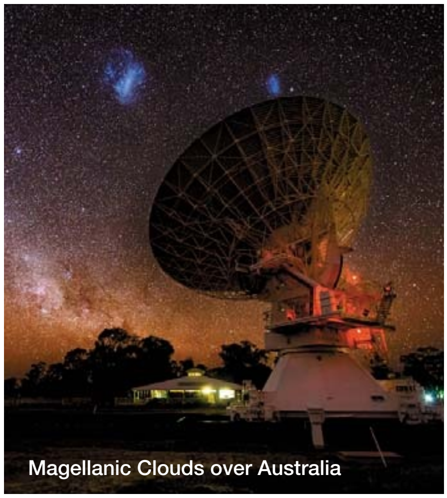
■ DAVID DICKINSON



Asteroid 2014 JO_{25}

GALAXIES

Magnetic Bridge Found Between Magellanic Clouds



Magellanic Clouds over Australia

A MAGNETIC FIELD appears to span the space between the Large and Small Magellanic Clouds, the two largest dwarf galaxies being consumed by the Milky Way.

The field is part of an intergalactic structure called the Magellanic Bridge, a 75,000-light-year-long filament of gas and dust that stretches between the two dwarf galaxies. The bridge is probably a remnant of a close flyby, comprised of gas torn out of both galaxies as they passed by each other roughly 200 million years ago.

To detect the field's presence, Jane Kaczmarek (University of Sydney, Australia) and colleagues observed 167 known radio sources in the same area of the sky as the Magellanic Clouds but located far beyond the galaxies themselves. Some of these radio sources lie directly behind the bridge along our line of sight, while some of them are off to either side of it.

When emission from radio sources passes through a magnetized medium (such as a large gas filament) on its way to our telescopes, the direction of the light waves' undulation changes. The change in this polarization from what it was originally tells us about the strength of the magnetic field inside the intervening medium that caused the change.

From the observations, the magnetic field in the bridge is 0.3 microgauss, a millionth as strong as the field we experience on our planet's surface, the astronomers report in the May *Monthly Notices of the Royal Astronomical Society.* The result confirms the existence of a "pan-Magellanic field" — a magnetic field that spans the entire bridge.

Due to the particular structure of the field observed in the bridge, the authors think it might be a combination of both galaxies' magnetic fields being dragged along with the gas into the tidal structure when it formed.

■ SUMMER ASH

eter of 1.4 Earths, its average density is an incredible 9.1 to 15.9 g/cm^3 — two to three times higher than our world's.

LHS 1140 might prove to be special compared to other red dwarfs with exoplanets, Dittmann argues. Red dwarfs are often maligned as flare stars, but this one is quiet. "We don't see any flares in our years of monitoring it," he says. That's perhaps unsurprising, the team reports in the April 20th *Nature*. The star's rotation period of 130 days, combined with its lack of hydrogen-alpha emission, suggests the star is at least 5 billion years old.

■ DAVID DICKINSON

IN BRIEF

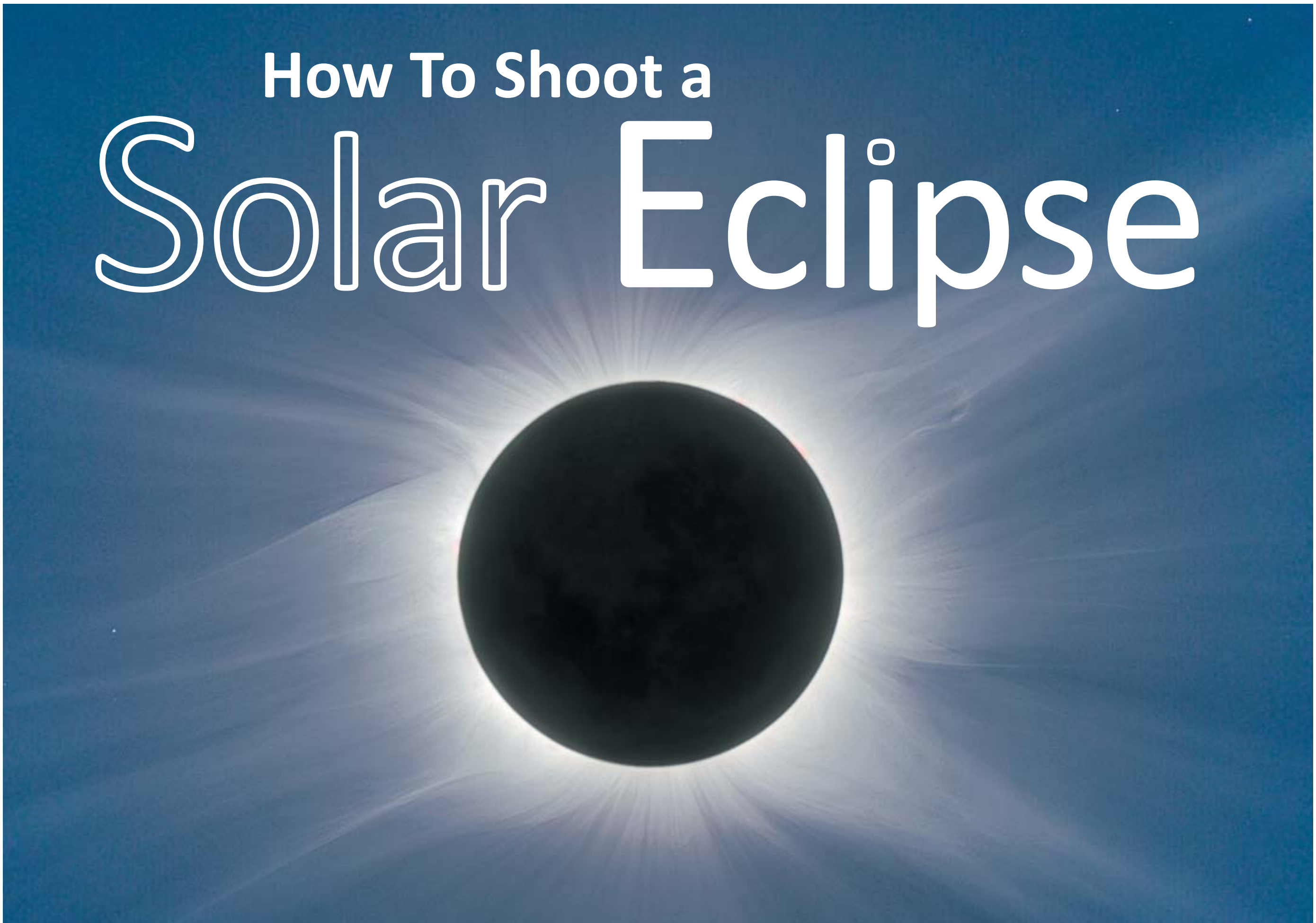
In Situ Formation for Warm Neptune?

Astronomers think the "warm Neptune" HAT-P-26b formed close to its star, instead of migrating inward from farther out. Theorists have long suspected that giant planets could only form in a planetary system's outer regions, where conditions are cold enough for molecules such as carbon dioxide and water to freeze into icy clumps and act as planetary building blocks. The many gas giants found near their host stars have thus been a conundrum. Hannah Wakeford (NASA Goddard) and colleagues used the Hubble and Spitzer space telescopes to measure the spectrum of light passing through HAT-P-26b's atmosphere as the exoplanet transited in front of its star. As the team reports in the May 12th *Science*, the spectrum shows a clear signature of water. Water serves as a representative of all the elements in the atmosphere heavier than helium. The low water abundance suggests the planet's composition is mostly hydrogen and helium — more like Jupiter's than Neptune's. In fact the gas is so untainted by heavier elements that the world must have come together relatively late during the system's formation, meaning it probably formed where it is now, the team concludes.

■ MONICA YOUNG

SOLAR SYSTEM: NASA / JPL-CALTECH / GSSR; MAGELLANIC CLOUDS: MIKE SALWAY

How To Shoot a Solar Eclipse



A little advance planning can help make your pictures memorable.

Avid eclipse chasers have called total solar eclipses nature's most spectacular *predictable* photo ops. And the one occurring in August will likely be the most-photographed one in history.

Having photographed nearly 20 solar eclipses during the past half century, I have witnessed a huge transformation in the techniques used to record these remarkable events. Digital photography, in particular, has made capturing them much easier than in the past. Consider, for example, this photo taken from Easter Island in 2010. It's perhaps my finest picture of totality to date, yet I took it with the simplest camera setup I've ever used for close-up eclipse photos.

That's the good news. The bad news is that today's digital cameras offer such a varied spectrum of features, it's impossible for an article like this to give specific instructions for using all of them. In fact, some of the most useful features that many digital cameras offer for eclipse photography are ones *not* used for daily shooting. You might need to check your camera's manual to find if you even have them. Thus, general suggestions and pitfalls to avoid are the order of the day.

First, a Warning

If this is your first time seeing a total or deep partial solar eclipse, think twice before committing to photographing it. You're going to be in for a shock at how quickly 2+ minutes of totality will pass. In 1980, astronomy popularizer Norm Sperling wrote that no matter how long totality lasts, it always seems like only

▲ **CLASSIC PORTRAIT** This view of the 2010 eclipse seen from Easter Island was captured with a Nikon D700 (full-frame) DSLR camera and a Tele Vue TV-85 refractor, which is effectively a 595-mm f/7 telephoto lens. Nine bracketed exposures ranging from 1/500 to ½ second at ISO 200 were combined to create an image showing detail across a wider range of the corona's brightness than would show in any single exposure.

UNLESS OTHERWISE NOTED, ALL PHOTOS BY DENNIS DI CICCO, ECLIPSE IMAGES PROCESSED BY SEAN WALKER

8 seconds. That concept resonates so well with veteran eclipse chasers that it's become known as "Sperling's 8-second Law."

There's a lot to experience in the minutes surrounding totality, and time spent fiddling with cameras is precious time that you won't have available to absorb other things going on. Besides, in the days (even hours) after the eclipse, the internet will be awash with photos of the event. You'll have no problem obtaining a keepsake photo of the eclipse.

But it's also true that there's nothing like having your own photographs. I like my pictures of the Eiffel Tower more than those on postcards. So if you do have your heart set on shooting your own pictures of the eclipse, let's consider some details.

A Few Ground Rules

- Except during totality and a few seconds before and after, you must always use a *safe solar filter* when looking at the Sun with your unaided eye or through any optical device, including cameras. This includes times when then Moon partly covers the Sun, no matter how much or little.

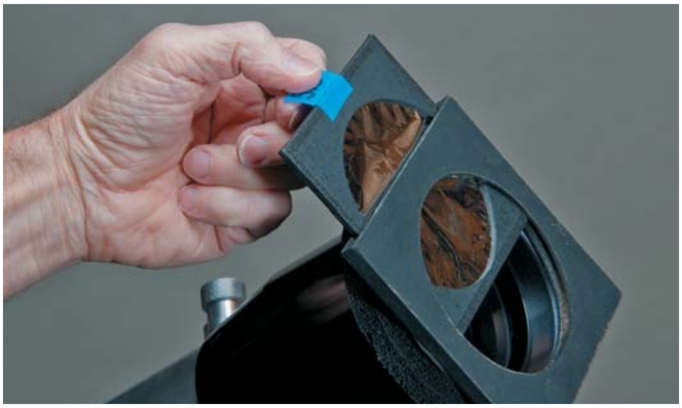
For the best results your filter should be securely mounted so that it can't be dislodged by an accidental bump or a gust of wind — but can still be quickly removed and replaced. Don't treat this issue lightly. The safe, fast, and easy removal and replacement of a filter can make all the difference when it comes to successfully capturing Baily's Beads, the diamond ring, and the Sun's electric-pink chromosphere in the fleeting seconds at the beginning and end of totality.

- The most useful feature for eclipse photography, one often found in today's premium digital cameras, is called *exposure bracketing*. It lets you shoot a sequence of images that automatically vary the exposure by preset amounts without you having to fiddle with settings on the camera other than initially enabling the bracketing function. Not all cameras offer automatic bracketing, but I've met a lot of eclipse chasers who were surprised to learn that it is indeed a feature of their cameras. Check your manual!

Bracketing is useful because there's no single, perfect exposure for capturing everything visible during totality. Short exposures record detail in the brightest portion of the corona near the Sun's limb (which has a *surface brightness* equal to roughly that of the full Moon's face). But this same coronal detail is blown out in the longer exposures needed to capture wisps of the faint outer corona. Even bright features like Baily's Beads and the diamond ring, which record well with a relatively predictable short exposure (see the table on page 18), will benefit from bracketing — especially if there is haze or thin clouds in front of the Sun.

- In addition to capturing different aspects of totality with bracketed exposures, you can also use special image-processing techniques to combine the different exposures and create one image showing detail over a wider range of brightness than is possible with a single exposure. This technique, called *high-dynamic-range* (HDR) imaging, is becoming increasingly popular among everyday photographers, and it's how my Easter Island image was processed.

WATCHING TOTALITY Digital photography has made shooting eclipses much easier than in the days of film. With little to do camera-wise during totality other than hit the shutter release for a bracketed set of exposures, the author could look up and enjoy the sights at the Easter Island eclipse in 2010.



▲ **DIY FILTER HOLDER** One key to successfully capturing rapid-fire events at the beginning and end of totality is the ability to quickly and easily remove and replace a solar filter without disturbing the aim of your photo setup. Cardboard, masking tape, a little hot-melt glue, and black spray paint were all the author needed to make this simple slide-out holder for his Baader AstroSolar filter material.

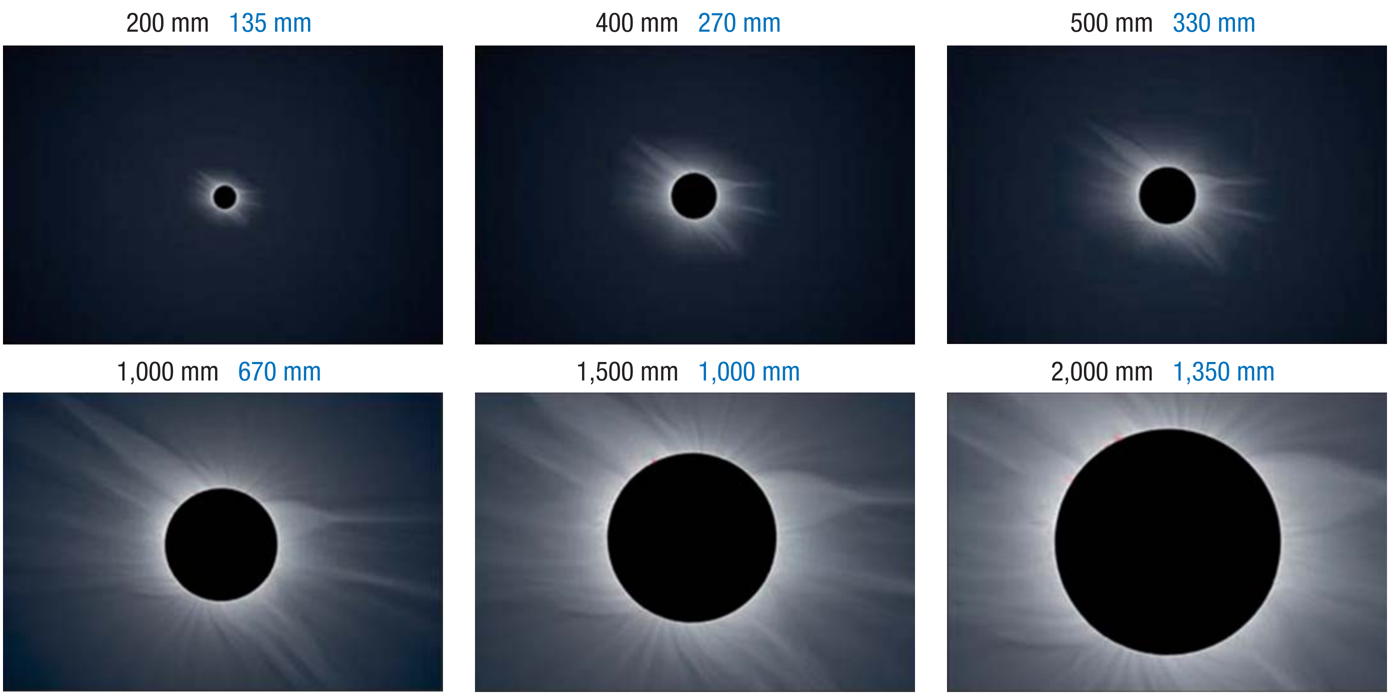
• If your camera has a flash, *turn it off.* Except for very specific photo setups where extra light is needed to illuminate the foreground, a flash offers no advantage for eclipse photography and will almost certainly annoy others around you.
• You should also disable any auto-ISO setting your camera may have. Auto ISO is designed to boost a camera's sensitivity in low-light situations — but at the expense of increasing the digital noise in images. While an eclipse scene might be dark overall, tricking your camera to use a high ISO setting, the detail you're generally trying to capture, including the corona, is bright enough to record well with a lower (and thus low-noise) ISO setting. For most cameras this falls between ISO 50 and 400.
• If your camera can save images in RAW format, use it. Capturing images is only half of the story when it comes to creating an eclipse masterpiece. The other half is image processing, and the best results always come from processing RAW-format images.
• My last generality involves the focal length of lenses. In this article, as well as other material you might encounter, most lenses are stated has having an *equivalent* focal length.

The issue is that many modern cameras use an APS sensor that's smaller than a standard 35-mm frame, essentially cropping and enlarging the view by 1.5×. This is known as the crop factor. If your camera has an APS-format sensor, you need to do the math to determine the real focal length of the lens you want to use to achieve a given field of view. For example, a 200-mm lens on an APS-equipped camera has a field of view equivalent to that of a 300-mm lens on a full-frame 35-mm camera (200 × 1.5 = 300).

Close-Up Photos

Photographs of the partial eclipse, Baily's Beads, the diamond ring, and the chromosphere don't need to cover a field of view much larger than the ½° diameter of the Sun's disk. As such, focal lengths up to 2,000 mm are reasonable. On the other hand, anything shorter than about 400 mm will sacrifice

Lens Focal Length vs. Field of View



▲ **CHOICE OF LENS** To capture coronal detail, you'll need a telephoto lens with a focal length of at least 300 to 400 mm. This comparison shows what some typical lenses will show during totality. Note: The blue values are for cameras equipped with APS (cropped-frame) sensors.

BOTTOM: FRED ESPENAK (6)

▲ **ECLIPSE SEQUENCE** This composite view of the 2008 eclipse seen from China was assembled from a series of exposures made at 5-minute intervals with a Nikon D200 camera and 24-mm lens. The partial-eclipse images were shot through a solar filter, which was removed for a bracketed set of exposures made during totality, recording the foreground, eclipsed Sun, and the planets Mercury (close to the Sun's upper left) and Venus (farther out at upper left). The author's telescope is aimed into a siderostat mirror for shooting the eclipse, which explains its unusual pointing angle.

detail, showing a small image of the Sun in an empty sky.

Much of the same advice that applies to any extreme-telephoto photography also applies to this type of eclipse shooting. You'll need a very solid camera support and some form of external shutter release so you don't have to touch the camera itself to snap pictures. While it's a physical inconvenience to keep tripod legs their shortest when you're trying to aim a camera high in the sky, the increased stability is worth the discomfort. Consider hanging weight like a gallon jug of water from the tripod head to further increase stability.

Critical focus is important at these long focal lengths, and you can't count on a camera's auto-focus to work for eclipses. Fortunately, many cameras have a "live-view" feature that produces a real-time, zoomable image on the camera's viewing screen, which assists with critical focusing. But, here too, eclipses present problems — especially in the final moments before totality when you're trying to make last-second focus tweaks using the shrinking crescent Sun visible through your solar filter. This scene, all black except for the thin sliver of Sun, might cause a camera's live-view electronics to blow out the image on the monitor, making it all but impossible to focus.

Your best bet is to actually shoot a picture and check the resulting image at high magnification on the camera's monitor. Do this when there's still about 5 minutes to go before the start of totality, since it could take a few iterations of adjusting the focus to get everything perfect.

Medium-field Photos

Exposures made with effective focal lengths of 400 to 800 mm are ideal for capturing the full extent of the Sun's corona. Many photographers consider these the classic images of totality.

The key to success here is to bracket your exposures. With ISO settings of 100 to 400 and lenses with f/ratios between f/5.6 and f/11, essentially any exposure from 1⁄1,000 second to 2 seconds will record an interesting aspect of the totally eclipsed Sun. Given the variables of sky conditions and the Sun's corona, it's difficult to recommend which of these exposure times will produce a single "best overall" shot during totality, but my experience shows that the sweet spot is between 1⁄8 and 1⁄60 second at ISO 200 with an f/8 lens. As mentioned earlier, bracketed exposures can be combined to create an HDR image showing an extended range of coronal brightness.

◀◀ **ADDING MAGNIFICATION** A wide variety of so-called zoom-lens accessories for cellphones, such as this 8× model, might seem like a good way to get better shots of an eclipse, but there are still hurdles to overcome, including the need to manually control the camera's focus and exposure with special camera apps. You also need a stable support for the camera, albeit not one that's particularly elaborate!

◀ **SMARTPHONE SUCCESS** A smartphone with a clip-on telephoto lens recorded the Sun's corona and even a pink prominence along the limb during a total solar eclipse seen from Indonesia in 2016. But such setups can be tricky to use.

For shooting the partially eclipsed Sun through an ND5 solar filter at ISO 100, use an exposure of 1/2,000 second with the lens set at f/4, 1/1,000 at f/5.6, and 1/500 at f/8. Again, bracket your exposures.

In the days of film, carefully tracking the Sun's motion across the sky was essential for exposures long enough to record the Sun's faint, outer corona. This was especially true when photographing with focal lengths of 500 mm or more, which magnify the Sun's diurnal motion. But the sensitivity of digital cameras makes such long exposures a thing of the past. My 2-second digital exposures now routinely record more outer corona than I captured with 16-second exposures on film. With exposures this brief, you can get away with not tracking the Sun even when working with focal lengths up to 600 or even 800 mm. Part of the reason is that detail in the outer corona is relatively diffuse and thus not blurred by the Sun's apparent motion during a 2-second exposure.

Wide-field Photos

Despite having an image of the eclipsed Sun too small to show much detail, wide-angle views during totality can be exceptionally dramatic. In addition to including foreground, these images often capture stunning sky coloration along with the brighter stars and planets visible during totality. And some can even show the Moon's approaching or receding shadow. I've had very good success shooting these scenes with lenses ranging from fisheyes that take in the full 180° of heaven's vault up to conventional wide-angle lenses of 24- to 35-mm focal length. I've also had very good success shooting these photos using my camera's auto-exposure setting, but bracketing is still a good idea.

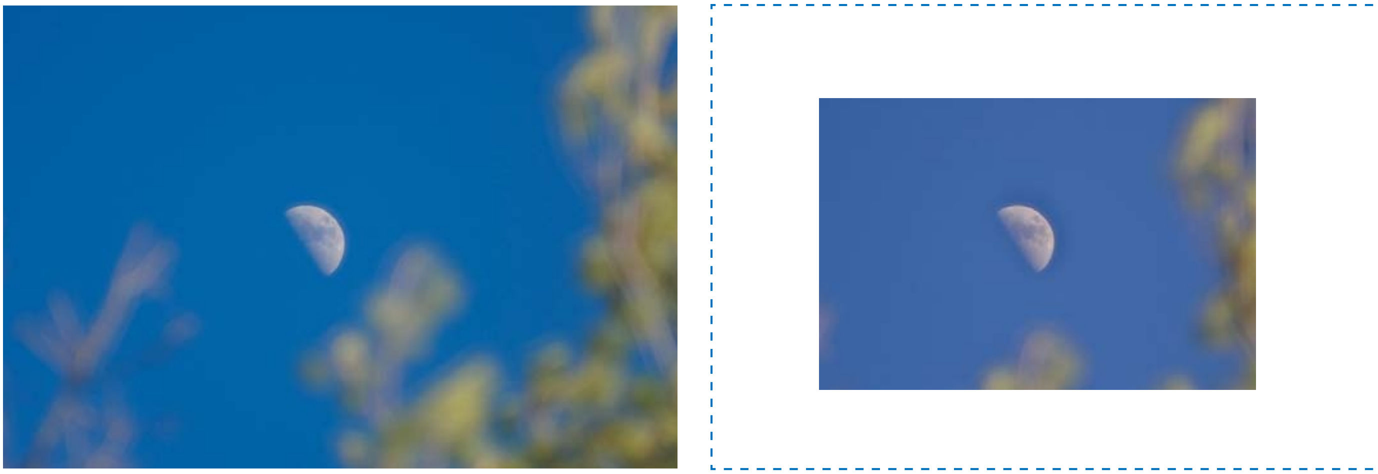
The composite picture on page 17, made during the 2008 eclipse in China, is one of my personal favorites. It was taken with a camera and equivalent 36-mm lens on a small tripod about 25 feet behind me. The camera's internal intervalometer snapped a bracketed set of exposures every 5 minutes for the multi-hour duration of the eclipse. Unlike the days of film when multiple exposures were recorded on a single frame of film and you had to carefully plan shooting intervals beforehand, with digital images you can shoot on short intervals and select frames to composite later. It takes approximately 2 minutes for the Sun to move its own diameter across the sky, so

Best Exposures for Recording the Total Eclipse

f/ratio for ISO 100:	f/2.8	f/4	f/5.6	f/8	f/11	f/16
Baily's Beads*	—	—	1/2,000	1/1,000	1/500	1/250
Diamond ring**	1/1,000	1/500	1/250	1/125	1/60	1/30
Prominences	1/1,000	1/500	1/250	1/125	1/60	1/30
Chromosphere	1/2,000	1/1,000	1/500	1/250	1/125	1/60
Inner corona	1/250	1/125	1/60	1/30	1/15	1/8
Outer corona	1/8	1/4	1/2	1	2	4
Wide-field view***	1/4	1/2	1	2	4	8

* These exposures assume the camera's solar filter has been removed. ** Use longer exposures to capture more corona around the "ring." *** For especially dark horizons, use longer exposures.

SMARTPHONE IMAGE: MARK BENDER



▲ **NO MAGIC** Regardless of the camera body it's attached to, the 420-mm lens used for these shots produces an image of the Moon the same size on the camera's sensor (3.8 mm in this case). But the small sensor on the camera with a 1.5× crop factor [right] captures a smaller field of view than the full-frame camera (left), making it seem like it's a more powerful telephoto — which it really isn't.

images spaced at 5-minute intervals work well for compositing.

If you try a photo like this, keep in mind that you'll want to include a picture made during the middle of totality at your location, so you'll need to calculate the start time of your sequence by stepping backward from this time in increments of your exposure intervals. The only other thing I had to do for my photo was remember to remove the solar filter for the bracketed burst made during totality, and replace the filter quickly afterward.

Use a Smartphone? Yes, But . . .

Experienced eclipse photographers might sneer at the thought of shooting the eclipse with a smartphone's camera. But given that virtually everyone today has one, there will probably be more pictures of the upcoming eclipse taken with phones than with any other type of camera. And I wouldn't be surprised if some, especially ones in the wide-field category mentioned above, turn out quite good. That said, location and luck, more than photographic skills, will likely be the determining factors.

There are two large hurdles to overcome when shooting close-ups with a smartphone: focus and exposure.

Notice that I didn't mention magnification. That's because you'll find a seemingly endless variety of gizmos made to attach cell phones to telescopes and binoculars, not to mention a growing assortment of so-called zoom lenses that clip over your phone's built-in lens. I've tried a handful of them with varying degrees of success, but the best focused and exposed results have always been with terrestrial pictures (think birds on a feeder). These scenes have lighting that's easy for the camera's auto-exposure algorithms to interpret, and they are also filled with detail for the auto-focus to latch on to.

Neither of these exists with close-up views of an eclipse. There are apps, however, that let you control the smartphone's auto focus and exposure. I've used them to photograph the Moon in twilight conditions that will likely mimic the sky during totality at the coming eclipse. They do work, but they may cost you a lot of time that could be better spent enjoying totality. If you are set on trying to shooting the eclipse with a smartphone, get the necessary accessories and camera-control apps well before the event and learn to use them by shooting the Moon or Sun (with an appropriate solar filter) ahead of time.

Moving Pictures

Video brings the added dimensions of motion and sound to eclipse photography, and both can be extraordinarily dramatic. Even years later, playing back an eclipse video and hearing the rising excitement of people around you as you see the shrinking crescent give way to the corona can bring back memories of an eclipse unlike any that a still photograph ever will. But you'll also being paying a price for the advantages that video brings. Views of the corona captured with consumer-grade video devices will lack the dynamic range and overall detail recorded with even relatively simple still photography.

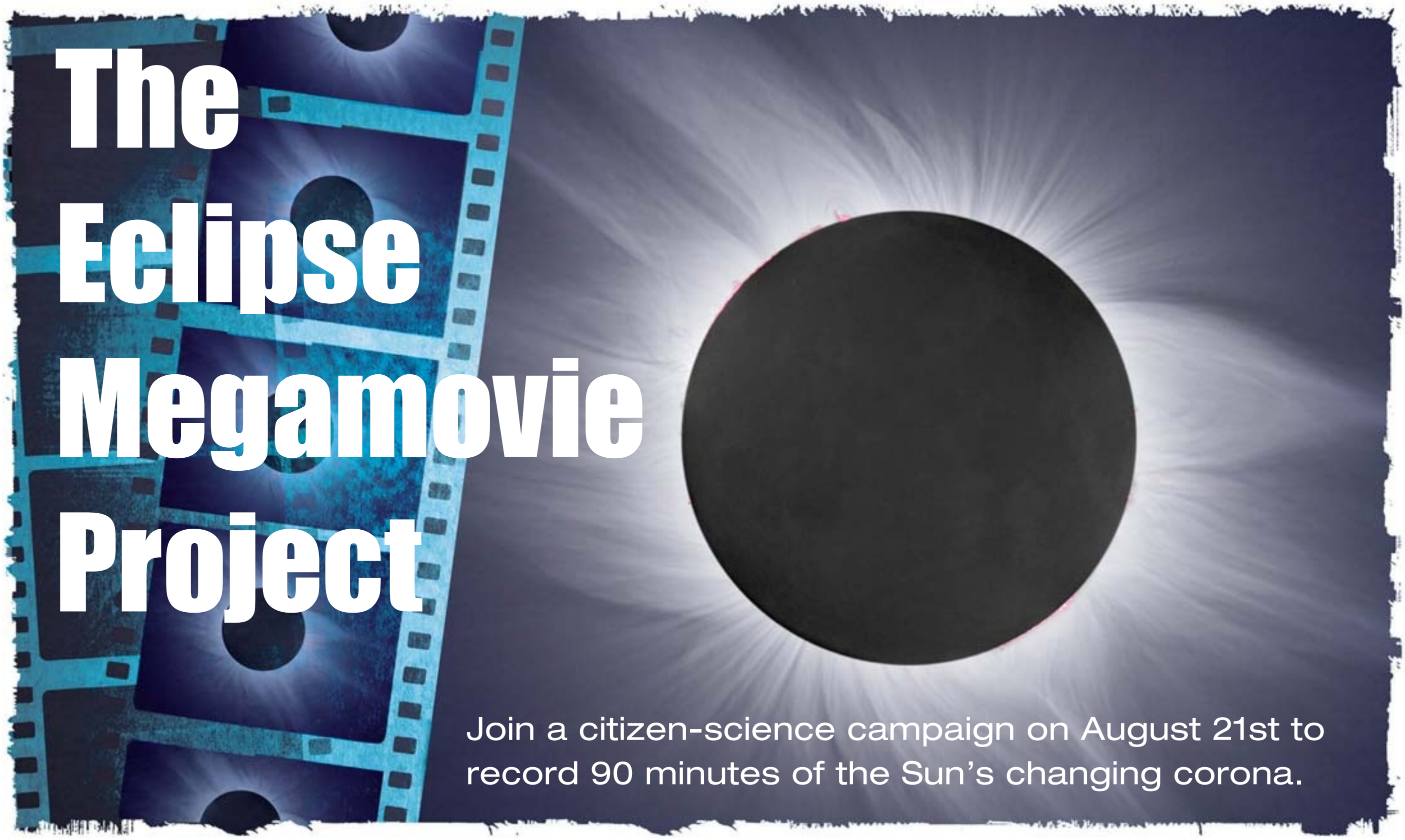
If you do shoot video, most of the same rules mentioned above for still photography also apply. And you should heed my advice about having a safe solar filter that can be quickly and easily removed and replaced. The most dramatic moments to be captured on video are the fleeting seconds at the beginning and end of totality as the Sun's shrinking crescent gives way to Baily's Beads and the diamond ring. You don't want to lose them fumbling with the filter.

Regardless of how you record the eclipse, the best advice is to always to become familiar with your equipment, practice using it, and plan ahead. That way you'll be able to enjoy the event for years to come with treasured memories *and* photographs.

■ **DENNIS DI CICCO** still claims that someday there will be an eclipse that he simply watches and doesn't photograph. This article appears, along with many others, in *S&T*'s special publication, *America's 2017 Eclipse*, available now on newsstands and at **shopatsky.com**.

 by Hugh Hudson & Mark Bender

The Eclipse Megamovie Project



Join a citizen-science campaign on August 21st to record 90 minutes of the Sun's changing corona.

▲ **BUTTERFLY AT MINIMUM** This photo of the March 29, 2006, eclipse shows the solar corona as it looked one sunspot cycle ago. During this last quiet period of solar activity, the corona appeared more extended at the equator than at the poles. The 2017 corona will likely present similarly.

ECLIPSE: LORENZO COMOLLI & ALESSANDRO GAMBARO

As the "Eclipse Across America" rushes toward us, how can we best use such a wonderful opportunity? With totality traveling across the continental U.S. for a full 90 minutes, it will be the longest and best-observed total solar eclipse of the digital era. Watchers will have tools that could hardly have been imagined in 1918, the year of the last cross-country total eclipse in the U.S. For the first time we'll have a chance to record vast numbers of images that continuously track the spectacle from coast to coast.

These images will not just be pretty mementos. A big part of totality's beauty is the Sun's wispy outer atmosphere, the corona. Its delicate tendrils create a breathtaking aura around the blacked-out Sun. Since the corona's appearance changes with time, observers across North America will see slightly different views from their different perspectives.

The corona, much hotter than the Sun's visible surface, is full of waves and flows that are rooted in the Sun's magnetic activity. One key to understanding these ephemeral mysteries lies in time sequences of high-quality images. After eclipse day, we should have many thousands of consecutive glimpses of the corona as it evolves through the long totality — a time when the Moon acts as a celestial parasol, blocking out the bright solar disk and enabling us to see deeper into the seething atmosphere than is possible from Earth at any other time. Nobody has seen coronal motions with such time resolution before.

Variability in the corona will also show us the subtle evolution of our star's "magnetic skeleton," which dictates the shapes that we see. During years of low solar activity, such as this one, the coronal magnetic field resembles that of a simple — but truly colossal — bar magnet. Inside the Sun this field periodically develops twists and kinks that cause sunspots and other magnetic activity to come and go every 11 years in a (mostly) predictable cycle. How will the corona of 2017 compare to the corona one cycle before, as seen above?

Our Plan

The Eclipse Megamovie Project hopes to enlist more than 1,000 volunteers, each armed with digital single-lens reflex cameras (DSLRs), telephoto lenses, and tripods to help unravel these scientific mysteries. The project will stitch together a near-continuous view of totality as the eclipse crosses the country from northwest to southeast. GPS metadata is also desirable for the DSLRs; see **https://eclipsemega.movie** for up-to-date information about equipment and arrangements. Relatively quickly after the eclipse, depending on volunteers' connectivity, an algorithm will stitch together thousands of photographers' images into a movie that spans the full 90 minutes the eclipse spent over land.

However, the core of the Megamovie Project will not be the immediate movie, but the archive of all the observations, taken from many different sources and having many different quirks. Human eyes and brains — mostly those of citizen scientists — will need to dig through these images to spot and measure interesting features and their motions. (The image below shows a remarkable example of this kind of find.) Thus, the Megamovie Project will continue long after the event; its image archive, available for study and curation, will enable all kinds of analyses and discoveries after the fact.

In addition to the DSLR-based part of the project, we're developing a free app ("Megamovie Mobile," available in June for Android and iOS) that will help spectators capture the event at lower resolution. The app will automate the smartphone's camera, ensuring proper exposures during all phases of the eclipse. The app will also use the phones' GPS metadata to obtain precise times for the events at totality's beginning and end, capturing the moments when bits of sunlight peek through valleys along the Moon's rugged limb to create the flashes known as Baily's Beads.

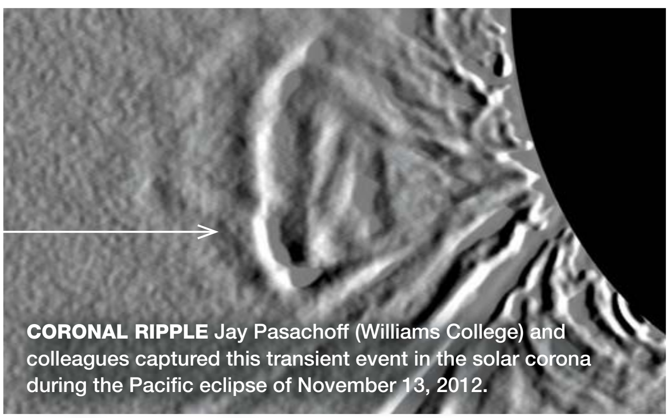
Smartphones on tracking mounts and equipped with cheap external lenses are quite suitable for recording the corona at modest resolution. But even a handheld smartphone with no external lens can serve as a photometer, precisely timing the lunar shadow at any location along the path of totality.

App Adventure in Patagonia

The South American annular solar eclipse last February 26th gave us an opportunity to test the app. Could it actually control the camera, sensing its own GPS location to obtain well-timed images? Coauthor Mark Bender led a small team (James McClean, Andreas Joensen, and Juan Carlos Martínez-Oliveros) to Patagonia in southern Argentina to find out.

Based in the small town of Facundo, the party of four split up to cover the centerline (James and Juan Carlos), the north edge (Mark), and the south edge (Andreas) of the path of annularity. The alpha test version of the app only came together after the team members were in place, but they were able to download it to six smartphones after they arrived. Juan Carlos also deployed his Raspberry Pi camera — a DIY project based on inexpensive components.

As this was an annular eclipse, with no totality, the team could only test geolocation and timing rather than coronal



CORONAL RIPPLE Jay Pasachoff (Williams College) and colleagues captured this transient event in the solar corona during the Pacific eclipse of November 13, 2012.

TOTALITY CARTOON: ECLIPSE MEGAMOVIE PROJECT; CORONAL RIPPLE: PASACHOFF ET AL. *ASTROPHYSICAL JOURNAL*, 13 FEB. 2015

THE MEGAMOVIE: WHAT YOU'LL NEED

- Digital lens reflex camera (DSLR)
- Telephoto or zoom lens, minimum focal length 300mm
- A stable, level tripod
- The ability to identify GPS coordinates and the times, to the nearest second, of your photographs.

imaging. We were hoping to record Baily's Beads, so only very short intervals at the eclipse's second and third contacts were of real interest for the test.

Spreading the team out over a 60-km-long line, with one observer totally isolated in the desert, was tricky using only two vehicles. But the app correctly located the observers' positions and fired off 300 images at the right time, as it was preprogrammed to do. So far, so good.

But then came the drama. The images looked blank!

The adventurers' northern counterparts (Braxton Collier of Ideum, Inc., in New Mexico and coauthor Hugh Hudson in Glasgow, UK) went to bed depressed. But all was not lost. Overnight, Andreas in Facundo took a closer look and realized that we had goofed on the exposure time. The beads were there, they were just underexposed — the app itself had succeeded! (See the data at **https://is.gd/annular_eclipse_2017**).

How to Participate

Google is one of our wonderful partners in this project. In addition to providing the upload portal for participants, Google will algorithmically stitch together the flood of data to generate the Megamovie. To make all of this work, though, we need lots of photographers to join us. If you have camera equipment and plan on being on the path of totality, please head to our website (**https://eclipsemega.movie**), create a profile, and apply to join the team.

Even if you have nothing but a GPS-enabled smartphone, we've designed the app to provide a particularly easy path for your participation. So whatever your level, please join us this August as we explore the solar corona!

■ **HUGH HUDSON** is a solar physicist at the University of California, Berkeley, now living in Glasgow, UK.

■ **MARK BENDER** is a veteran eclipse-chaser, documentary filmmaker, and administrator of Eclipse Across America (**eclipseacrossamerica.org**).

Eyes of the Dragon

FEIRIN / BIGSTOCKPHOTOS.COM

Look the fiery beast in the face as you track down these binocular doubles in Draco.

Observing double stars with binoculars might seem like a crazy pursuit. Many double star observers like to challenge themselves by splitting tight doubles; however, the low magnifications of binoculars put a fairly low cap on what can be split. Still, it's a big sky, with plenty of challenges for every aperture and magnification. I tend to relax a little more when I'm observing binocular doubles. There's no pressure to try and tease out the fine details, as with planetary or deep-sky observing. Just look out and see what's looking back — if there's more than one star, that's mission accomplished.

Double stars come in two types. Binaries are truly gravitationally bound and orbit their common center of gravity, which may well be inside the larger star. In contrast, optical doubles are physically unrelated but coincidentally aligned along our line of sight. I used to be a snob and favored the binaries, as their astrophysical connection made them more interesting to me. But then I read amateur astronomer Stephen Saber's take: "Personally, I prefer the opticals as they are unique to our perspective from Earth. Binaries, on the other hand, can't help but be doubles." So now I'm more omnivorous in my double star observing.

Prepare Yourself

Splitting double stars usually comes down to two things: the visual magnitudes of the stars, and their apparent separation in the sky. Doubles are easiest to split when the two stars are of similar magnitudes — even if the companion star is fairly bright in absolute terms, it can get lost in the glare of a brighter primary. In theory, 35-mm binoculars should reach down to 9th magnitude, 50-mm binos down to 10th, and 70-mm guns down to 11th. In practice, the actual limits are somewhat lower, especially for handheld binoculars.

Apparent separations are the brass tacks of double star observing, as a couple of famous examples will illustrate. At 208″ (arcseconds), the major pairs of Epsilon (ε) Lyrae, also known as the Double Double, are a tight naked-eye split and a nice, wide binocular pair even at 7×. The blue and gold components of Albireo, the most famous color-contrast double, are separated by 35″. The component stars can be separated at 10×, but only just; I usually require 15× to get a clear split. This is where double star observing differs from chasing faint fuzzies — for splitting doubles, the limiting factor is usually magnification, not aperture.

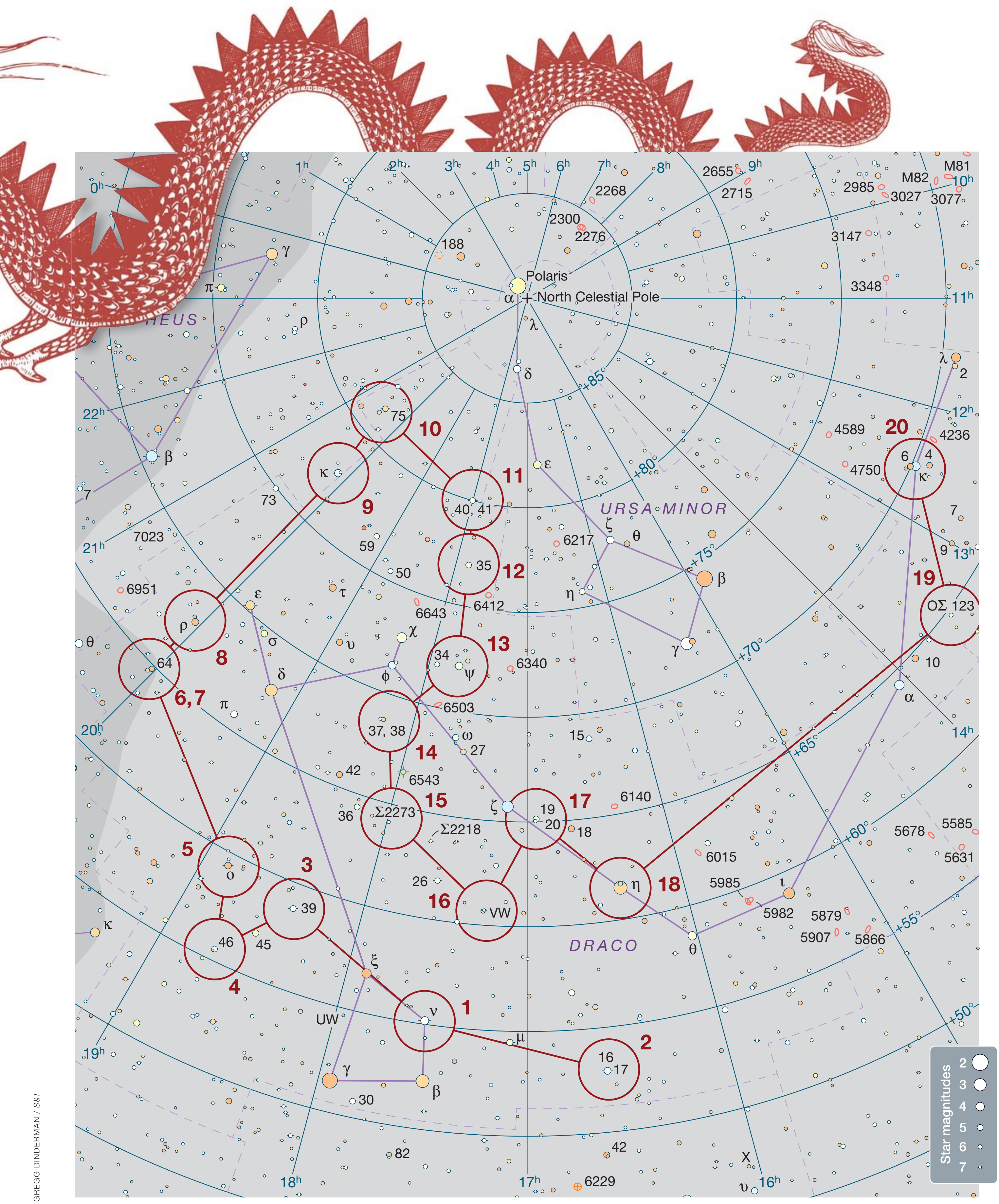
Probably the most vexing question facing the binocular double star observer is whether to mount the binoculars on a tripod or roll freehand. I prefer handheld binos, and I always make my first attempts with them, then mount up for challenging targets. Sometimes just resting the binos on top of the car or against a handy fencepost settles the shakes enough to crack the hard targets.

Enter the Lair

In this tour we'll visit 19 double or multiple stars in the constellation Draco, the Dragon, and one in Cepheus. Most will be easy even in 7×35 binoculars, but a few tight binaries will challenge observers with big, mounted instruments. Whatever binoculars you have on hand, you'll find some targets to push your skills, and hopefully even more to simply enjoy.

We'll start with **Nu (ν) Draconis**, dimmest of the four stars that make up the "head" of the dragon in most constellation figures. Even 7× binoculars will reveal a pair of equally bright stars staring back like a pair of eyes. The effect is particularly pronounced early in the evening in July and August, when the "eyes" are lined up horizontally in the sky. Spooky!

From Nu Draconis, go west and slightly south past Mu (μ) Draconis — itself a telescopic double with a separation of 2.5″ — and onward for 4.5° to find **16** and **17 Draconis**. Like Nu, the stars are about equally bright, so they look like another



GREGG DINDERMAN / S&T

pair of eyes, but unlike Nu, 16 and 17 Draconis are an optical pair, not physically related.

Now, go back east-northeast to Nu and then on, past Xi (ξ) Draconis and on another 4.5°, to **39 Draconis**. With a separation of 89″, 39 Draconis is as widely split as 16 and 17 Draconis, but the two components differ greatly in brightness. The primary shines at 5th magnitude, while the secondary is just brighter than 8th magnitude.

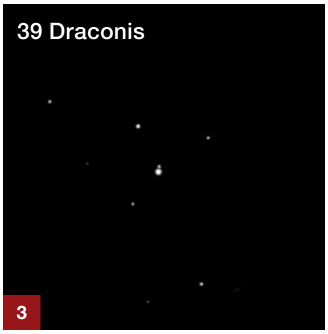
See how 39 Draconis forms a roughly equilateral triangle with 46 Draconis and Omicron (ο) Draconis? The other points of the triangle are also double stars. **46 Draconis** is a nifty optical multiple. A pair of faint companions flanks the 5th-magnitude primary, with all three stars in a straight line. One of the sidekicks has a magnitude of 7.5, the other 8.2. Can you distinguish them based on brightness alone?

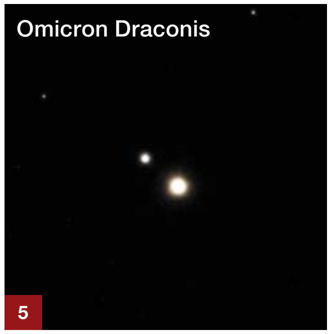
I suspect **Omicron Draconis** will be the first really challenging double on this tour for most observers. It's a tight pair at 37.3″, and wildly uneven, with a difference of over 3.5 magnitudes between the primary and secondary. I'll confess: I had to go to mounted 15×70s to make the split.

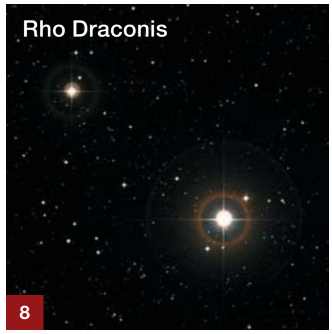
Doubles in the Dragon

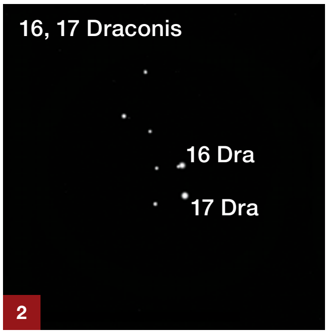
Primary	Companion	Type	Mag(v)	Separation	Position Angle	RA	Dec.
Nu^1 Draconis	Nu^2 Draconis	Binary	4.88, 4.89	62.3″	131°	17^h 32.5^m	+55° 10′
17 Draconis	16 Draconis	Optical	5.07, 5.51	90.2″	13.3°	16^h 36.6^m	+52° 53′
39 Draconis	HD 238865	Optical	5.03, 7.90	88.9″	19.6°	18^h 24.2^m	+58° 49′
46 Draconis	HD 173580	Optical	5.03, 7.46	354″	154°	18^h 43.0^m	+55° 34′
	HD 238925	Optical	8.15	331″	340°		
Omicron^1 Draconis	Omicron^2 Draconis	Binary	4.63, 8.26	37.3″	319°	18^h 51.5^m	+59° 25′
64 Draconis	65 Draconis	Optical	5.23, 6.26	748″	154°	20^h 01.7^m	+64° 52′
65 Draconis	HD 190696	Optical	6.26, 7.94	99″	333°	20^h 02.5^m	+64° 41′
Rho Draconis	HD 191372	Optical	4.51, 6.32	892″	51.5°	20^h 02.9^m	+67° 55′
	SAO 18673	Optical	9.06	138″	315°		
	BD +67 1224	Optical	10.0	150″	153°		
Kappa Cephei	HD 192763	Optical	4.40, 6.98	442″	337°	20^h 08.3^m	+77° 46′
75 Draconis	HD 196565	Optical	5.36, 6.53	197″	282°	20^h 27.1^m	+81° 29′
41 Draconis	40 Draconis	Binary	5.67, 6.01	18.8″	232°	17^h 58.9^m	+80° 00′
35 Draconis	HD 163767	Optical	5.03, 7.53	319″	319°	17^h 48.7^m	+76° 58′
Psi Draconis A	Psi Draconis B	Binary	4.57, 5.59	29.6″	17.1°	17^h 41.6^m	+72° 09′
37 Draconis	38 Draconis	Optical	5.96, 6.78	555″	95.1°	18^h 15.2^m	+68° 46′
Σ2273 A	Σ2273 B	Binary	7.28, 7.63	21.4″	283°	17^h 59.3^m	+64° 09′
VW Draconis	HD 156890	Optical	6-7, 6.88	238″	311°	17^h 16.7^m	+60° 39′
19 Draconis	20 Draconis	Optical	4.88, 6.44	375″	157°	16^h 56.1^m	+65° 07′
Eta Draconis	HD 148374	Optical	2.73, 5.67	662″	352°	16^h 24.3^m	+61° 29′
ΟΣ 123A	ΟΣ 123B	Binary	6.63, 7.03	69″	147°	13^h 27.6^m	+64° 39′
Kappa Draconis	4 Draconis	Optical	3.89, 5.03	0.66°	207°	12^h 34.2^m	+69° 42′
	6 Draconis	Optical	4.94	925″	24.6°		
	HD 109822	Optical	6.54	880″	47.9°		

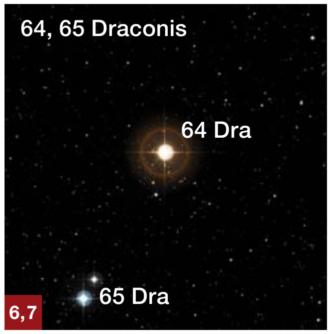
Angular sizes and separations are from recent catalogs. Visually, an object's size is often smaller than the cataloged value and varies according to the aperture and magnification of the viewing instrument. Right ascension and declination are for equinox 2000.0.











Now zoom 10° northeast to locate **64 Draconis**. It's not a true double, but it does make a very wide (748″) optical pair with nearby **65 Draconis**. At 5th and 6th magnitudes, 64 and 65 Draconis should be visible, and splittable, with the naked eye — can you do it? 65 Draconis is itself an optical double with the considerably dimmer HD 190696. Try comparing the brightnesses of 65 Draconis and 39 Draconis. Their companions are equally dim at magnitude 7.9, and at comparable separations, but 65 Draconis is over one magnitude dimmer than 39 Draconis.

About 3° north of the pentagon formed by 64 Draconis and its companions is bright **Rho (ρ) Draconis**. Any binoculars should show a 6th-magnitude optical companion about ¼° northeast of Rho. You'll need 10× or 15× binos, probably mounted, to pick out the 9th- and 10th-magnitude outriders lurking about 150″ to either side of the primary.

Just about 10° due north of Rho you'll find the wide optical double **Kappa (κ) Cephei**. I'm cheating a bit here, since Kappa isn't actually in Draco, but it's on the way and it's pretty, so there's nothing to lose by looking. With

1 Scott MacNeill of Frosty Drew Observatory, Charlestown, Rhode Island, captured this image of Draco's penetrating "eyes" with fifty 30-second exposures through a Canon 60D camera mounted on a 6-inch Ritchey–Chrétien telescope.

2 The view through a 200-mm (8-inch) Maksutov-Cassegrain telescope at 222× revealed a hint of blue to the otherwise white *B*9 dwarf stars, 16 and 17 Draconis. Most images and sketches of double stars are made with telescopes, rather than binoculars, so don't be disappointed if your view doesn't match the resolution of published images. Use the images here to judge the relative brightness and position angle of the binary components.

3 The primary of 39 Draconis is a main-sequence *A*-type dwarf star, while the secondary is an *F*-type. Higher magnifications may reveal a bit of color in the secondary, but in binoculars both will appear white, with the 5th-magnitude primary shining more brightly.

4 The 5th-magnitude star 46 Draconis is a blue-white main-sequence *A*-type. The optical companions are both *K*-type dwarf stars. The 8th-magnitude star HD 238925 lies northwest of 46 Dra while 7th-magnitude HD 173580 lies almost the same distance from 46 Dra to the southeast.

5 Two *G*-type main-sequence stars compose Omicron Draconis. Observers usually perceive the primary as a golden or orange yellow, with the secondary described as lilac or turquoise. You'll need to break out big binos to split this one, as the components are separated by a mere 37.3″.

6, 7 The *M*-type star 64 Draconis isn't a true double, but forms a wide optical double with 65 Draconis. Although many *M*-class stars are quite dim, *M*1 super giants like 64 Dra should be visible to the naked eye. 65 Draconis is *G*-type main-sequence star.

8 Look for the 6th-magnitude optical companion to Rho Draconis about ¼° northeast of the primary. If you have big binos on your tripod, try for the 9th- and 10th-magnitude companions northwest and southeast of Rho.

9 Wander north of Rho Draconis to find the *B*9-class double star, Kappa Cephei.

1: SCOTT MACNEILL; 2 & 3: MIKE WOOD / WEBB DEEP-SKY SOCIETY; 5: BLAKE NANCARROW; 4, 6, 7, 8, 9: POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY

Are you ready for further adventures?

Find more Draco double stars at **https://is.gd/DracoDoubles.**

4th- and 7th-magnitude stars separated by a generous 442″, Kappa Cephei is an easy and pretty split. Kappa itself is a true binary, but at 7.2″ it's best left to telescopes.

Another 4° north brings us to **75 Draconis**. It's an easy, uneven optical double, with the primary about three times as bright as the companion.

Now swing 6° west-southwest to **40** and **41 Draconis**, a pair of yellow main-sequence stars that constitute a true binary system. At a separation of 18.8″, they're the tightest pair in this tour. I had to use mounted 15×70s, and even then they were barely split. Good luck!

Go south 3° to pick up **35 Draconis**. It's a wide split at 319″, and the magnitude-7.5 companion is just dim enough to be a challenge in handheld 10×50s. My eyes aren't particularly sharp, so you may do as well or better with small binos.

Another 5° along the same line will bring you to **Psi (ψ) Draconis**, a binary. With magnitudes of 4.6 and 5.6, the components are bright enough, but the separation is only 29.6″, so this is another tough target for anything less than mounted 15× binos.

Now cut southeast, right into the belly of the beast, to find **37** and **38 Draconis**, probably my favorite double in the whole constellation. Sixth-magnitude 37 Draconis is an orange *K*-type star. 38 Draconis is a bit dimmer at magnitude 6.8, and as a *B*-type giant it's very blue. The two stars are a wide, easy split at 555″, and their colors will show in almost any instrument.

Since that split was so easy, how about another challenge? Find double star **Struve 2273** (Σ2273) approximately 5° south-southwest of 37 and 38 Draconis. This binary pair of

10 The cool, dim, yellow-white *G*9 giant sun 75 Draconis, in the northernmost reaches of the constellation, makes an easy optical double with its neighbor, HD 196565, a yellow-orange *K*0 star.

11 The yellow *F*7 main-sequence dwarf stars 40 and 41 Draconis form a true binary. The separation between them is slight, just 19″, so you'll need big binos or a small telescope to split these two. This sketch shows the view through a 6-inch f/8 Newtonian reflector, so don't be disappointed if you aren't able to make a split here.

12 With a separation of 319″, the blue-white subgiant 35 Draconis should be a much easier split than 40 and 41 Draconis, but the 7th-magnitude companion may be difficult to pick up in small binoculars.

13 In the 19th century, Admiral William Henry Smyth described Psi Draconis as "a neat double star on the Dragon's back," considering both stars to be "pearly white." Double star expert Sissy Haas considers it a "showcase pair . . . mildly unequal . . . very lemony white in color."

14 Orange *K*-type 37 Draconis and blue *B*-type 38 Draconis make a striking pair in the binoculars. Color perception is highly subjective, particularly when directly comparing two stars, so don't be surprised if you perceive colors differently than your observing companions.

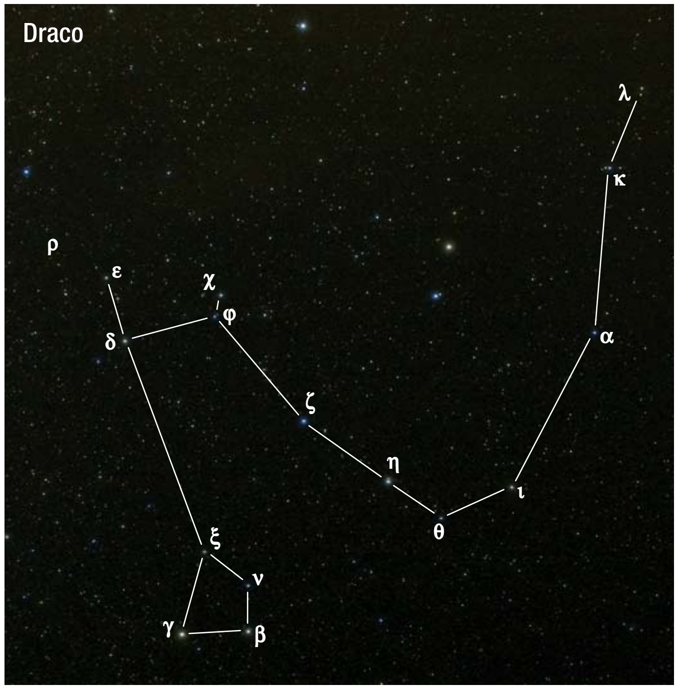
15 Sissy Haas described Σ2273 as "an ordinary but pretty couple." The component stars for this binary are of almost equal magnitude (7.6 versus 7.7), but their separation is only 21.4″. You'll need your best binoculars for this pair.

16 The brightness of VW Draconis ranges from 6th to 7th magnitude, but its period is so long — 6 months — you won't notice much variation on a night-to-night basis. But for a challenge, you can track its appearance over time as compared to its optical companion, HD 156890.

17 Although of unequal brightness, 19 and 20 Draconis are both yellow-white, hydrogen-fusing main-sequence stars. 19 Dra is a dim *F*8 dwarf, while 20 Dra shines as a more intrinsically luminous *F*2 dwarf.

10, 12, 14, 15, 16, 17: POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY; 11: JEREMY PEREZ; 13: GABRIELE VANIN

See how many of them you can pick out with your naked eyes, and then use your binoculars ...



7th-magnitude stars is separated by only 21.4″, so bring your big glass, your "A" game, or both.

Another 6° southwest and you'll find the variable star **VW Draconis**. Its brightness ranges from 6th to 7th magnitude over a period of six months, so sometimes it's as dim as its optical companion, HD 156890, which lies a generous 238″ to the northwest. HD 156890 is also a binary, with a 10th-magnitude companion 9.8″ away — a definite challenge for those with large, mounted binoculars.

Now hop 5° northwest, just across an imaginary line connecting Zeta (ζ) and Eta (η) Draconis, to pick up **19** and **20 Draconis**. With magnitudes of 4.9 and 6.4 and a separation of 375″, they're an easy split. 20 Draconis is another binary, but at a brutally tight 1.1″ it will take an excellent scope and excellent skies to split.

18, 19 & 20: POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY

18 Like Psi Draconis, Eta is one of the dragon's "backbone" stars. It forms a wide optical double with 5th-magnitude HD 148374.

19 Double star OΣ 123 lies about 4° west of bright Alpha Draconis. Its components are uneven in brightness (magnitudes 6.6 and 7.0). Can you see a difference?

20 Kappa Draconis is a blue-white *B*6 giant about 500 light-years from Earth. *K*3-type 4 Kappa lies slightly more distant at 550 light-years, and class *M*4 6 Kappa lies even more so at 580 light-years.

THE SUMMER DRAGON
Above right: Draco bends and stretches between Ursa Major and Minor, its head pointing toward the heel of Hercules. The northwest corner of the dragon's head is marked by the perfectly matched double star Nu. The origin story of this constellation is a bit murky but may be traced to Graeco-Roman mythology. Draco could represent Ladon, the dragon killed by Hercules during his 12 labors, or it may depict a twisting beast tossed to the heavens by Minerva during the battle between the Giants and the Olympian gods.

Eta Draconis is one of the "backbone" stars of the dragon asterism, and a wide optical double. Its companion is a 5th-magnitude star, HD 148374, 662″ away on a nearly direct line to the celestial pole. This is an easy catch in binos and should be a pretty straightforward split with the naked eye as well.

For our last two stops, we're going to zoom far to the west, into the dragon's tail. Find Alpha (α) Draconis and sweep 4° west to **Otto Struve 123** (OΣ 123). It's a binary pair with a fairly generous separation of 69″. See if you can detect the subtle difference in brightness between the two stars.

Our final stop has lots to offer — it's the optical multiple star anchored on bright **Kappa (κ) Draconis**. Kappa is flanked by two 5th-magnitude stars, 4 Draconis ⅔° to the south-southwest and 6 Draconis ¼° to the north-northeast. Another ¼° to the northeast lies magnitude-6.5 HD 109822. See how many of them you can pick out with your naked eyes, and then use your binoculars to sweep down to Lambda (λ) Draconis at the tip of the dragon's tail. The whole stretch from Kappa to Lambda is packed with neat little asterisms and optical doubles.

Observing Programs

As usual, I've only hit a few of the best and brightest here. If you have an interest in observing double and multiple stars with binoculars, I recommend the Binocular Double Star and Advanced Binocular Double Star programs offered by the Astronomical League. The observing lists are freely available online (**astroleague.org/observing.html**). Wonders await you — go look the cosmos in the eyes.

■ In addition to touring the celestial dragon, Contributing Editor **MATT WEDEL** goes on dinosaur digs to hunt the real thing.

In the Dark About Dark Matter

Astronomers' favorite candidate for the universe's invisible matter is running out of places to hide.

Maybe we should be looking for something else.

SEEING THE UNSEEN This composite image reveals the distribution of matter in the galaxy cluster Abell 1689. Using the observed positions of 135 lensed images (smears) of 42 background galaxies, astronomers calculated the locations and amount of matter concentrations. The matter map, tinted blue, is overlaid here on an image from the Hubble Space Telescope. If the cluster's gravity came only from the visible galaxies, the lensing distortions would be much weaker.

NASA / ESA / D. COE (NASA / JPL-CALTECH / STSCI) / N. BENITEZ (INSTITUTE OF ASTROPHYSICS OF ANDALUSIA, SPAIN) / T. BROADHURST (UNIVERSITY OF THE BASQUE COUNTRY, SPAIN) / H. FORD (JOHNS HOPKINS UNIVERSITY)

The universe is filled with dark matter. To some, this might seem a bold claim — after all, we can't actually see it. But while we have not detected it directly, dark matter's influence is all around us, on galactic and cosmological scales. Over the last several decades, the evidence for this mysterious, gravitationally powerful stuff has become a rich tapestry of many independent observational threads. We know *how much* dark matter there is in the entire universe, the *role* it plays in the formation of the galaxies we observe near and far, and that it must be *something new*.

The question of the nature of dark matter is a thrilling focus right now for physics and astrophysics. An enormous amount of work has gone into experiments that could directly detect dark matter or might somehow produce a dark matter particle. The greatest focus has been on *weakly interacting massive particles* (WIMPs), beefy hypothetical entities that interact with matter only weakly. In the gloom of the cosmic unknown, WIMPs have been the super-bright lamppost under which we've been looking the most (*S&T:* Jan. 2013, p. 26).

So far, we haven't found them. Experiments are reaching levels of sensitivity now that rule out more and more types of WIMPs (see page 30).

This is where the search gets exciting. It's also where optimism starts to be tested. How much should we be hedging our bets? How anxious should we be? There are so many possible lampposts out there — if we haven't found dark matter in the most obvious places, will we ever be able to find it at all? Does it even exist? There is a building appreciation that the universe may hold something beyond the WIMP, and that astronomical observations may offer exciting insights that can lead us to it.

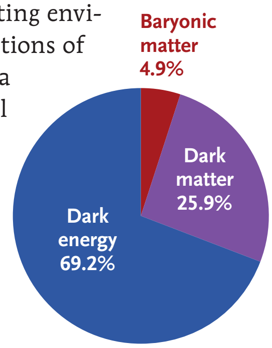
An Astrophysical Necessity?

We don't need dark matter to understand the solar system. The planets orbit the Sun in a way that we can describe using Einstein's general theory of relativity. Their movement is perfectly explained by the mass of objects that we can see.

When we move up to the scales of galaxies, though, we notice something unexpected. Galaxies rotate much too quickly (see page 36), as do the huge swarms of galaxies bound together by gravity in clusters.

The whole idea of motion in a gravitating environment is that there is balance. The motions of stars within a galaxy, or galaxies within a cluster, are set by the amount of material that keeps them bound together in a continuous dance. And these stars and galaxies are zipping around at a dizzying speed compared to the amount of mass that we can see.

This puzzle leads to two possible solutions. One is that general relativity doesn't quite describe how gravity works on



S&T DIAGRAM

larger astronomical scales. This is certainly possible! A huge advantage in general relativity's corner, though, is that it is astoundingly successful in describing the universe *as a whole*. Everything from the hot Big Bang to the way the universe grows and its structure evolves has an elegant, crisp description in the framework of general relativity.

That is, as long as we introduce two special ingredients to the recipe of the universe: an anti-gravitational "force" we call *dark energy* (*S&T:* Feb. 2009, p. 22) and dark matter.

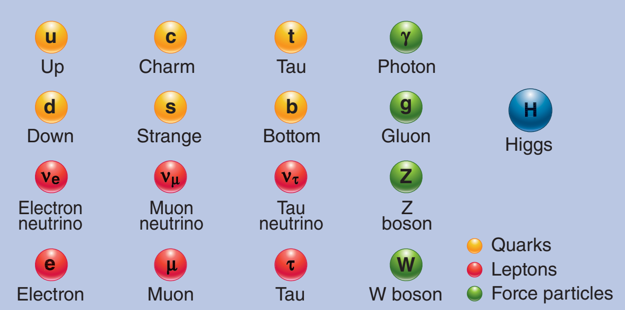
Observations actually reveal a lot about dark matter. First, it mainly (but possibly not only) must interact with itself and normal matter through gravity. If it didn't, these two types of matter would be mixed and distributed in profoundly different ways than we observe — and we *do* observe dark matter's distribution, thanks to its lensing effect on background light (*S&T:* Sept. 2016, p. 34).

Second, dark matter is neutral: It doesn't have a positive or negative electric charge. If it did, the particles would either repel one another, preventing matter from clumping and creating a dramatically different cosmic structure, or they would build a "dark sector" of atoms, molecules, and so forth that would leave their mark in the cosmic microwave background, a mark we don't see.

Third, it's "cold" — that is, it moves slowly enough that it clumps together easily. We have already been able to (gravitationally) detect how some of this clumping happens, because these clumps are the clouds of dark matter, called dark matter halos, in which galaxies form and live. Thus the name *cold dark matter* (CDM).

Finally, there's about five times more dark matter than normal matter. Dark matter dominates the universe! It's the fundamental scaffolding that galaxies and clusters are built on.

The Standard Model



The Standard Model of particle physics explains matter's fundamental building blocks and how they interact. All matter that we know of is made of elementary particles, which come in two types: quarks and leptons. There are six types of quarks and six types of leptons, split into three pairs each. The lightest and most stable of these pairs (the leftmost in this diagram) make up all stable matter in the universe, with heavier particles decaying to become lighter ones.

The Standard Model also includes four force-carrier particles and the Higgs, which are all a type of particle called bosons. The exchange of the force particles results in three of the four fundamental forces: electromagnetism (photons), the strong force (gluons), and the weak force (Z and W bosons). Gravity is not part of the Standard Model.

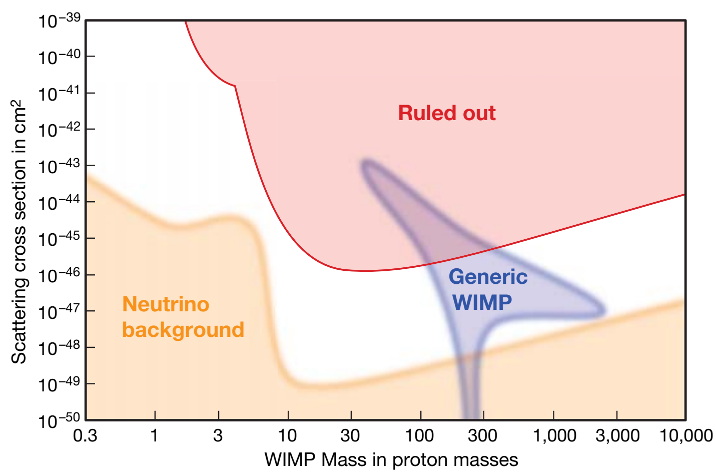
Fundamental particles acquire mass by interacting with the Higgs field. However, protons and neutrons, which are each composed of three quarks, mostly take their masses from the energy involved with the strong force holding their constituent quarks together. This means that the Higgs is only responsible for about 1% of the mass of "everyday stuff." *—Camille M. Carlisle*

Particle Physics Weighs In

Let's take a look at another view of these discoveries. Although our particle physics models that explain normal matter are very successful, there are some hints that we're missing something. For example, the so-called Standard Model of particle physics only includes three of the four fundamental forces: the strong, weak, and electromagnetic forces. Scientists haven't yet found a way to comfortably fit gravity into this framework.

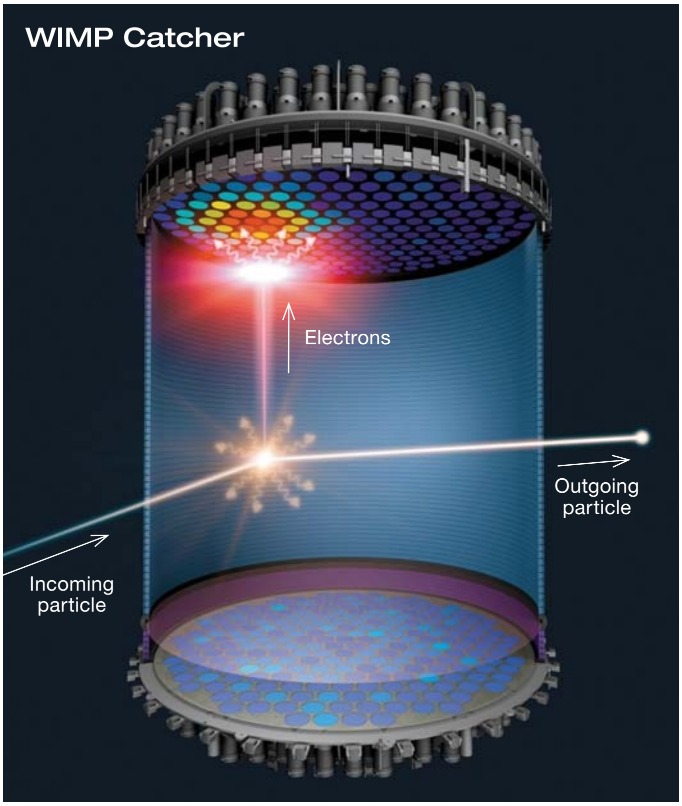
But it is possible that the Standard Model's greatest challenge is dark matter. If dark matter is indeed a particle, then it should fit into a greater, more encompassing particle physics framework, within which our current Standard Model has its place.

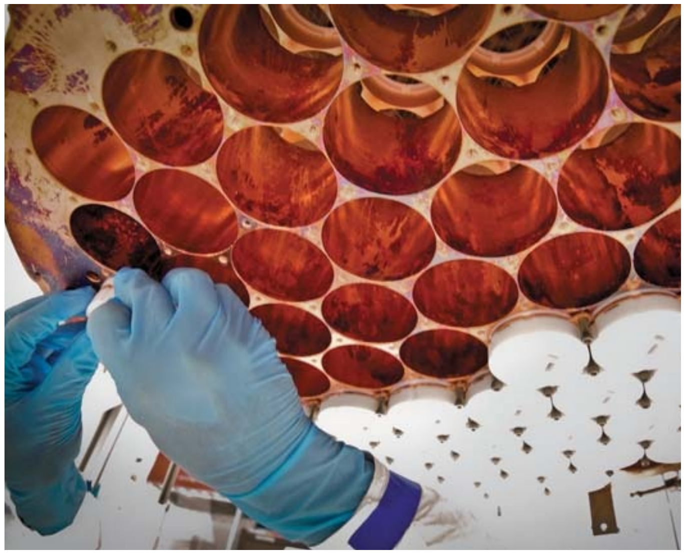
So when astronomers proposed cold dark matter, it excited particle physicists, because it enabled them to investigate what the characteristics of a CDM particle might be. For example, the very early universe was much more dense and



▲ **TIGHT SQUEEZE** More than a dozen experiments around the world have failed to detect WIMPs, ruling out an increasingly large range of particle characteristics (red). The white region between the red and orange curves marks what's left for scientists to explore. It still includes a fair amount of "generic WIMP" territory, a favored region (purple). The bumps in the neutrino background are from different kinds of neutrinos. Liquid xenon experiments are pushing the red curve down, whereas those using lighter elements are pushing it toward the lower left.

SIDEBAR: LEAH TISCIONE / *S&T*, SOURCE: DAN HOOPER; GRAPH: GREGG DINDERMAN / *S&T*, SOURCE: RAFAEL LANG





▲ **CATCHING DARK MATTER** *Left:* The idea behind experiments such as LUX-ZEPLIN (LZ) is to catch WIMP dark matter particles interacting with normal matter. In LZ's case, the normal matter is about 10 metric tons of liquid xenon. When a WIMP collides with a xenon atom, the atom emits light and causes a burst of electrons in the tank. Sensors at the top and bottom detect the initial light flash. An electric field pushes the electrons to the top of the chamber, where they generate a second flash of light (red). *Right:* A team member installs photomultiplier tubes in the bottom array of the LUX experiment, LZ's precursor.

hot than the universe today. There should be a time early on when dark matter and normal matter constantly interacted in non-gravitational ways, colliding all the time. Based on what the matter's temperature — and, thus, its density — was at that point, we can write down how likely such an interaction is. This is usually called a *cross section* and describes how easily a dark matter particle and a normal particle might feel each other's effect.

It turns out that the rough value of this cross section is close to the value we see in other parts of particle physics, in what are called *weak interactions*, which are responsible for how some particles decay. This led to proposing the WIMP: a family of particles apparently connected with the weak nuclear force and (the calculations tell us) with a mass of up to 10,000 times or more the mass of a proton.

Hunting WIMPs

How might one detect a WIMP? The basic idea is that the chance for a collision between a WIMP and a normal atom is not zero — just extremely low. Trying to catch one of these rare events, researchers set up experiments with carefully isolated and monitored materials and hope a WIMP hits an atom inside. For example, the upcoming LUX-ZEPLIN dark matter experiment — a merger of the recently completed Large Underground Xenon (LUX) and Zoned Proportional Scintillation in Liquid Noble Gases (ZEPLIN) experiments — will use a large chamber filled with liquid xenon. In this experiment, a WIMP collision with one of the xenon atoms would produce a small flash of light and drifting electrons.

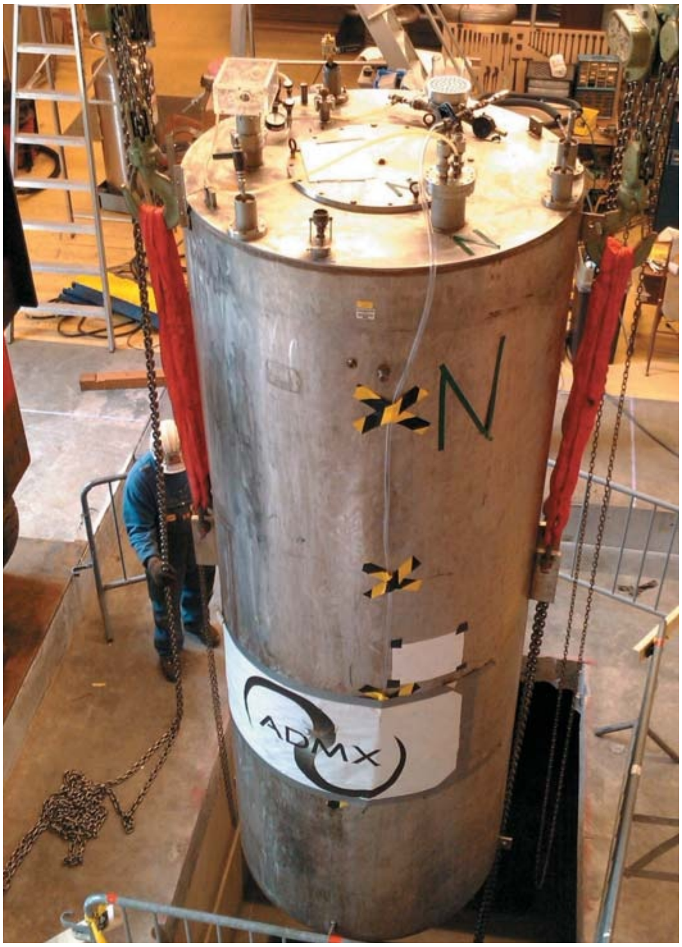
The two parameters physicists use to describe the sensitivity of this type of experiment are the cross section and the *WIMP mass*, which is related to how "cold" the particle is: The lower the mass, the zippier it might be.

Although we haven't detected a WIMP yet, we can now put limits on these two properties, because we know what each experiment would be sensitive to (see graph, facing page). There are many combinations of cross section and mass that we've ruled out. We've even excluded the predicted cross section values that first inspired this work. As sensitivity has pushed more and more into uncharted spaces, the excitement (and trepidation) has mounted. WIMPs are running out of places to hide.

There's a tantalizing line near the bottom of this chart: the neutrino floor. At the sensitivity level marked by the neutrino floor, experiments designed to detect dark matter will instead start detecting lots and lots of *neutrinos*. Neutrinos are nearly massless particles involved in many processes, including fusion and the creation of neutron stars. Many of those detected on Earth come from the Sun or cosmic rays hitting our planet's atmosphere. Hitting the neutrino floor will be a new window into how these particles work, but if WIMPs live beneath that sensitivity level, the sea of neutrinos we expect to detect will complicate the continuing search for dark matter.

"CROSS SECTION"

• A particle's **cross section** is the probability that it will interact with another particle.



▲ **FORCING PHOTONS TO CHANGE** The Axion Dark Matter Experiment (ADMX) hides a microwave cavity inside a large superconducting magnet (the cavity is about as wide as the inner circle on the top of the setup in this photo). The magnetic field should convert any axions of a certain mass that are passing through the cavity into microwave photons. Researchers slowly change the position of rods inside the cavity, trying to make the cavity resonate. The resonant frequency would correspond to the photons' frequency and therefore to the axions' mass.

▲ **SOLAR AXION SEARCH** The CERN Axion Solar Telescope (CAST) points a cryogenic, dipole-magnet "telescope" at the Sun, in an attempt to convert solar axions into X-rays.

With the stakes so high, the WIMP pursuit has to continue. The sense of unease is real, though. If dark matter isn't WIMPs, then what is it?

Fickle Photons

There are actually several options out there beyond the WIMP lamppost. Many arise as solutions to particle physics puzzles and happen, serendipitously, to also be good dark matter candidates. Two of these candidates stand out.

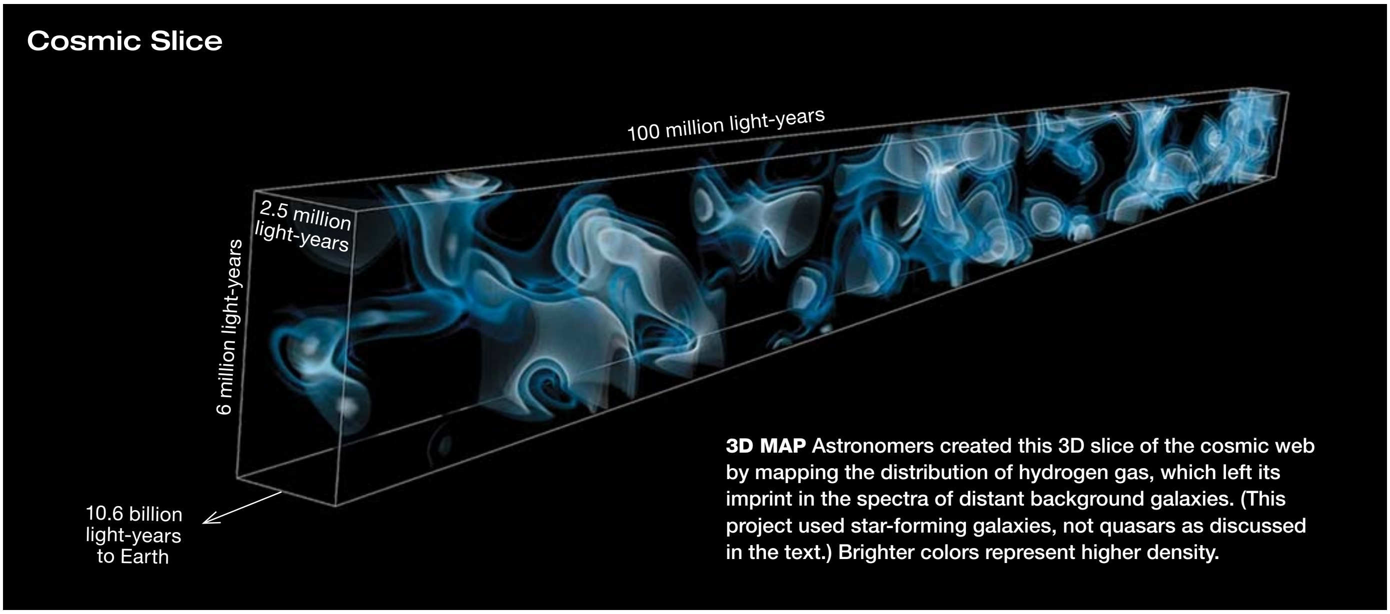
The first one could solve a persistent hole in particle physics called the *strong charge-parity problem*, which has been around since 1964. The Standard Model predicts that whatever might happen to a particle should also happen to its antimatter counterpart if you mirror-flip the spatial setup. There are some types of particles and situations for which this symmetry doesn't seem to apply.

One proposed solution is a hypothetical particle dubbed the *axion*. Axions have tiny masses, no charge, and largely no way of interacting with normal matter. They are also predicted to have a very special property: They convert to photons if they find themselves in extremely strong magnetic fields. The photon's energy will correspond to the mass of the axion particle, following the familiar relationship between energy and mass: $E=mc^2$. There is a cross section for this to happen, too — in other words, a level of probability that tells us about the nature of the axion itself.

We can use this transmogrification to our advantage. To find axion dark matter, we need to seek out places where there are strong magnetic fields — or create them ourselves. Researchers with the Axion Dark Matter Experiment (ADMX), for example, have built a tall cavity within a powerful, superconducting magnet to try to magnetically force any galactic axions that might be passing through the cavity to convert to photons. It's the ultimate parlor trick, since light would essentially appear out of thin air! In this case, though, the light ADMX is sensitive to would be at microwave frequencies. To detect the photons, scientists stick "tuning rods" into the cavity and carefully change the distance between them. If axions exist at masses corresponding to microwave energies, then there should be a separation that makes the cavity resonate at the created photons' frequency. It's kind of like tuning the dial on a radio, searching for a signal.

Other scientists look at strongly magnetic astronomical objects. Some have suggested that a transition to axion-like particles (and back again) could explain why more gamma rays reach us from black-hole-powered beacons called blazars than we think should survive the trip (*S&T:* July 2012, p. 17). Still others have looked for axion-signature photons emerging from the stellar embers called white dwarfs, which often have enormous magnetic fields — thus far with no success.

Another highly magnetic place is the Sun. Researchers at CERN (which runs the Large Hadron Collider), for example, have built an experiment with a powerful magnet that tracks our star like a telescope does its target, in an attempt to make axions streaming from the Sun convert to X-rays.

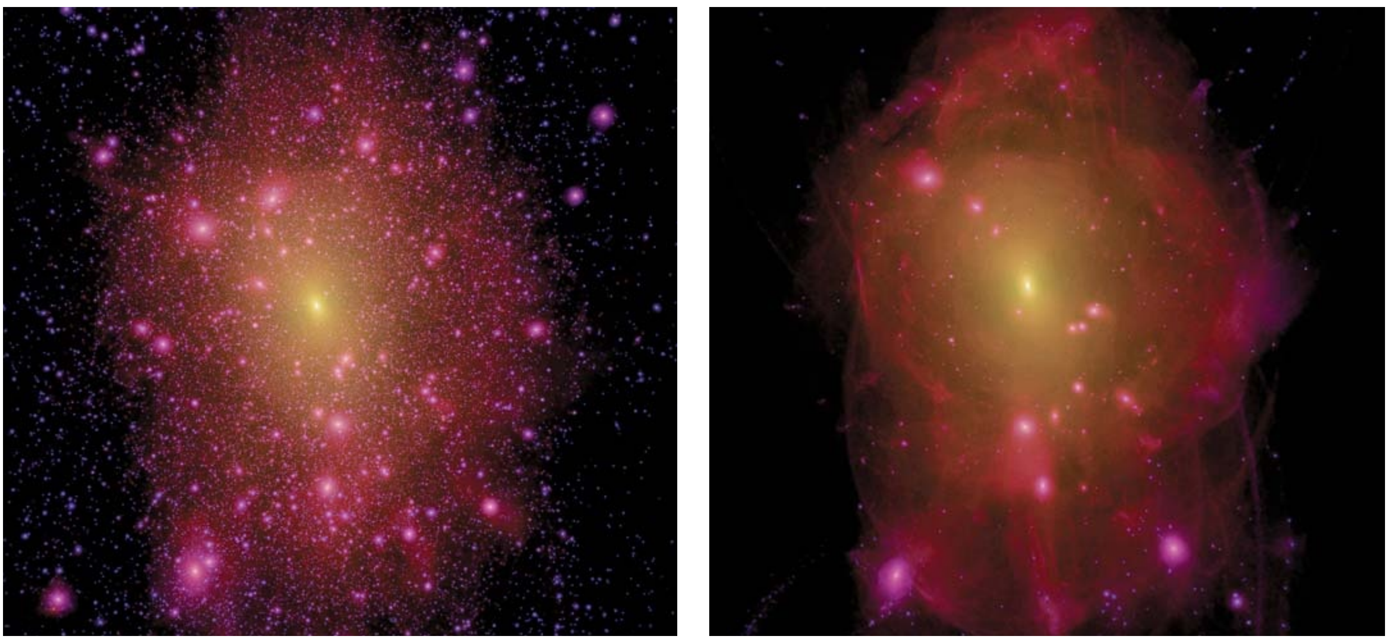


3D MAP Astronomers created this 3D slice of the cosmic web by mapping the distribution of hydrogen gas, which left its imprint in the spectra of distant background galaxies. (This project used star-forming galaxies, not quasars as discussed in the text.) Brighter colors represent higher density.

More fun arises when we ask whether the distribution of axion dark matter in the universe would be different from what might be expected for WIMPs. Axions are pretty "cold" in the sense of CDM. Overall, when we create giant computer simulations of the universe with CDM (*S&T:* May 2017, p. 34), the picture for WIMPs versus that for axions should be pretty much the same.

Except in some details. Axions are similar to a particle family we call *bosons*. Photons are bosons. A feature of bosons is that they don't mind overlapping in space. Many of them can crowd into the same point, and they don't get in one another's way in a conventional sense. This is very different from what happens with bosons' cousins, the fermions, which include electrons, protons, and even WIMPs. There can only be one fermion at any given point of space, like bowling balls. We call this rule the *Pauli exclusion principle*.

This remarkable property of being able to pile up *might* leave a detectable signature. Within a galaxy such as our very own Milky Way, streams of stars are constantly swirling around, as stars disperse from their star-formation cradles over time (*S&T:* Apr. 2017, p. 22). If a dense bit of dark matter were to punch through these streams, we might be able to see



▲ **COLD VS. WARM DARK MATTER** The average speed of dark matter particles affects how easily the particles clump together — and, therefore, how easily small lumps of material can form. Cold dark matter (which is slower, *left*) clumps more easily than warm dark matter (faster, *right*), as apparent in these simulations of a 5-million-light-year-wide box of cosmic structure.

TOP: CASEY STARK (UC BERKELEY) AND KHEE-GAN LEE (MPIA); BOTTOM: MARK R. LOVELL ET AL. / *MNRAS 2012* (2) the effect on the stars' motions. WIMPs will predominantly form cloud-like clumps, whereas axions might collect into super-high-density arcs, called *caustics*, and these two structures would plow through streams in a different way.

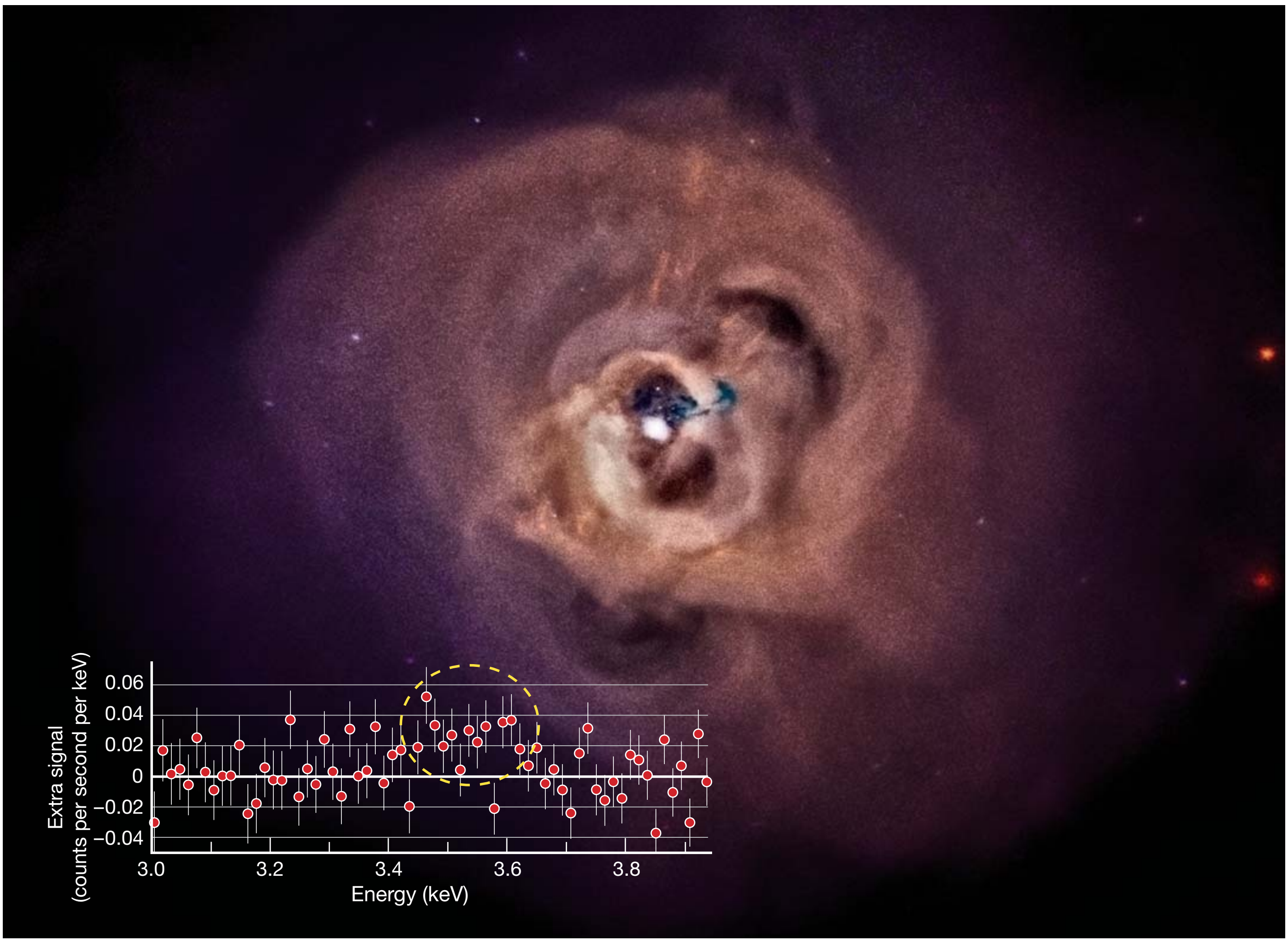
Caustics are a controversial idea, and recent particle physics work suggests that they might never form. On the astronomy side, we're starting to amass the observational data to test the proposal. Europe's Gaia satellite is measuring the positions and motions of more than a billion stars in the Milky Way and might uncover holes in stellar streams. In the mid-2020s, NASA's infrared WFIRST mission will also survey large areas of the sky, and combined with ground-based measurements of how quickly stars are moving along their line of sight, we may be able to make another level of breakthrough.

Getting Warmer

The second non-WIMP candidate we will discuss is generically called *warm dark matter*, or WDM. The "warm" basically means that its particles have a somewhat greater general speed than CDM, and so some of the smaller clumps that might form in CDM don't in WDM.

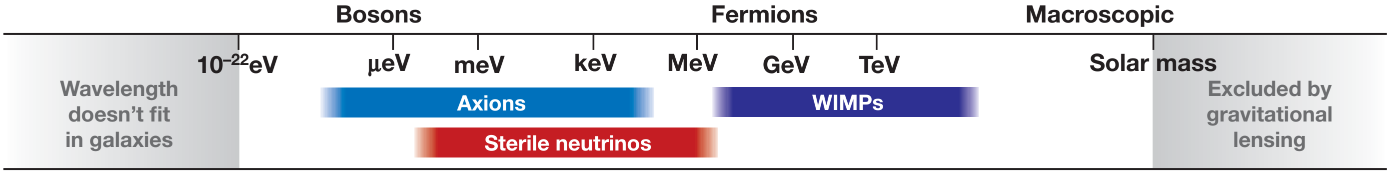
While most of our observations of the universe fit neatly into expectations from CDM, there are small but persistent puzzles. Some of these have to do with the existence of the smaller clumps within our Milky Way's galactic family or even at the earliest times of the universe. Astronomers have been having trouble finding as many small satellite galaxies around the Milky Way as CDM predicted should exist, although recent computer simulations show that the predictions probably were just overzealous because they didn't include normal matter (*S&T:* May 2017, p. 34).

Another cold versus warm signature might be revealed by counting how many small clouds of clumpy hydrogen gas there are in the vast spaces between galaxies. It's the same idea as with satellite galaxies. If dark matter is too warm to clump gravitationally, then the gas — which would ride along with the dark matter as it coalesced into clouds — will be spread out, too.



▲ **HINT OF DARK MATTER?** An unexpected "bump" in the X-ray emission from the Perseus Cluster (background image, shown in X-rays) and more than 70 other galaxy clusters might be created when sterile neutrinos transform into active ones. The slight bump is circled in the spectrum. The cluster's X-ray glow in the background image spans roughly 500,000 light-years.

NASA / CXC / SAO / E. BULBUL ET AL.



▲ **CANDIDATE MASSES** The playground of potential dark matter candidates spans roughly 90 orders of magnitude in particle mass. (The above is thus not an exact scale.) All matter can be described as both a particle and a wave, and dark matter must fit within a galaxy, so the bottom limit corresponds to a particle wavelength that is larger than a galaxy. The upper limit of about 1 solar mass comes from gravitational lensing studies, which have essentially ruled out primordial black holes down to this size. There are many candidates in addition to the three most popular ones shown here, but we've excluded them for simplicity's sake. For context, the proton's mass is about 1 GeV.

GREGG DINDERMAN / S&T, SOURCE: RAFAEL LANG

These hydrogen clouds would normally be impossible to detect. So astronomers use cosmic spotlights. These are bright objects called quasars, brilliant galactic centers powered by accreting black holes, and the light they emit has properties that we have characterized very well. As quasar light traveling to us intercepts these hydrogen clouds, the clouds absorb some of the light. The absorption happens at particular wavelengths that correspond to the electron energy levels in hydrogen atoms.

By the time we detect the quasar light on Earth, it has picked up a series of wavelength-specific "blackouts," small light-absorption signatures from each of the hydrogen clouds along that enormously long line of sight. Furthermore, each cloud's lines are redshifted by the universe's expansion according to how far away the cloud is from us, revealing not only when in cosmic history the light encountered the cloud but also *how many* clouds it hit. Once we've parsed the quasar's spectrum, we can count up the clouds and tackle the problem of how warm or cold dark matter may be.

One classic WDM candidate is the *sterile neutrino*. In our now-familiar Standard Model of particle physics, there are three types of regular, or "active," neutrinos. The Standard Model also predicts that neutrinos should have zero mass, and each neutrino type should stay the same forever. However, physicists have shown that neutrinos do have a (small) mass, and it's possible for each of these so-called "flavors" of neutrino to transform into one another.

These particle conundrums open up new doors. One introduces a type of neutrino that only interacts with matter through gravity — unlike the active neutrinos, which also interact via the weak force. This is why it's called the sterile neutrino. These particles have one revealing feature, though: Given a large enough span of time, a sterile neutrino would occasionally convert to a regular, active neutrino plus a photon. The particle masses that could fill the role of dark matter would produce X-ray photons when they decay.

So if dark matter is made of sterile neutrinos, then in places where there is a lot of dark matter, we might see lots of X-ray photons. If we return to our friendly galaxy clusters, which helped start this quest many decades ago, and observe them in X-ray wavelengths, we might detect a ghostly signal in the cluster's spectra that matches none of the known atomic lines and that could come instead from the dark matter halo that each cluster lives in.

Back in 2014, two teams of astronomers suggested that they might have found this sterile neutrino signal, as a 3.5-kiloelectron-volt bump in X-ray emission from 73 galaxy clusters and the Andromeda Galaxy (*S&T:* Oct. 2014, p. 16). Astronomers are still arguing about how to interpret these X-rays. They may need to wait a while for the data they need to fully explore sterile neutrinos, though: Although both the Chandra and XMM-Newton space telescopes (see page 57) detected the emission, the Japanese X-ray telescope Hitomi would have given us the best tool to date to investigate this hypothesis, and it tragically broke up only a month after launch (*S&T:* July 2016, p. 11). NASA and the Japanese Space Agency are exploring a replacement for Hitomi.

Still in the Dark

What a journey. In picking up clues from dark matter's gravitational effects in the universe, scientists are making tantalizing connections with long-standing puzzles in particle physics. At the same time, by studying the predictions from particle physics, astronomers' view of the universe is challenged, informed, and enriched. The world of dark matter has benefitted so much from the classic ideas of CDM and WIMPs. They have given us a bright and clear spotlight, under which we have learned a lot about the universe and how it operates.

And yet, what we have covered in these pages only scratches the surface of what dark matter *could* be. The question of the nature of dark matter remains a profound one in both physics and astrophysics. Over time, and facing many challenges, we are beginning to turn the lights up on the whole cosmic room.

We may reach a breakthrough at any moment. It's even possible that we might confirm more than one of these theories! There is nothing to say that dark matter must consist of only *one* type of particle; it's entirely possible that it may be made up of more than one of the candidates we've explored here. That would be a very interesting universe, indeed.

After all, we've been surprised before.

■ **LEONIDAS MOUSTAKAS** manages the astrophysics section at the Jet Propulsion Laboratory in Pasadena, California. He explores what astronomical observations can teach us about dark matter and is also a deputy project scientist with NASA's upcoming WFIRST mission.

Vera Rubin's Universe

ON THE LOOKOUT Even in her final years, Rubin sought to discover what we didn't know about the universe. She appears here in her office at the Carnegie Institution of Washington at age 82.

THE WASHINGTON POST / LINDA DAVIDSON / GETTY IMAGES

By looking at things others didn't think were interesting, the astronomer often labeled the "mother of dark matter" forever changed our picture of the cosmos.

A flick of a switch, and Vera Rubin disappeared. Moving by instinct, she took a few steps, grabbed the banister of a staircase, and climbed upward. Her footsteps echoed throughout the pitch-black dome. At the top, she reached a door. Putting her key into the lock, she turned the knob and pushed.

Nothing happened.

Rubin lowered her center of gravity and threw her weight against the hinged hunk of metal, knocking it open with her hip. A gust of wind smacked her in the face as she stepped outside onto a rusted, iron catwalk. She looked up toward the heavens. Stars speckled the southern Arizona sky in all directions. The seeing was good.

Rubin traced her way around the outside of the dome to another door. Opening it, she looked in, her eyes adjusting to the darkness to make out the 84-inch telescope that she and fellow astronomer Deirdre Hunter (Lowell Observatory) were about to awaken.

It was November 2007. Rubin and Hunter were at Kitt Peak National Observatory, just southwest of Tucson, to continue work Rubin's team had started in the 1960s — measuring the velocities of stars as they whirl around the far reaches of their galaxies. It began as unglamorous work. But Rubin's tenacious efforts helped her and her colleagues confirm the existence of dark matter, the invisible stuff that makes up more than 80% of the material universe. That realization was a historic achievement, one that took astronomers' understanding of the universe and stood it on its head: What we see is only about 15% of the matter in the cosmos.

And it came in part because Rubin liked to ask questions others thought weren't worthy of study.

Staring at the Stars

In 1933, just shy of Rubin's fifth birthday, Caltech astronomer Fritz Zwicky was grappling with odd observations of the Coma Cluster. Galaxies inside were whipping around the cluster way too fast. If the material astronomers could see was the only mass there, then the galaxies should have been shooting off into space. But they weren't.

Zwicky reasoned that some form of invisible matter had to be tugging on the galaxies, holding the cluster together. He called this stuff *dunkle Materie*: dark matter. But not many paid attention to that paper, published in German in a Swiss journal, nor to his 1937 follow-up or similar work by Sinclair Smith on the Virgo Cluster. The mystery was a scientific time bomb waiting to explode.

The person who would trigger that bomb was still in grade school. At 10, Rubin and her family moved to Washington, DC, from Philadelphia. Night after night, she looked out the window and traced the paths of the stars and meteors she saw. Those nights inspired her to become an astronomer. To pursue that dream, she chose to attend Vassar College, where Maria Mitchell, the first American woman to become a professional astronomer, had worked.

There, Rubin connected with Maud Makemson, director of the Vassar Observatory and the first "real" astronomer with whom Rubin had direct contact. But the summer before her final year, Rubin met and fell in love with Robert Rubin. By Thanksgiving of 1947, she was engaged and planning a summer wedding. Her relationship with Makemson became strained. "I probably wasn't serious enough for her," Rubin recalled in a 2007 interview. "I think she thought I was going to go off and get married and that would be the end of astronomy."

Obviously, it was not the end. Rubin moved to Cornell University to join Robert, where he was working on his PhD. She worked on a master's degree. She studied with physics greats Philip Morrison, Richard Feynman, and Hans Bethe. Less well known, but perhaps more influential, however, was Martha Stahr Carpenter, a young astronomer studying galaxy dynamics. Her work may have inspired Rubin's thesis, which suggested groups of galaxies exhibited extra motion, in addition to their predictable motion due to the expanding universe. There was even a slight hint that the universe itself had some sort of rotation. Astronomers scoffed at Rubin's thesis results. Such criticism may have encouraged Rubin's sense that she "wasn't a real astronomer yet" and, along with her love for data, may have driven her to collect droves of evidence in her future endeavors.

From Galaxies to Stars Again

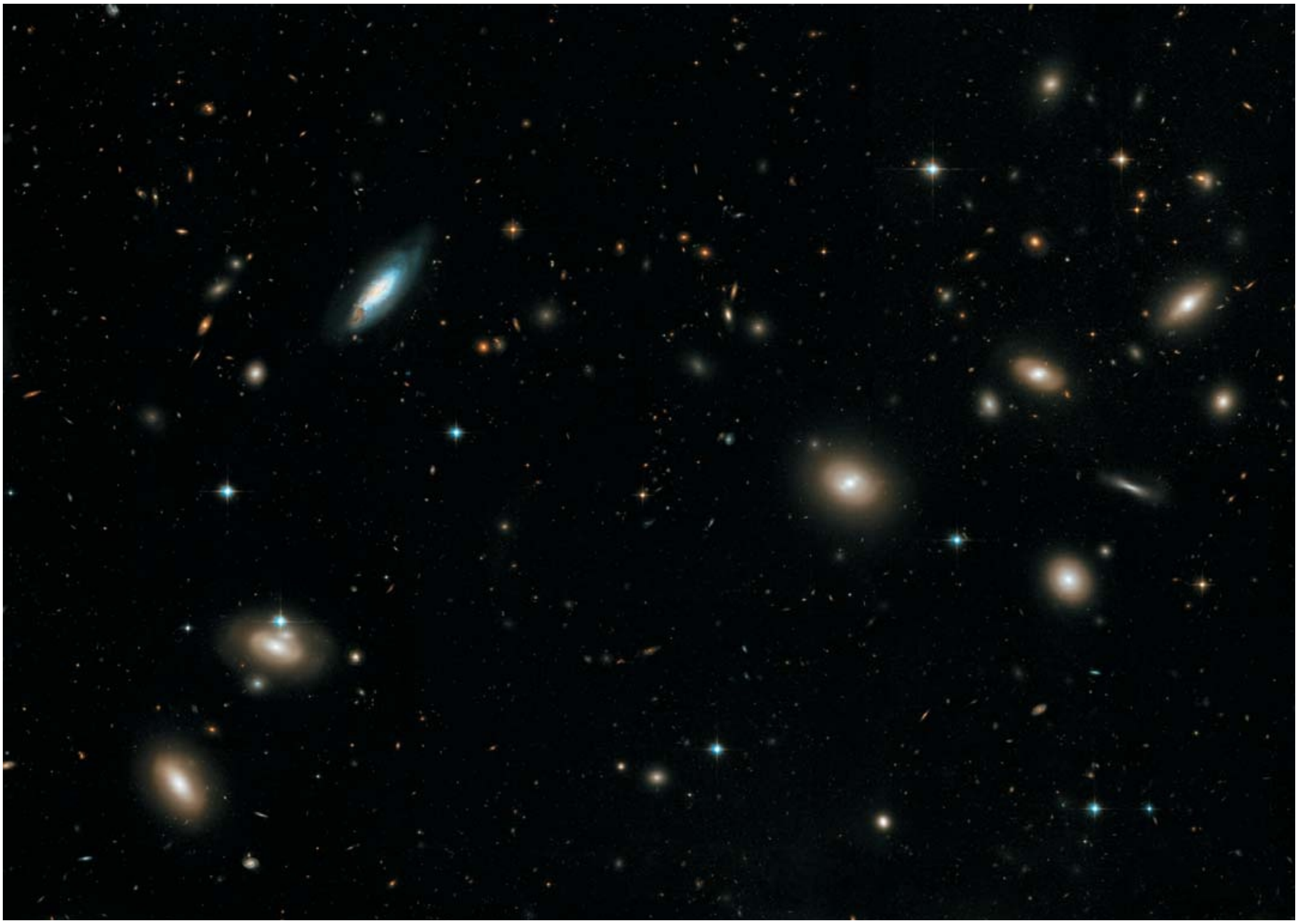
There was a point in Rubin's career when she wasn't doing astronomy. She and her husband had just moved to Washington, DC, so that Robert could take a position at Johns Hopkins' Applied Physics Laboratory in Maryland.

"Bob went off to work every day, and I stayed home with the baby," Rubin said. She would cry when the *Astrophysical Journal* arrived in the mail, containing papers about work that she wished she were doing. "It was tough. It was just too tough *not* doing astronomy."

Robert Rubin recognized immediately his wife's frustration. "She was very unhappy with the life she was leading," he said during the same interview. "It was clear that something would have to be done." Always Vera's greatest supporter and trusted

VASSAR COLLEGE, COURTESY AIP EMILIO SEGRÈ VISUAL ARCHIVES

▶ **IN LOVE WITH THE STARS** Vera Florence Cooper (later, Rubin), shown here at about age 19, peers through a telescope at Vassar College. She graduated from Vassar in 1948.



▲ **COMA CLUSTER** In the 1930s Fritz Zwicky found that galaxies in the Coma Cluster (Abell 1656) move so quickly, they should fly out of the cluster unless some invisible matter is holding them in place. This image is of a section about one-third of the way out from the cluster's center.

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

confidant, he encouraged her to earn her PhD. Not long after that decision, physicist George Gamow, then best known for his theories on the origins of the chemical elements (and who heard about Rubin through Robert's office mate), called Rubin to discuss her thesis. He became her PhD supervisor, even though the only place to earn an astronomy PhD was at Georgetown and he was at George Washington University.

After completing her PhD and joining the ranks at Georgetown, Rubin returned to studying stars, starting in the Milky Way. The working hypothesis at the time was that stars in our galaxy, and all galaxies, should follow Newton's law of gravitation: The tug two objects have on each other is directly proportional to the product of their masses and inversely proportional to the *square* of the distance between them. Thus, the gravitational force two objects exert on each other should drop precipitously as they move farther apart.

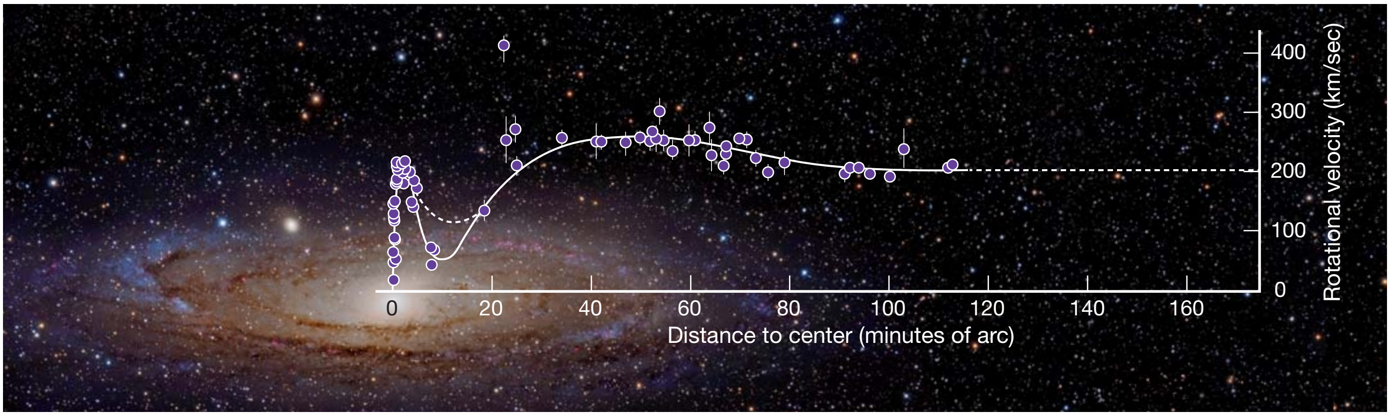
By extension, this law means that a star revolving around a galaxy should experience an attractive force from all the matter between it and the center of the galaxy, as though the matter were concentrated right in the galaxy's center. The more mass inside the orbit, the faster the star should move.

Visually, most of a galaxy's mass appears to be concentrated within a few tens of thousands of light-years of its center. So outside that point, the effect of distance should start to override the effect of mass: The gravitational force should plummet with increasing distance from the galactic center, meaning stars farther out should travel slower in their orbits around the galaxy than stars closer in.

But when Rubin's team plotted the relationship of the stars' distance from the galactic center against their velocities — a plot called a *rotation curve* — they found no drop-off in velocity. The Milky Way's rotation curve seemed to be flat.

Despite these paradoxical results, Rubin didn't immediately rush to the telescope to study the rotation curves of other galaxies. It didn't immediately click that something was off. Even if it had, female astronomers struggled to obtain telescope time at the nation's leading observatories.

That, however, started to change for Rubin with a fortuitous move west. Robert took a fellowship at the University of California, San Diego, in part so that his wife could work with astrophysicists Geoffrey and Margaret Burbidge and study the rotation curves of galaxies.



▲ **FLATLINE** If galaxies were only made of visible matter, then the right-hand side of Rubin and Ford's 1970 rotation curve for M31, the Andromeda Galaxy, would decline toward the galaxy's visible edge. Instead, the outer stars' high velocity demonstrates that there must be a considerable amount of invisible matter present. The data points are taken from both sides of the disk but combined on a single graph.

Collaborating with the Burbidges, Rubin finally began to feel like she could be a "real" astronomer. "Up till that point I sort of wondered if I would, especially when I was scrubbing the kitchen floor or something," she said in a 2007 interview. "I mean really, I would occasionally say to my children, 'Do you think Margaret Burbidge is scrubbing her kitchen floor?'"

But not only was Margaret Burbidge studying galaxies, she was married, and she had a child. "One day I called her from Washington, and I remember her saying, 'Can I call you back in ten minutes? Because Sarah's here with her friends and I was just starting to scramble some eggs' — or something like that," Rubin recalled. "That was such a nice, reassuring sentence coming from her." It was the life Rubin longed for. She saw she could indeed have it all.

▲ **INSPECTING SPECTRA** Rubin and her collaborators carefully gathered spectra from galaxies, revealing that stars and gas on the galactic outskirts revolved around the system faster than expected.

Star by Star, Galaxy by Galaxy

And she started to. In 1964, renowned Palomar Observatory astronomer Allan Sandage sent Rubin an application to compete for telescope time at Palomar, editing the form's warning, "Due to limited facilities, it is not possible to accept applications from women," to include "usually." She became the first woman to legally observe there.

She also earned telescope time at Kitt Peak National Observatory, where the facilities were open to all astronomers, including women. Drawing on the work she did with the Burbidges, Rubin set out for Tucson, determined to collect data on the velocities of stars in the Milky Way. Upon finishing her observations, Rubin's galactic rotation curve extended about five times farther than it had in the early 1960s — and it was still flat.

She also started to pay attention to the work of astronomer Bernard Burke, who was studying galaxies using radio telescopes. Rubin met with Burke and, not long after, she started working with him at the Department of Terrestrial Magnetism in Washington, DC. There, she also collaborated with a young instrument maker named Kent Ford, who was building an *image tube spectrograph*, a tool that would help Rubin study the velocities of stars in galaxies far beyond the Milky Way.

Yet at first, they focused on the hot topic of the time: quasars — beacons in the cores of distant galaxies, powered by very active supermassive black holes. Astronomers discovered that quasars are stunningly powerful, distant sources in 1963 (*S&T:* Sept. 2013, p. 24). For a few years, Rubin and Ford joined in the frantic excitement of trying to understand them. Rubin soon found the work to be too competitive, however; it didn't favor the meticulous and unrushed way she wanted to work. So she and Ford went back to galaxies.

In avoiding the limelight, however, they stepped right into it.

They started with the Andromeda Galaxy, finding that it, too, exhibited a flat rotation curve. So they moved on to other galaxies. "Soon 20, then 40, then 60 rotation curves, and they were all flat," she said in a 1989 interview. No one doubted the data, she said. Or, if they did, they didn't do it in front of her.

TOP: M31 IMAGE: ADAM EVANS / CC BY-NC 2.0, DATA: V. C. RUBIN & W. K. FORD, JR. / *ASTROPHYSICAL JOURNAL* VOL. 159 (FEBRUARY 1970); AT DESK: AIP EMILIO SEGRÈ VISUAL ARCHIVES, RUBIN COLLECTION

▲ **PART OF THE CLUB** The influential astronomer Allan Sandage (left), known for his work on galaxy formation and other topics, encouraged Rubin in her work — even breaking Palomar regulations by inviting her to observe there. Sandage and Rubin appear here with Vatican Observatory astronomer Martin McCarthy at a dinner party.

With the help of Ford and many Carnegie postdocs, Rubin studied all kinds of galaxies, including the more irregular ones. They were each special in their own way, but they all shared at least one common characteristic: a flat rotation curve. The flatness of the curves was just so easy to see, Rubin said. "You could show someone a couple of spectra," which revealed the stars' velocities around the galaxies, and "they knew the whole story."

"Vera was motivated by the science. She had no patience for astro-politics," Hunter says. "She was very careful about reducing and analyzing the data and listening to what the data were telling her, rather than what she expected the data to tell her."

Because Rubin was so data driven, Hunter says, she was confident in her results and fearless in standing up for them when others expected different answers.

"So much of Vera's success came from who she was on the inside," says Sara Seager, an astrophysicist and planetary scientist at MIT: Rubin was always positive, encouraging, and tenacious.

Faced with the flat rotation curves, astronomers had to concede that their conception of the cosmos was missing something significant. Some sort of invisible matter had to be filling galaxies and cocooning them in far-reaching halos, keeping the gravitational force on seemingly "outskirt" stars strong and enabling their high velocities. Dark matter, as Zwicky had suggested, had to exist.

A Continued Quest

Dark matter, even decades later, still remains a mystery (see page 28) — but one that never really bothered Rubin, says Princeton astrophysicist Neta Bahcall. Rubin took the mystery as encouragement and a reminder to be humble, sometimes wondering aloud that, if we can't figure out what dark matter is, what else is out there that we don't understand?

It was that curiosity that had Rubin returning to the telescope again and again, even in her late 70s. "I will always cherish the pure joy Vera derived from science," Hunter says. "She would get very excited about telescope proposals, being assigned telescope time, and analyzing data."

The last time Hunter and Rubin were at Kitt Peak — perhaps the last observing run Rubin ever did before her death on Christmas Day, 2016 — they were looking at a galaxy called UGC 2885, which is located 270 million light-years from Earth in the direction of the constellation Perseus. The galaxy is gigantic: It's 10 times larger than the Milky Way (depending on whom you ask) and rotates slowly, once every two billion years. Our galaxy, by contrast, spins around once every 230 million years or so. Rubin began observing this galaxy in the 1970s, and now she wanted to use the newest technology available to see if she could push her rotation curves even farther, measuring the velocities of material far, far beyond the galaxy's center.

Thus even in her final years, Rubin was aiding in astronomers' quest to uncover the boundary where a galaxy's dark matter halo drops off — or, whether the halo touches its nearest neighbors. Answering this question will offer clues to where dark matter is in the cosmos and how it's spread throughout space, something we might not ever have come to consider had Rubin not fallen in love with the stars.

■ **ASHLEY YEAGER** is a freelance science writer and editor, with a keen interest in astronomy and physics. This article is adapted from her 2008 MIT master's thesis.

▲ **STARSTRUCK** Rubin paired a profound passion for astronomy with a delightful personality. She passed away on December 25, 2016, at the age of 88, survived by three of her four children. She appears here in a photo from 2010.

OBSERVING
August 2017

2 **EVENING:** Golden Saturn gleams about 3° or 4° lower left of the waxing gibbous Moon.

7–8 **EVENING AND NIGHT:** A shallow partial lunar eclipse is visible for eastern Europe, most of Africa and Asia, and Australia; see page 50.

11–13 The Perseid meteor shower peaks on August 12th. The waning gibbous Moon rises before midnight daylight-saving time, however, so conditions are not ideal for meteor watching this year.

16 **MORNING:** The waning crescent Moon is 1° or 2° from Aldebaran for viewers in North America. The Moon will occult Aldebaran for the Caribbean and northern South America. Europe and northern Africa will get a daylight occultation.

19 **DAWN:** Hunt the thin crescent Moon 5° below Venus, low in the east.

21 **NEW MOON (2:30 P.M. EDT)** This is seen as a total solar eclipse across a narrow band of the United States, and as a partial solar eclipse over the rest of North and Central America and northern South America; see page 48.

25 **DUSK:** The waxing crescent Moon, Jupiter, and Spica form a triangle low in the west-southwest.

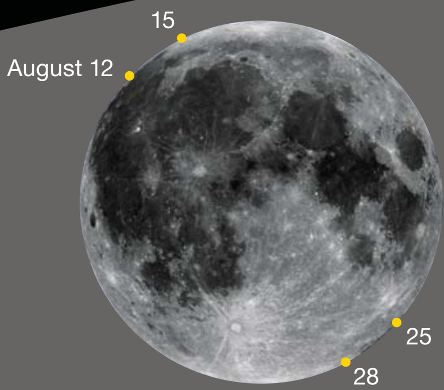
29, 30 **EVENING:** The first-quarter Moon shines about 7° right or upper right of Saturn on the 29th. The next night, the Moon poses to Saturn's upper left.

This composite image of two 25-second exposures taken from the same location in Death Valley, California, captured the glow of the Milky Way above desert mud cracks just before sunrise on April 2, 2017.

AUGUST 2017 OBSERVING

Lunar Almanac

Northern Hemisphere Sky Chart



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

NASA / LRO

MOON PHASES

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

FULL MOON
August 7
18:11 UT

LAST QUARTER
August 15
01:15 UT

NEW MOON
August 21
18:30 UT

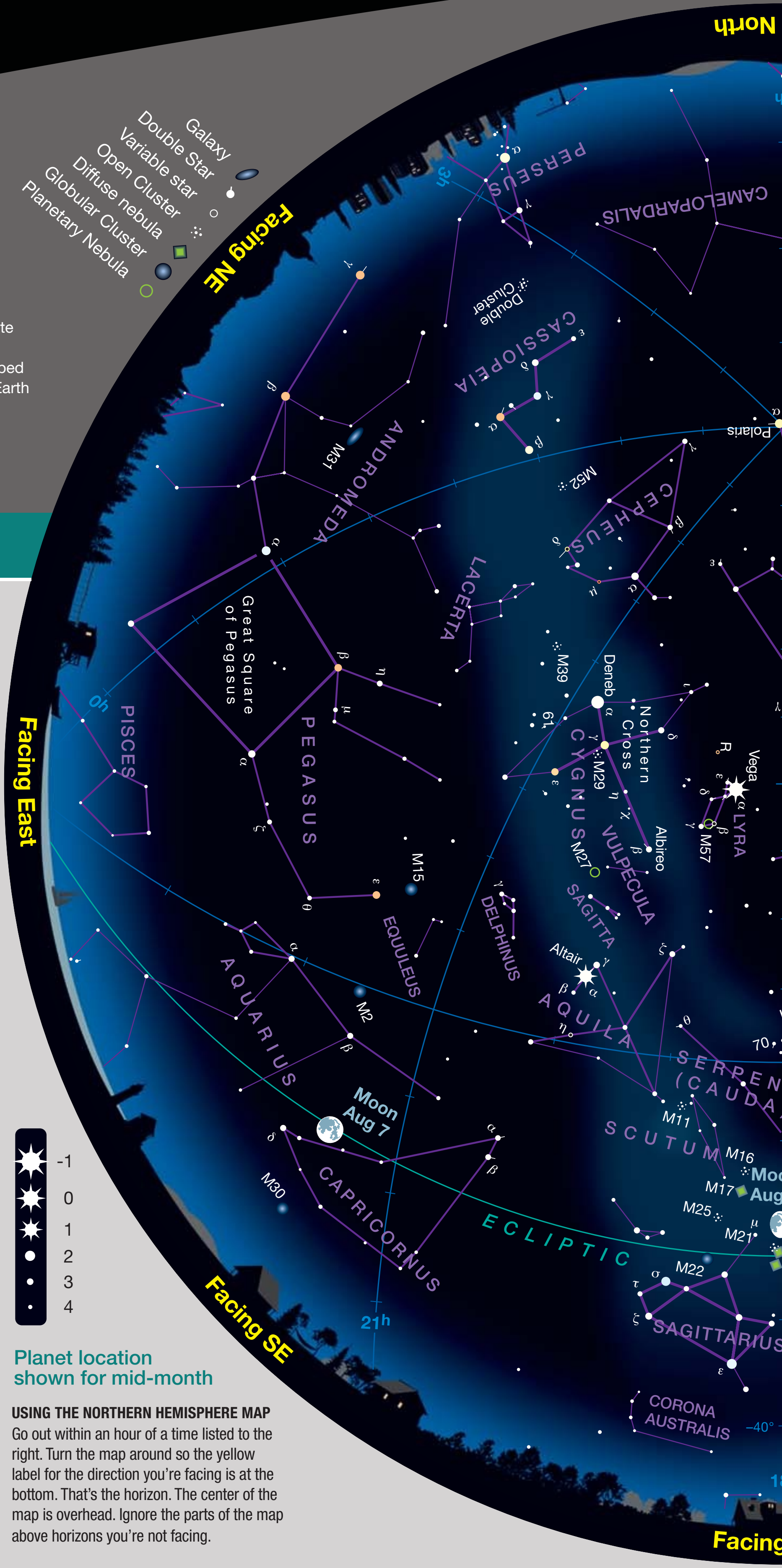
FIRST QUARTER
August 29
08:13 UT

DISTANCES

Apogee 405,024 km	August 2, 18^h UT Diameter 29′ 30″
Perigee 366,123 km	August 18, 13^h UT Diameter 32′ 38″
Apogee 404,306 km	August 30, 11^h UT Diameter 29′ 34″

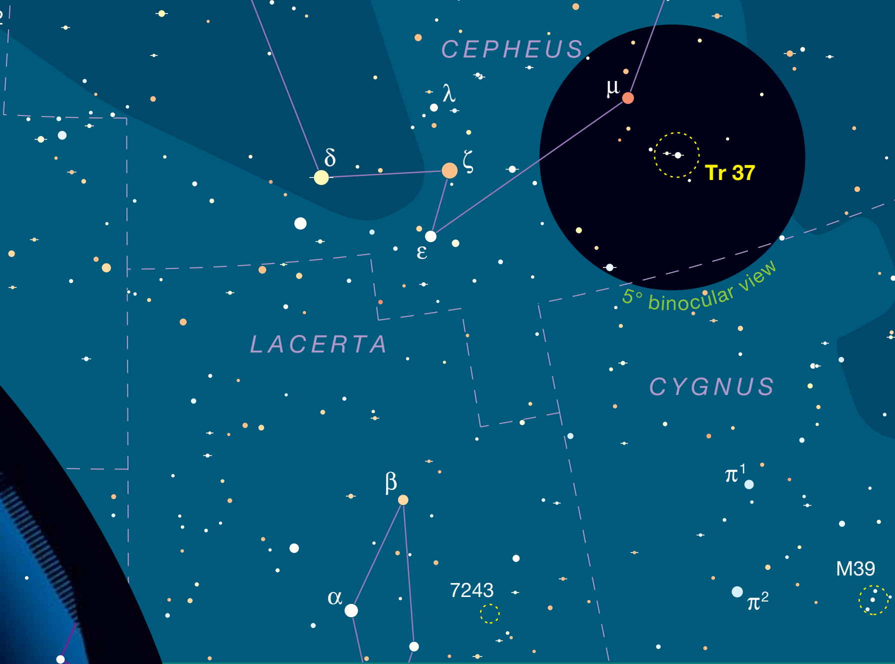
FAVORABLE LIBRATIONS

Lavoisier Crater	August 12
Pythagoras Crater	August 15
Abel Crater	August 25
Boussingault Crater	August 28



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 June	1 a.m.*
Early July	Midnight*
Late July	11 p.m.*
Early Aug.	10 p.m.*
Late Aug.	Dusk

*Daylight-saving time

Binocular Highlight by Mathew Wedel

Lucy in the Sky

Sometimes being a paleontologist-slash-amateur astronomer is like standing in a hall of mirrors, surrounded by reflections on all sides.

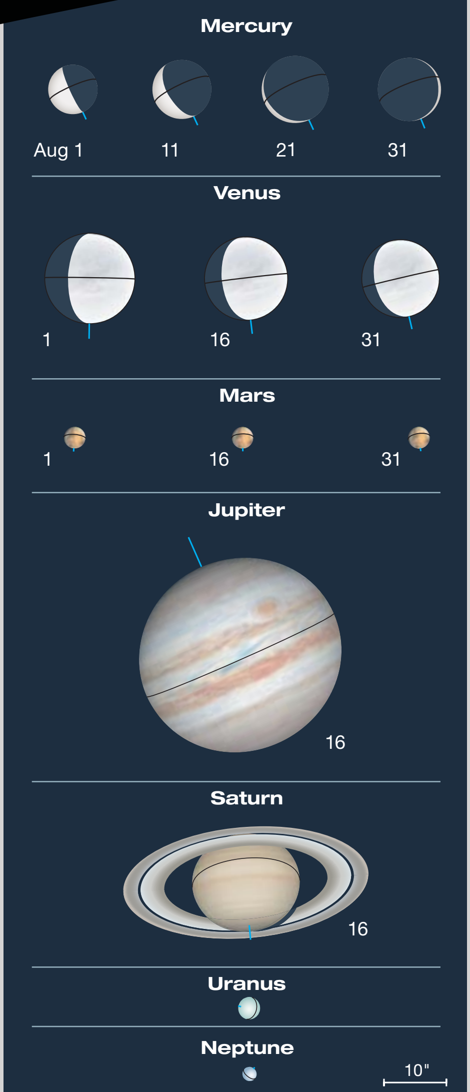
I was sweeping through the constellation Cepheus, named for the legendary king of Ethiopia, when my eyes fell on **Trumpler 37**, a charming open cluster located just over 1° south-southwest of Mu (μ) Cephei, Herschel's Garnet Star. The cluster truly is a binocular highlight — a rich concentration of suns that sprawls across almost 1½°. Visually, Trumpler 37 is centered on a binocular double formed by 5th-magnitude HD 206267 and 8th-magnitude HD 239729, which are themselves telescopic binaries. Astrophysical studies suggest that the cluster formed 3 to 4 million years ago.

Now, the office next to mine belongs to Dr. Thierra Nalley, a paleoanthropologist. As I'm writing this, she and her coauthors are publishing a description of a baby *Australopithecus* from Dikika in Ethiopia. The Dikika baby lived about 3.3 million years ago, even before "Lucy," that most famous of all australopithecines. When the Dikika baby and her family looked to the night sky and the constellation Cepheus, which would come to bear the name of the king who would one day rule their land (at least in tales), what is now Trumpler 37 was a vast nebula that probably rivaled Orion. That cloud of gas and dust gave birth to stars by the dozen, and in the process, evolved into the open cluster we see today. At the same time, the Dikika baby's relatives gave birth to future generations that eventually evolved into us. Where they saw a nebula, we see connections — between fossils, stars, and ourselves.

So when you observe Trumpler 37, I hope you'll keep another night in mind: a night long ago when a baby might have looked into the sky over Ethiopia and seen something marvelous being born.

■ **MATT WEDEL** likes to kick back with his binoculars on a driveway in Claremont, California.

Planetary Almanac



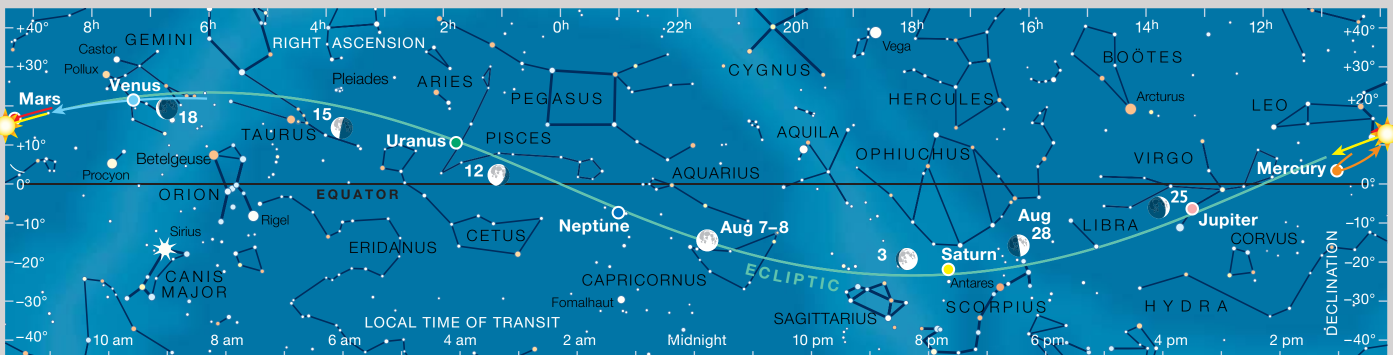
PLANET DISKS have south up, to match the view in many telescopes. Blue ticks indicate the pole currently tilted toward Earth.

PLANET VISIBILITY: Mercury: Out of sight all August • **Venus:** Visible all August before and during dawn, ENE to east • **Mars:** Out of sight until month's end, then very low in the dawn. **Jupiter:** All month, early evening, WSW • **Saturn:** All month, evening, south to SW.

August Sun & Planets

	Aug	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	$8^h 44.6^m$	+18° 05′	—	–26.8	31′ 31″	—	1.015
	31	$10^h 37.0^m$	+8° 44′	—	–26.8	31′ 41″	—	1.009
Mercury	1	$10^h 27.9^m$	+7° 52′	27° Ev	+0.4	8.0″	44%	0.845
	11	$10^h 45.2^m$	+4° 02′	23° Ev	+1.1	9.5″	26%	0.709
	21	$10^h 33.5^m$	+4° 01′	12° Ev	+3.3	10.8″	6%	0.623
	31	$10^h 04.4^m$	+8° 21′	8° Mo	+3.8	10.2″	4%	0.662
Venus	1	$6^h 00.9^m$	+21° 52′	39° Mo	–4.0	14.5″	74%	1.147
	11	$6^h 51.0^m$	+21° 52′	36° Mo	–4.0	13.7″	78%	1.214
	21	$7^h 41.5^m$	+20° 53′	34° Mo	–3.9	13.1″	81%	1.278
	31	$8^h 31.5^m$	+18° 55′	32° Mo	–3.9	12.5″	83%	1.338
Mars	1	$8^h 39.4^m$	+19° 33′	2° Mo	+1.7	3.5″	100%	2.658
	16	$9^h 18.3^m$	+16° 54′	6° Mo	+1.8	3.5″	100%	2.655
	31	$9^h 55.9^m$	+13° 50′	11° Mo	+1.8	3.5″	100%	2.637
Jupiter	1	$13^h 03.6^m$	–5° 29′	68° Ev	–1.9	34.3″	99%	5.747
	31	$13^h 21.4^m$	–7° 23′	44° Ev	–1.7	32.2″	100%	6.128
Saturn	1	$17^h 22.9^m$	–21° 55′	133° Ev	+0.3	17.8″	100%	9.344
	31	$17^h 21.0^m$	–21° 58′	103° Ev	+0.4	17.0″	100%	9.779
Uranus	16	$1^h 45.7^m$	+10° 17′	115° Mo	+5.8	3.6″	100%	19.470
Neptune	16	$22^h 59.3^m$	–7° 29′	160° Mo	+7.8	2.4″	100%	28.994

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-August; 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.

Shadow From Beyond Our World

How can we describe the wonder and awe we experience during a total solar eclipse?

Far more powerful and poignant is the effect in a serious tale of Faerie. In such stories when the sudden "turn" comes we get a piercing glimpse of joy, and heart's desire, that for a moment passes outside the frame, rends indeed the very web of story, and lets a gleam come through.

Seven long years I served for thee,
The glassy hill I clamb for thee,
The bluidy shirt I wrang for thee,
And wilt thou not wauken and turn to me?
He heard and turned to her.
— J. R. R. Tolkien, "On Fairy-Stories"

PRILL / ISTOCK BY GETTY

The column you're reading is called "Under The Stars," and this edition concerns everybody's favorite star, the Sun, at its most extraordinary moment.

How do you communicate the awe that someone experiences when they witness a total eclipse of the Sun? The words of Tolkien and the ending he quotes from the fairytale "The Black Bull of Norroway" convey a sense of awe and heartlifting wonder as potently as any writing I know. In my first published book, *Wonders of the Sky* (Dover Publications, 1982), I had this to say about the experience of my first totality on March 7, 1970: "For just under two minutes I stood there, more than what we call a person — or perhaps I was the pure core of wonder which lies buried deep in the mind of every person. I was witnessing a total eclipse of the Sun."

A vocabulary of awe. For my college students, I often write a list on the whiteboard of words and phrases used in connection with a total eclipse of the Sun. "The coming of the sudden shadow," the approach of the umbra, shadow bands, Baily's Beads, the chromosphere and flash spectrum, totality, the corona, "the eye of God," coronal loops and streamers, darkness at midday, the "360° sunset," the (ruby-red) solar prominences, the eclipse wind (and temperature drop), planets and stars visible in a midday sky of midnight blue — and what I take to be the most staggering sight in all of astronomy: the diamond ring.

"Shadow bands" is the answer I give students after asking them, "When is a shadow not a shadow?" Shadow bands are alternations of light and dark that glide across the landscape; they're caused by the crescent Sun, or its cusp points, twinkling. Imagine: the Sun twinkling.

The eye of God, the finger of God. Jack Zirker was apparently the first to call the totally eclipsed Sun "the eye of God," in his 1984 book *Total Eclipses of the Sun*. I'm not sure who came up with the idea of calling Earth's most violent storm, an F5 (now EF5) tornado, "the finger of God." But if you think about it, the Moon's umbral shadow could also be called the finger of God — only in this case, it's a dark finger nearly a quarter-million miles long, touching the surface of Earth with daytime darkness.

Under the right sky conditions, the approaching umbra of the Moon looks like a purple-black thunderstorm climbing the western sky. But even this August's unusually narrow shadow will be much wider than a thunderstorm, may be visible from up to a few hundred miles away, and will approach you at between 1,400 and 2,400 miles per hour. Some storm!

Totality to be continued. Most subscribers to *Sky & Telescope* will receive a copy of the September issue sometime in late July, or at least a few weeks before the August 21st eclipse. So in the next installment of this column, I'll talk about not just special September sky-sights, but also more about total solar eclipses, including some of the lesser-known marvels of totality, including the F corona and a particular phenomenon of atmospheric optics.

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

Eclipse, At Last

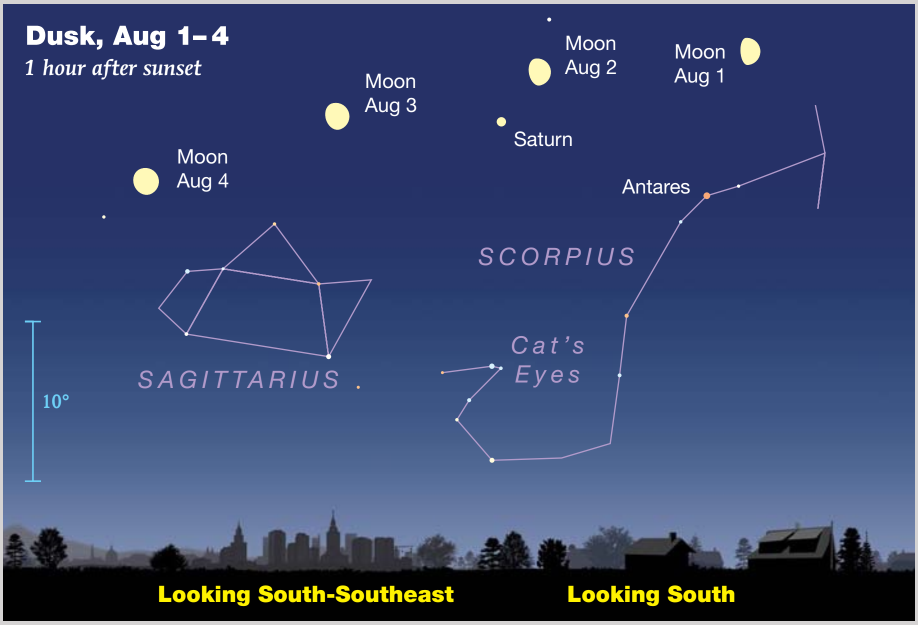
The "Great American" total solar eclipse is this month's star attraction.

Are you ready to be awed? On Monday August 21st, the Moon paints a streak of deep midday darkness from Oregon to South Carolina with a swift and narrow brush of umbra during the long-awaited "Great American" total eclipse of the Sun. All of the Americas north of the equator get a partial eclipse. This month also features a partial lunar eclipse for the opposite side of the world, visible across most of the Eastern Hemisphere on the night of August 7–8.

But what are the planets up to in this month of Sun and shadow? Jupiter appears in the west-southwest at nightfall and sets in late evening. Saturn shines in the south at dusk and sets in the middle of the night. Venus rises an hour or so before morning twilight begins, beaming high in the east as sunrise nears. Mars and Mercury are too near the Sun for viewing this month, outside of the brief minutes at totality during the solar eclipse.

AT TOTALITY

Mars was in conjunction with the Sun on July 27th and is lost from view in the solar glare throughout August — except when its 1.8-magnitude light might be glimpsed about 8° right of the Sun during the total eclipse on August 21st. Brilliant **Venus**, a bit more than four times farther right from the Sun than Mars, will be easy to see during totality. Depending on the transparency of your sky, you may be able to catch Venus when the Sun is only 85–90% covered by the Moon. **Mercury**, at 4th magnitude, shines too faintly, and **Jupiter**, about 77° from the Sun, is bright but low in the southeast. Most tantalizing is **Regulus**, magnitude 1.4, only about 1° left of the eclipsed Sun's disk. That's about two solar diameters. Binoculars will help.



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

EVENING

Jupiter declines from about 22° to 11° high in the southwest when observed 45 minutes after sunset in August. Jupiter fades from magnitude –1.9 to –1.7 and its disk shrinks from about 34″ to 32″ wide over the course of the month. The gap between Jupiter and Spica narrows from about 8° to 4°. On August 10th binoculars show Jupiter at its closest (0.6°) to 4th-magnitude Theta (θ) Virginis.

Saturn, magnitude +0.4, hovers in southeastern Ophiuchus this month, glowing at its highest (about 27°) due south in late twilight.

Saturn's rings will appear slightly more open in October, when they reach maximum tilt (27.0°) from our perspective for the first time since 2002. But we can catch Saturn higher at nightfall now, when the ring tilt is essentially the same. The planet's globe shrinks only slightly in the eyepiece this month, from 18″ to 17″ in equatorial diameter.

Saturn becomes stationary in right ascension and ecliptic longitude on August 25th. The next day, the magnitude +0.4 world stands a minimum 12.6° upper left of distinctly less bright Antares; it then starts moving away from the star with direct (eastward) motion.

NIGHT

Neptune, in Aquarius, rises during evening twilight and finishes the month

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

just days from opposition. The 8th-magnitude ice giant transits about 3 a.m. daylight-saving time at the beginning of the month, 1 a.m. by the end.

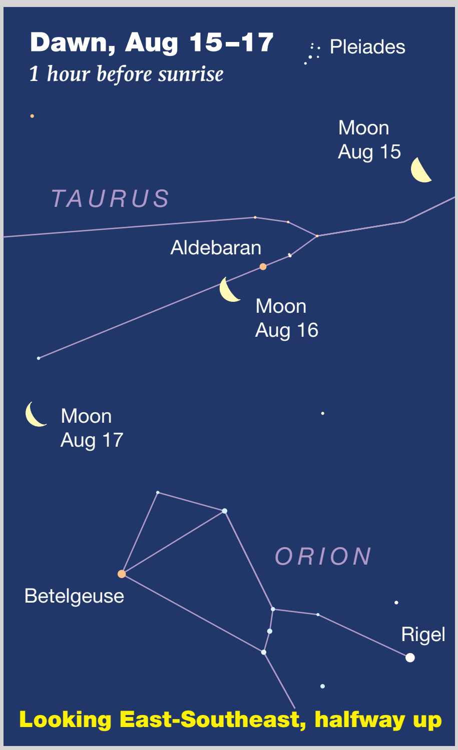
Uranus, two magnitudes brighter than Neptune, awaits you in Pisces. It rises in the late evening and is highest just before morning twilight. Check **skyandtelescope.com/urnep** for finder charts for both Neptune and Uranus.

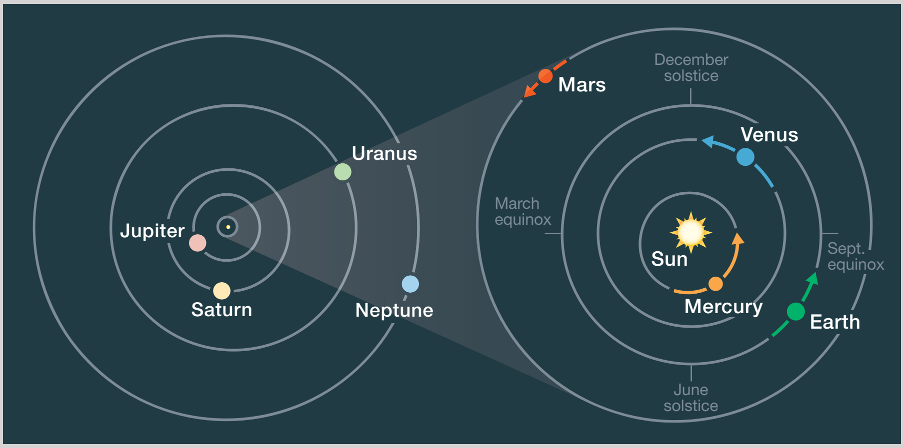
DAWN

Venus comes up roughly 3 hours before the Sun in August, long before the very first sign of dawn, shining at magnitude –4.0 in the first half of the month and –3.9 in the latter half. Its gibbous phase thickens to 83% lit, while its apparent diameter shrinks from 14½″ to 12½″.

Venus was at greatest elongation west of the Sun back on June 3rd but reaches its greatest sunrise altitude, about 30° high, on August 2nd for skywatchers near latitude 40° north. That morning, binoculars or telescope show the big open cluster M35 just 2½° upper left of Venus.

The resplendent planet spends most of the month crossing Gemini. On the morning of August 17th, Venus blazes 1° directly below Delta (δ) Geminorum and 8° right of Pollux. By the morning of August 25th, Venus has crossed into Cancer, where the planet ends the month as it began: on the verge of passing a big open star cluster, in this case M44, the Beehive.





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

SUN AND MOON

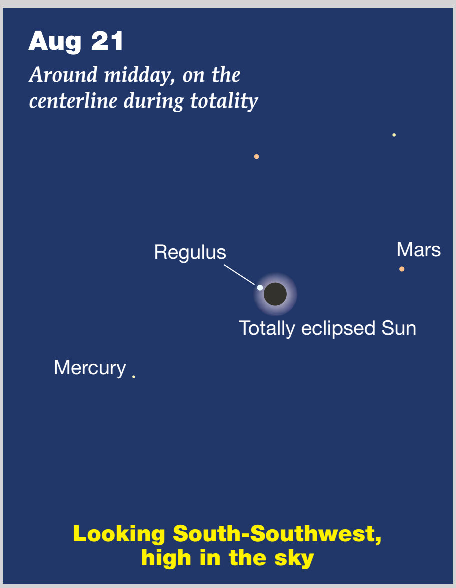
The waxing gibbous **Moon** shines about 3° or 4° upper right of Saturn on the evening of August 2nd. The Moon is partially eclipsed for most of the Eastern Hemisphere on the night of August 7–8; see page 50.

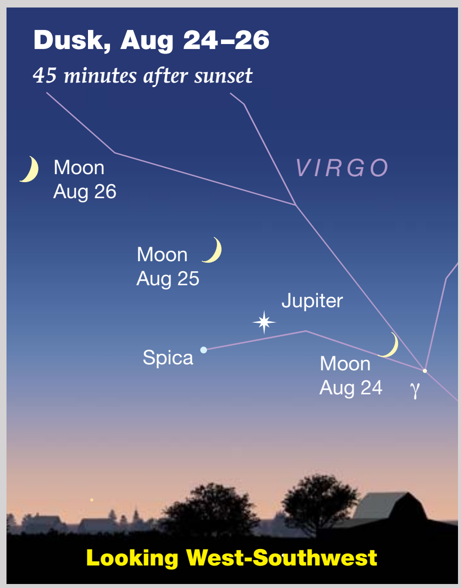
The waning crescent Moon is close to Aldebaran as they rise on the night of August 15–16. A much thinner lunar crescent hangs directly below Venus on the morning of August 19th. A still thinner crescent may be viewable with binoculars the next morning, far lower left of Venus.

The **Sun** is totally eclipsed by the new Moon on August 21st; see pages 20 and 48 for more.

The waxing crescent Moon hopscotches past Jupiter and Spica on the evenings of August 24th and 25th. It passes Saturn on the evenings of August 29th and 30th.

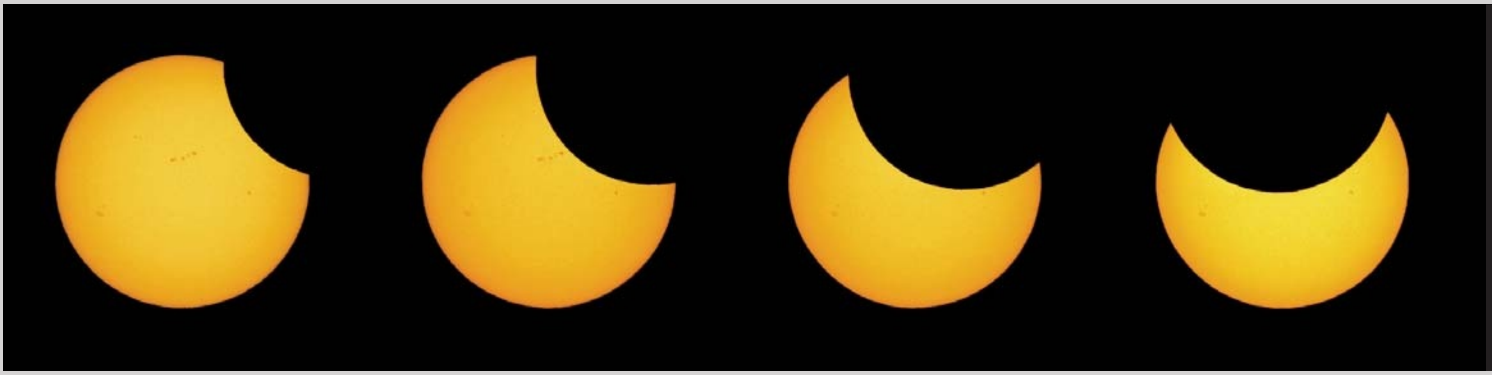
■ Contributing Editor **FRED SCHAAF** welcomes your letters and comments at fschaaf@aol.com.

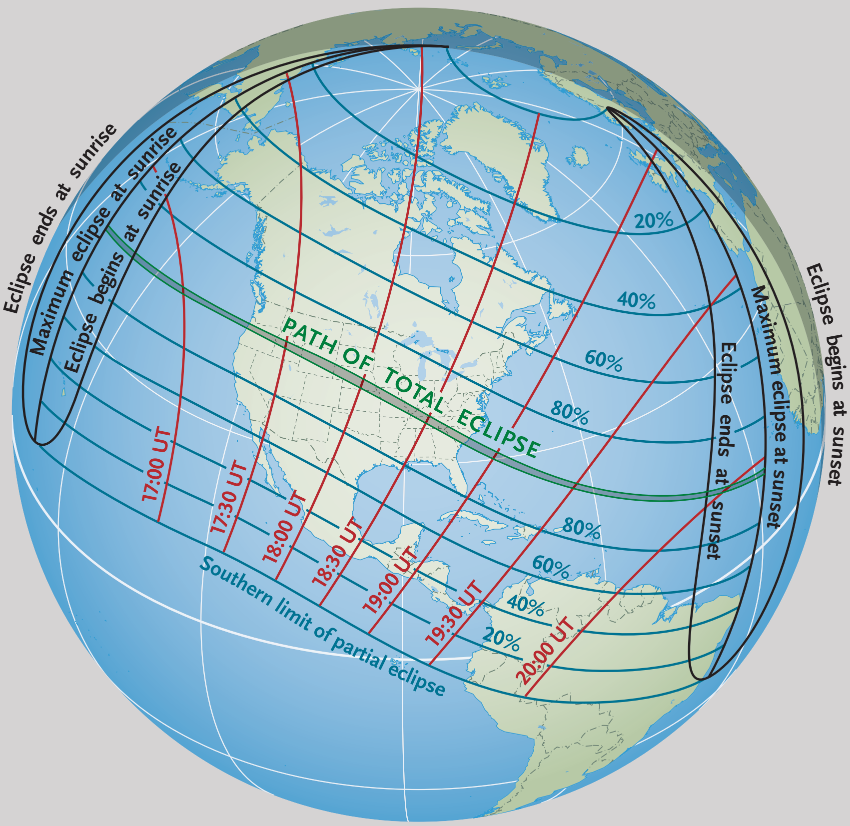




The Solar Eclipse for the Rest of Us

Totality watchers get the best show, but a far greater number of people will be in partial-only territory. Here's how to make the most of it.





▲ The partial eclipse crosses most of the Americas. The red lines give the Universal Time of mid-eclipse. The blue lines tell the eclipse magnitude (the percent of the Sun's diameter covered) at that time. Of totality's 8,600-mile-long track, about 30% falls on land.

Over the years we've had a lot to say about America's total eclipse of the Sun coming up on August 21st. See pages 14, 20, and 66 in this issue, catch up on more online at **skyandtelescope.com/2017-eclipse**, and get local maps as detailed as you want at **https://is.gd/2017eclipsemap**. But as the broader maps on these pages show, for the vast majority of people in North America, Central America, and northern South America, the eclipse will be only partial.

Here are ways to make the most of it — without endangering your eyes.

How to Watch

The blindingly brilliant surface of the Sun can be *actually* blinding, perhaps permanently, if you stare at it for any length of time. And that also goes for the bright part of a partially eclipsed Sun.

You have two basic ways to watch safely: directly through a *safe solar filter,* or indirectly by *projection.*

Direct viewing. For this you'll need a filter that's specifically designed for Sun viewing: one that reduces the Sun's invisible infrared and ultraviolet rays as much as it does visible light. All of the inexpensive little "eclipse glasses" that we've tested do fine, but just to

SERIES: FRED ESPENAK; GLOBE: *SKY & TELESCOPE*, SOURCE: FRED ESPENAK be sure, look for "ISO 12312-2" printed on them.

For binoculars or telescopes, you can buy solar-filter material made of glass or thin, metal-coated plastic film — either as a sheet you can cut with scissors to attach over the front of your optics, or pre-mounted in a cell sized to fit firmly onto the front (don't let it blow off!). Leave the film slack; wrinkles don't matter, but stretching it will haze out the view and compromise safety. When

oldest, simplest, but poorest projection method is to use a pinhole. For instance, take a long box, cut a hole in one end, tape aluminum foil over the hole, and put a pinhole in the foil. Tape white paper inside the other end of the box, close it up, and cut a big hole in the side so you can look at the paper. Aim the pinhole at the Sun, and an image of the Sun's face will fall on the paper.

But the image will be very small and dim. Experiment with different sized

instrument at the Sun (without looking in it! Move it around until its shadow is minimized and light floods out of the eyepiece). On a telescope, use your lowest-power eyepiece. Focus the image with the focus knob and/or by moving the paper catching the image closer or farther back. If the scope's aperture is larger than about 3 inches, cut a clean, 3-inch hole in thin cardboard and tape it over the front. You don't want to let a damaging amount of solar heat inside.

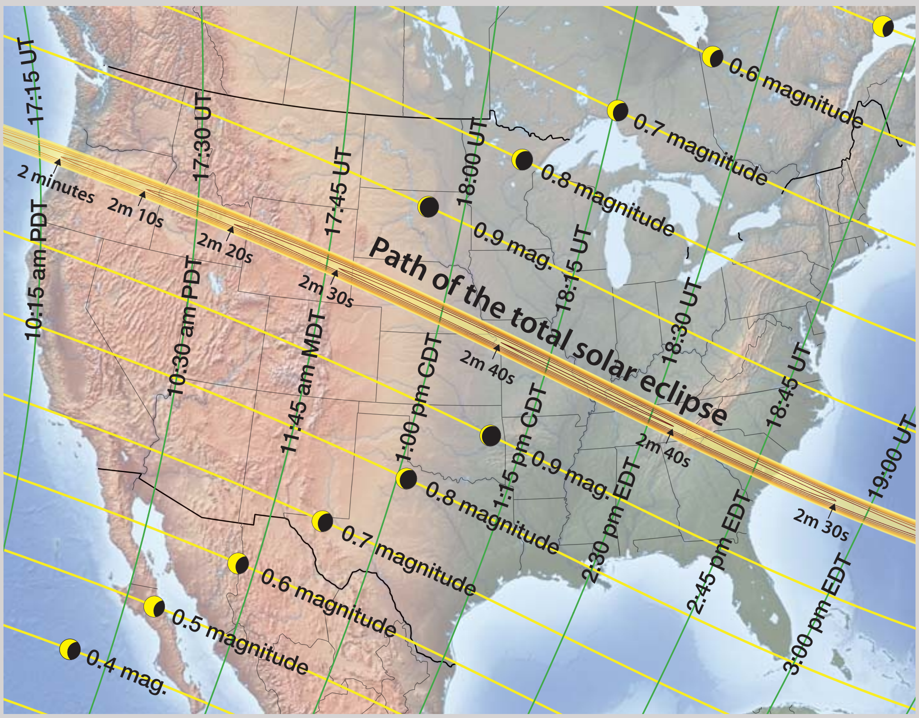
The Christmas 2000 eclipse was partial only. For photographer Fred Espenak, its maximum "eclipse magnitude" (middle image) was 43%.

we tested various glass and thin-film solar filters few years back, we liked the Baader Astro-Solar thin film the best.

Projection means projecting an image of the Sun onto a piece of white paper and watching the paper. The

pinholes. A large one makes the image bright but fuzzy; a small one makes it sharp but dim.

Much better is to use binoculars or a telescope to project a big, bright image, as shown on the next page. Aim the



MICHAEL ZEILER

◀ Zooming in for more detail. Along the path of totality, extremely narrow red ellipses tell the duration of total eclipse by time ticks at their ends.

What To Watch For

- Can you see any **sunspots?** Don't get your hopes up; the Sun is well past the 2014 maximum of its 11-year activity cycle, and its face these days is pretty quiet, sometimes completely blank. But if you do see a spot or two, they will be landmarks for events coming up. If you're projecting the Sun's image onto paper, wiggle the paper to distinguish sunspots from tiny paper flaws.
- **First contact** is the moment when the edge of the Moon first touches the Sun's western edge. Find the exact time of this event for your location by clicking on the Google Map at **https://is.gd/2017eclipsemap**. But the Moon's edge will take a little while after first contact to intrude enough to begin to show. How well can you time when this happens? What's the delay as seen with your setup? Set your timepiece accurately beforehand.
- As the Moon leisurely intrudes farther onto the Sun, look for irregularities

▲ Projecting the Sun. Put binoculars on a tripod and point them sunward. Adding a cardboard shield around them creates a large shaded area for viewing the projected image.

Partial Lunar Eclipse

BY NO COINCIDENCE, the Moon will pass through the edge of Earth's shadow on August 7th, half an orbit before it casts its own shadow onto us. (The Moon's orbital line of nodes points toward the Sun this month.) Facing the Moon at the time of the lunar eclipse will be eastern Europe (around sunset on the 7th), Africa and Asia, and Australia (before sunrise on the 8th local date).

The time of maximum partial eclipse is 18:20 UT August 7th. At that time 25% of the Moon's diameter will be in the dark umbra of Earth's shadow. Partial eclipse runs almost two hours, beginning at 17:22 and ending at 19:18 UT. Pale penumbral shading will be detectable on the side of the full Moon for another 40 minutes or so before and after. For details and a world map of the eclipse's visibility, see **http://is.gd/lunareclipseAug2017**.

showing up on the edge of the Moon's silhouette. These are **lunar mountains** and valleys seen in profile along the Moon's limb. The Sun's edge, by contrast, is perfectly smooth.

• Keep an eye on those sunspots. If the black lunar silhouette approaches a big one, and if you're looking through a fairly large filtered scope, you should be able to see that, by comparison, the **sunspot's dark umbra is not truly dark**. Photos to the contrary, sunspot umbras shine with about 20% the surface brightness of the rest of the Sun. They would appear blindingly brilliant if the rest of the Sun weren't there and dictating the density of your solar filter.

• As the eclipse progresses, look around at the **landscape and blue sky**. Is the blue becoming deeper and purer? You may be surprised by how much sunlight has to be lost before the world *looks* any different. This is a measure of how well our eyes naturally adapt to changing lighting conditions.

If the partial eclipse at your site is deep and the Sun becomes a thin crescent, watch for the landscape to take on a slightly alien, silvery look, with shadows turning crisper than usual.

• **How deep** will the eclipse become at your location? The Google Map tells this two ways. The maximum *magnitude* of the partial eclipse is the *percent of the Sun's diameter* that the Moon will cover. The *obscuration* tells what fraction of the Sun's *surface area* is covered. That's also about how much light is lost (although the Sun's disk is a little dimmer around its edges than near its middle, a solar-atmosphere effect called *limb darkening*).

• **Venus and Jupiter** may become visible if the sky turns a deep enough blue. Venus is your first try. Look for it 34° (about 3½ fists at arm's length) to the Sun's celestial west. Next brightest is Jupiter, 50° to the Sun's east.

Unless the eclipse becomes total or very nearly so, you don't have much hope for Mars (magnitude +1.8) some 8° west of the Sun, Regulus (+1.4) just 1° to the Sun's east-southeast, and certainly not Mercury, fainter still at +3.3, 10° to the Sun's southeast.

• Look for dim **dapples of sunlight on the ground** under trees. A leaf canopy may form many pinhole projectors, and

▲ During the partial eclipse, cross two hands so your fingers make a waffle pattern. The holes between them act as pinhole projectors to create tiny crescent Sun images in the shadow below.

Lunar Occultation in Libra

EARLY ON the evening of July 31st, telescope and binocular users in central and eastern North America can watch the dark limb of the Moon, just past first quarter, occult the close double star Gamma Librae, total magnitude 3.9.

The occultation will occur in two quick steps as seen from most locations. The stars of the pair are nearly twins, magnitudes 4.7 and 4.9, but they are only 0.1 arcsecond apart (oriented southeast-northwest), much too close for amateur telescopes to resolve. The Moon moves that far along its orbit in just 0.2 second, so be prepared for the two steps of the disappearance to happen so fast they'll be almost indistinguishable. They'll happen a little more slowly for observers near the occultation's southern limit, which crosses the Florida Keys.

Some times of the star's disappearance: **Kansas City,** 9:21 p.m. CDT; **Austin,** 9:38 p.m. CDT; **Chicago,** 9:29 p.m. CDT; **Atlanta,** 10:52 p.m. EDT; **Toronto,** 10:39 p.m. EDT; **Montreal,** 10:45 p.m. EDT; **Miami,** 11:29 p.m. EDT; **Washington, DC,** 10:52 p.m. EDT; **western Massachusetts,** 10:52 p.m. EDT.

BINOS: *SKY & TELESCOPE* (2); FINGER-SPREADING: J. KELLY BEATTY during a partial eclipse each dapple will show an identical dent. Or make little holes between the fingers of your two hands laid across each other, as shown in the photo at lower left.

And then watch everything slowly unwind in reverse, until the Moon's last trace slides off eastward into invisibility, and last contact ends the show until next time.

And when is that?

The next North American partial eclipse happens for the northeastern U.S. and eastern Canada around sunrise on June 10, 2021. Then nearly all the continent is partially eclipsed on October 14, 2023, when an annular eclipse runs from Oregon to Texas and points south.

The next *total* solar eclipse awaits North Americans on April 8, 2024, running from Mexico through Texas, the Midwest, northern New England, and the Maritimes. Again, almost all of the continent will be partially eclipsed.

Perseid Forecast: Partly Moony

▲ When things go right: A Perseid fireball dove across Taurus while sky photographer Kim Myoung Sun had his shutter open on the morning of August 13, 2013. Below it, Orion is rising.

KIM MYOUNG SUNG

IN THEORY, the Perseid meteor shower this year should reach its peak around 19^h Universal Time August 12th, during broad daylight for North Americans. But the peak usually continues for at least 24 hours, enough to overlap the prime late-night Perseid-watching hours — from 10 or 11 p.m. until the beginning of dawn — on the nights of August 11-12 and 12-13 for our part of the world.

The Moon is approaching last quarter on those nights, rising right about when the prime hours begin: that is, when the shower's radiant point (between Perseus and Cassiopeia) starts getting pretty high in the northeast. The moonlight in the sky will interfere somewhat, but not nearly as badly as when the Moon is near full.

So you may expect to see a Perseid every couple of minutes, on average, late those nights. Lie back in a reclining lawn chair, keep the Moon and any bright lights out of your field of vision, and watch whatever part of your sky is darkest. Relax, be patient, and unless you have really bad light pollution (or bad luck), you'll probably witness the brief, bright ends of at least a few ancient comet particles.

Want to try doing a real meteor count, moonlight and all, for reporting to the International Meteor Organization? Read how at **imo.net/visual/major**.

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.

Changes Real and (Mostly) Imagined

Even renowned lunar observers have sometimes been fooled by tricks of lighting and resolution.

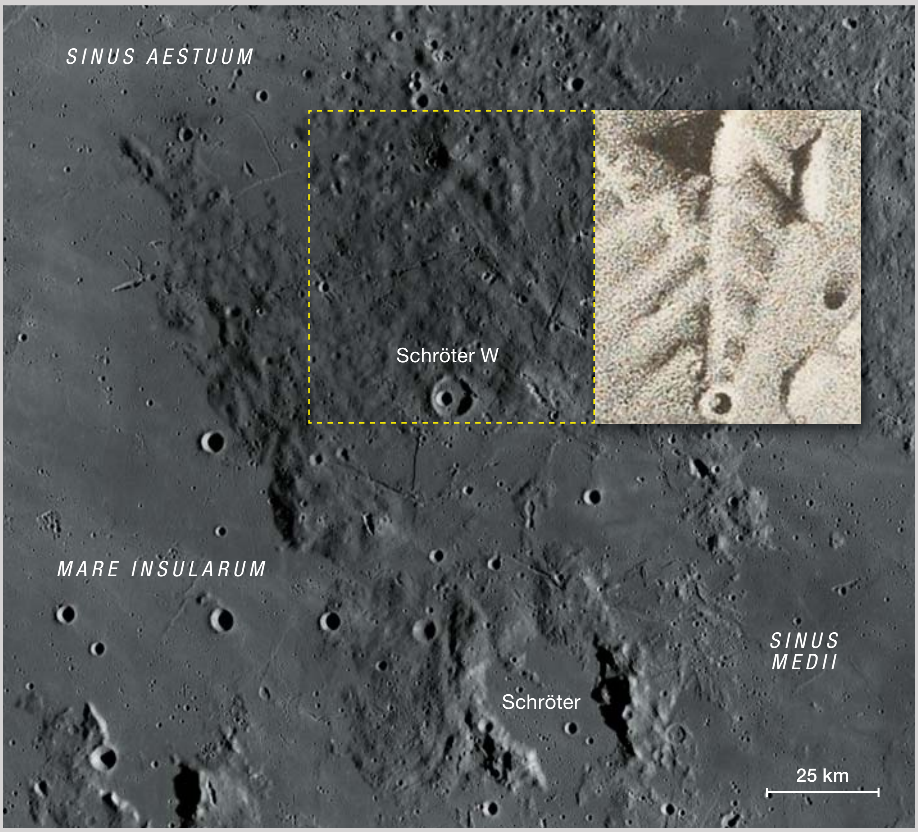
The 19th century was a period of great progress in lunar mapping. A succession of German observers produced progressively larger and more detailed maps of the Moon that provided the foundation for future studies. But some of their contemporaries devoted much effort to investigating small features that purportedly changed their appearance or had newly formed.

The search for such alterations followed widespread speculation during the 17th and 18th centuries that life must be common throughout the solar system, including on the Moon. Consequently, many observers accepted that changes occur on the Moon, as they do on Earth, either naturally or from the work of intelligent creatures.

William Herschel, the greatest observational astronomer of the time, reported volcanic eruptions at the crater Aristarchus in 1787, and he thought Mare Humorum was a great forest. In 1822 German observer Franz von Paula Gruithuisen discovered a nearly rectilinear complex of ridges that he interpreted as a walled city (pictured below). Two years later he claimed to have seen differences, presumably evidence that the city was still under construction. Although other observers detected his odd formation, in time they dismissed Gruithuisen's fantastical interpretations and concluded that his "city" was likely a natural formation.

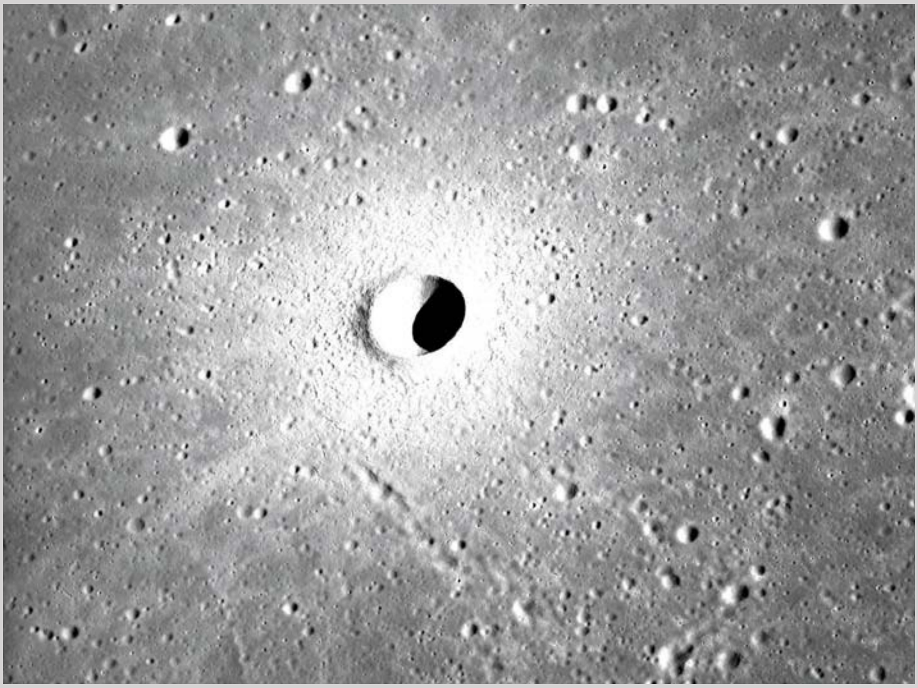
In the mid-1830s, Wilhelm Beer and Johann Mädler published their magisterial map and book *Der Mond,* in which they concluded that the Moon had no atmosphere and apparently no water and thus was unlikely to host life. The authority of *Der Mond* curtailed the idea of a changing Moon for a generation. But by the 1850s, observers with bigger telescopes began to notice minute details, such as a small crater on the wall of **Helicon** in western Mare Imbrium, that were missing from Beer and Mädler's map. They often interpreted such inconsistencies as tantalizing evidence for the recent formation of these small features.

Then in 1866, J. F. Julius Schmidt, the greatest lunar observer of the time, announced that Linné, depicted as a 10-km-wide crater in *Der Mond* and on detailed maps by Wilhelm Gotthelf Lohrmann, had disappeared. This set off an excited frenzy of observing that led to widespread confirmation of Schmidt's discovery. Many reported seeing Linné as just a diffuse bright spot with a tiny, 2-km-wide pit at its center. This evidence, combined with great respect for Schmidt, led observers to accept that a real change had occurred. Schmidt himself proposed that a volcanic eruption had covered the original Linné, and



◀ This patch of lunar terrain on the eastern margin of Mare Insularum looks nondescript. But in 1824, observer Franz von Paula Gruithuisen believed the region's low ramparts to be walls of a lunar city under construction (as he sketched in the inset). North is up.

NASA / LUNAR RECONNAISSANCE ORBITER; INSET: NATURAL SCIENCE COLLECTION / HAAB WEIMAR



▲ Seen as imaged during the Apollo 15 mission, the 2.4-km-wide crater Linné sits near the western edge of Mare Serenitatis. Its extensive apron of highly reflective ejecta is obvious near full Moon — but spotting the crater itself can be challenging.

indeed other observers perceived that the tiny new crater, presumed to be volcanic, was enlarging, suggesting that the eruption had continued.

More than a decade later, another reported lunar change again excited European astronomers. The British *Selenographic Journal* of February 21, 1879, reported that Hermann Klein, an experienced German observer, had discovered a deep and conspicuous new crater near the Hyginus Rille (known today as **Rima Hyginus**). For the next year many observers searched for "Hyginus N" (for nova or new), finding instead a shallow depression that appeared dramatic only under very oblique sunlight.

And for many decades, from the 1870s onward, amateur astronomers debated the appearance and disappearance of tiny craterlets on the floor of **Plato**. When they weren't seen, proponents invoked a mist or other obscuration.

Reality Check

Change *does* occur on the Moon, because craters form all the time. Last year a team led by Emerson Speyerer (Arizona State University) published a compilation of 222 new craters spotted in before-after pairings of Lunar Reconnaissance Orbiter images. None of these, including two seen as bright flashes from Earth as they formed, are more than a few tens of meters across — far too small to be seen telescopically.

But there's no convincing evidence for the kinds of lunar surface changes reported by Gruithuisen, Schmidt, and Klein. These ephemeral sightings weren't the result of geologic or atmospheric phenomena — the real causes were poor seeing, poor illumination, inferior optics, or bad eyesight. In *Epic Moon,* authors William Sheehan and Thomas Dobbins explain that observers of that era *expected* changes to occur on the Moon, so this became the default explanation for unusual sightings. Although a handful of 19th-century astronomers did express misgivings about the veracity of earlier maps, the desire for a dynamic Moon overwhelmed caution.

The search for lunar changes continues, now gentrified under the catchall term *transient lunar phenomena*. Remarkably, some past reported changes do involve accurately documented observations of topographic appearances that only reoccur under specific illumination and libration conditions. Our astronomical predecessors were often careful observers but not critical thinkers.

You can see for yourself how difficult it can be to make reliable observations by looking at some famous examples. For example, Herschel's "volcanic eruptions" occurred when earthshine flooded **Aristarchus** — a very bright crater whose visibility varies according to seeing and illumination conditions. Check on Aristarchus each time you observe the Moon before first quarter to see if you detect any "eruptions."

Gruithuisen's walled city is hard to find unless the illumination is just so; otherwise its ramparts become scraggly ridges. The "wall" pattern is within the dark pyroclastic deposits between **Sinus Aestuum** and the crater **Schröter**.

The bright apron of pulverized ejecta that surrounds **Linné** is easy to spot whenever the Sun is positioned high over western Mare Serenitatis. Conversely, glimpsing its small crater pit requires decent seeing, a low Sun angle, a telescope with an aperture of at least 4 or 6 inches, and high magnification.

As you look at these and other regions you might notice small features that don't appear on previous maps. If so, please don't tell me.

■ Contributing Editor CHUCK WOOD has been taking *S&T* readers on telescopic lunar explorations since July 1999.

▲ Of the hundreds of new craters identified by NASA's Lunar Reconnaissance Orbiter, this one — 43 meters across — is the largest. Colors represent elevation, with dark blues the lowest.

TOP: NASA; BOTTOM: NASA / LUNAR RECONNAISSANCE ORBITER

Overlooked Wonders of Summer

Take some time to explore these lesser-known deep-sky sights.

The summer sky hosts such an amazing wealth of celestial wonders that the more obscure ones receive little notice from many skygazers. Let's dedicate this tour to some of the overlooked denizens of the deep that wend their way high across the sky for observers at mid-northern latitudes.

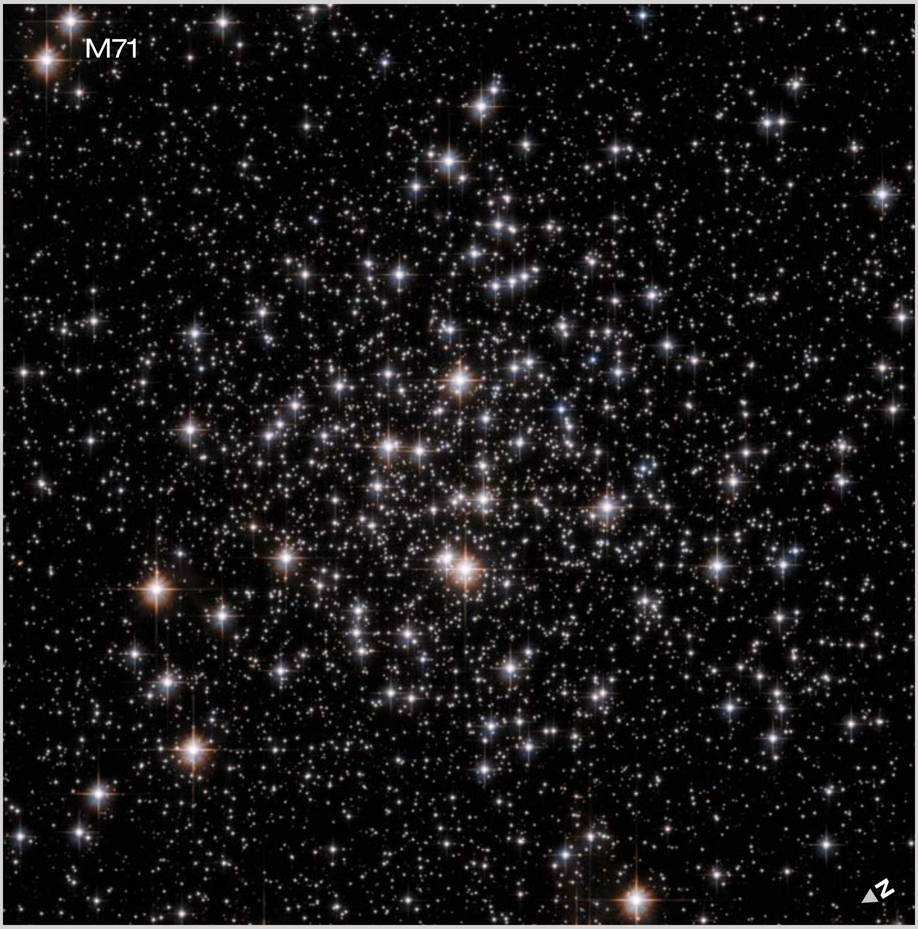
We'll begin in little Sagitta, the Arrow, perchance a stray bolt from the bow of Sagittarius that now lies awash in the misty river of the Milky Way. The only commonly visited object in Sagitta is the globular cluster **Messier 71**, but even it is frequently passed by in favor of the much brighter globulars that adorn the sky at this time of the year. Yet M71 has a charm of its own.

Messier 71 handsomely poses about halfway along and a little south of an imaginary line connecting Sagitta's two brightest stars, the red giants Gamma (γ) and Delta (δ) Sagittae. In a moderately dark sky, the cluster is a small, fairly faint fuzzball through 12×36 binoculars. Off its western side, three equally spaced stars in a straight line increase in brightness with distance from the cluster, ending with 6th-magnitude 9 Sagittae.

In my 130-mm refractor at low power, M71 presents a faint, 7′ halo and a bright, 2½′ core closely guarded by a dim star to its south. The cluster is lovely at 117×, with at least 20 diamond-chip stars tangled in its silvery web. Some of the brightest are arrayed in an east-northeast to west-southwest line across the center. At 164× the cluster bears the glittery appearance of many stars on the verge of resolution. M71's core looks nearly triangular through my 10-inch reflector at 166×. Nearby stars craft the stem of an arrowhead that points west-southwest.

M71 is a sparkling globe teeming with 15,000 stars. At a distance of 13,000

▲ One of the great pleasures of amateur astronomy is creating asterisms at the eyepiece. When viewed through a 14½-inch reflector at 112×, the open cluster Harvard 20 turns into a horse.



◀ This spectacularly deep image of M71 was created from frames taken with the Wide Field Channel of the Advanced Camera for Survey on the Hubble Space Telescope. The field of view is about 3.4 arcminutes across.

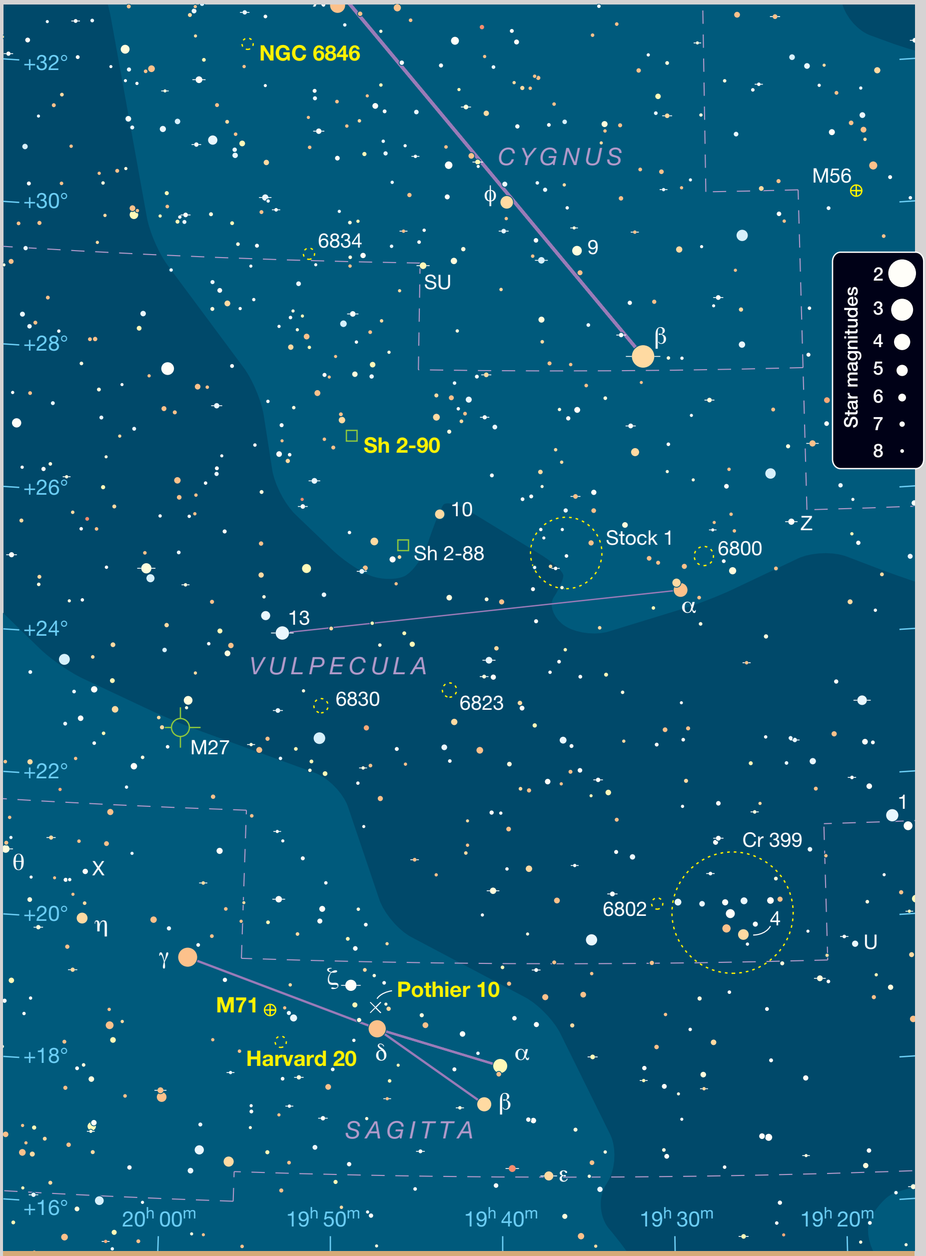
MESSIER 71: ESA / HUBBLE SPACE TELESCOPE / NASA; HARVARD 20: NICO DE JONGH light-years, it's the third-nearest globular cluster in Charles Messier's catalog, topped only by M4 in Scorpius at 7,200 light-years and M22 in Sagittarius at 10,000 light-years. Ensconced in the dusty disk of our galaxy, M71's true glory is regrettably diminished. It would shine nearly a magnitude brighter were we favored with a clear view.

The open cluster **Harvard 20** can share the field of view with M71 at low to medium magnification and is about the same size, yet it's even more neglected. The 130-mm scope at 23× reveals two moderately bright and three faint stars in an 8′-long, zigzag line. At 117× about 25 stars emerge, mostly gathered into a wide band with two nice star pairs in its east-southeastern end. Through his 14½-inch reflector at 112×, Dutch amateur Nico de Jongh sees Harvard 20 as a standing horse, with many of its stars glimmering at 15th magnitude. He also reports that another Dutch amateur could see the horse clearly in a 20-inch scope. Can any of you large-scope enthusiasts spot Nico de Jongh's Horse?

Although Harvard 20 may look close to M71 on the sky, it's only two-fifths as distant. According to a 2013 star-cluster catalog by Nina Kharchenko and colleagues, Harvard 20 has 123 probable members. The designation Harvard comes from the second monograph of the Harvard Observatory series, written by Harlow Shapley. It was published as the book *Star Clusters* in 1930 (McGraw-Hill Book Company).

French amateur Yann Pothier came across an interesting star group 18′ north of Delta Sagittae, now known as **Pothier 10** or the HD 350541 Group. My 130-mm scope at 68× shows a 6′ dusting of a dozen faint suns, with 10.8-magnitude HD 350541 inside its northeastern edge. A magnification of 102× increases the star count to 22. Merely masquerading as a cluster, Pothier 10 has proved to be a chance alignment of unrelated stars.

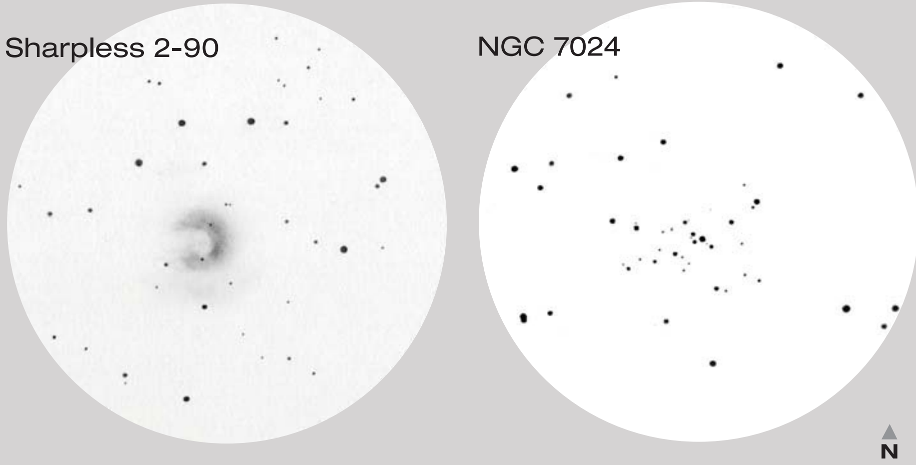
Let's hop north into Vulpecula and take a look at the emission nebula **Sharpless 2-90**, found 1.6° northeast of 10 Vulpeculae and 17′ southwest of 6.5-magnitude, yellow HD 187614



Oft Overlooked Objects

Object	Type	Mag(v)	Size/Sep	RA	Dec.
Messier 71	Globular cluster	8.2	7.2′	$19^h\ 53.8^m$	+18° 47′
Harvard 20	Open cluster	7.7	10′	$19^h\ 53.2^m$	+18° 19′
Pothier 10	Asterism	—	6.0′	$19^h\ 47.5^m$	+18° 50′
Sharpless 2-90	Emission Nebula	—	6.8′	$19^h\ 49.3^m$	+26° 51′
NGC 6846	Open cluster	14.2	0.9′	$19^h\ 56.5^m$	+32° 21′
NGC 7024	Open cluster	—	10′	$21^h\ 06.1^m$	+41° 30′
Burnham 988	Double star	9.9, 10.1	9.3″	$21^h\ 07.0^m$	+41° 25′

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.



▲ *Left:* A narrowband filter will improve your view of the emission nebula Sharpless 2-90 (also cataloged as LBN 144) in Vulpecula. Although relatively bright, this nebula is probably out of reach for urban viewers. An 8-inch scope will reveal it under darker skies. *Right:* The "non-existent" open cluster NGC 7024 is actually composed of 30 or more stars spanning about 10′.

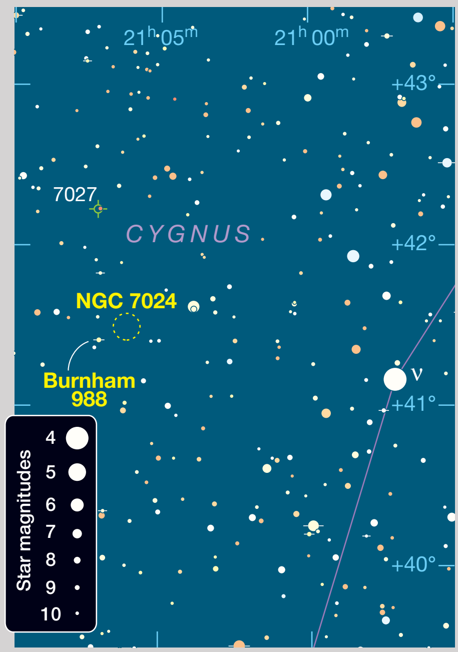
SHARPLESS 2-90 & NGC 7024: JAAKKO SALORANTA

(SAO 87785). From my semirural home, the nebula is quite elusive through the 10-inch scope at 115× with a narrowband nebula filter. At 187× I sketched the arc-shaped glow without a filter, and later compared it to an image in the online sky atlas Aladin. This confirmed a fat, C-shaped band of nebulosity running through the four dim stars on my sketch. Finnish observer Jaakko Saloranta was able to stunningly capture even more of its gauzy glow using his 8-inch scope at 96× with a narrowband filter.

A 2014 study by Manash Ranjan Samal and colleagues suggests that the formation of the massive hot stars and young stellar objects (YSOs) found at the periphery of Sh 2-90 may have been triggered by the expansion of the nebula into its surrounding molecular cloud.

Continuing northward into Cygnus, we'll come to **NGC 6846**. This small open cluster often goes unnoticed because many references give a position that's 2° too far south. In addition, there are no naked-eye stars nearby, except when the Mira-type variable Chi (χ) Cygni is at maximum, which won't occur again until the latter half of October. The lack of bright signposts is unfortunate, because spotting the cluster at low power through a small telescope is probably impossible. Consider this a challenge object.

In my 130-mm scope at 164×, NGC 6846 is a ball of extremely faint haze a bit brighter in the center. Averted vision and an exact knowledge of the cluster's position aid in seeing it. It's still faint but much easier to see through the 10-inch scope at 115×. At 213× I estimate a size of ¾′ for the cluster. A very faint star sits just off the western side, and a couple of stars or stellarings are intermittently visible within. The cluster's glow is reasonably bright with my 15-inch scope at 247×, and it holds a few very faint points of light.



We owe NGC 6846's shy and retiring appearance to the fact that it's 14,500 light-years away, more distant than the globular cluster M71, and suffers about three magnitudes of extinction from interstellar dust along our line of sight.

Also in Cygnus, but easier to find, is **NGC 7024**, located 1.7° east-northeast of Nu (ν) Cygni. This open cluster lacks attention partly because it was deemed non-existent in *The Revised New General Catalogue of Nonstellar Astronomical Objects* (Jack W. Sulentic and William G. Tifft, 1973). Sulentic couldn't verify it on the 1950s National Geographic Society — Palomar Observatory Sky Survey prints. But as NGC/IC researcher Harold Corwin writes, "Even though RNGC claims non-existence for this cluster, it is a very nice object of about 30 stars close to the NGC position."

Even in my little 105-mm refractor at 47×, NGC 7024 displays a dozen faint to very faint stars. The cluster is accompanied by an eye-catching pair of nearly matched stars 12′ to east-southeast, **Burnham 988** (β988 or BU 988). At 87× I count 20 stars spanning 10′, including a small concentration of slightly brighter stars in the cluster's middle. The 10-inch reflector at 68× discloses an elongated knot of six stars enfolded by a cloud of fainter suns covering 9′. At 187× about 40 glistening stars, 11th-magnitude and fainter, loosely sprawl across 10′ of sky.

NGC 7024 is about 4,900 light-years away from us, its stars dimmed 2 magnitudes by the dusty disk of the Milky Way.

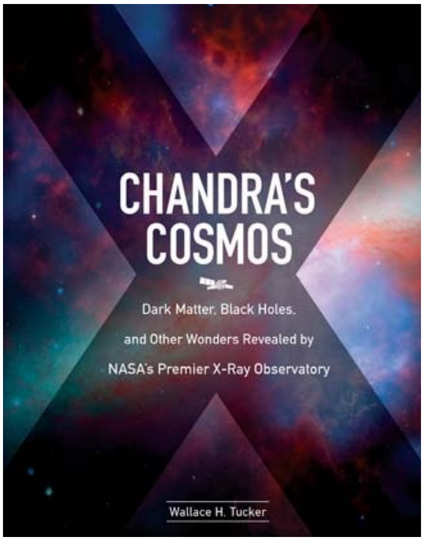
With the exception of Messier 71, none of objects along our journey could be rightfully called splashy, but it's sometimes nice to stroll the road less traveled in our wanderings among the stars, collecting a handful of wonders that few observers call their own.

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

X-Ray Revelations

CHANDRA'S COSMOS: *Dark Matter, Black Holes, and Other Wonders Revealed by NASA's Premier X-Ray Observatory*

Wallace H. Tucker
Smithsonian Books, 2017
272 pages, ISBN 978-1-58834-587-5
$29.95, hardcover.



LIKE MOST visual observers, I don't spend a lot of time thinking about X-rays when I'm at the eyepiece. Give me a telescope, a deep-sky atlas, and an O III filter, and I'm usually good for the night. But when *Chandra's Cosmos: Dark Matter, Black Holes, and Other Wonders Revealed by NASA's Premier X-Ray Observatory* landed on my desk, I picked it up immediately, hoping I would learn a thing or two. Good news: I didn't just learn a thing or two — I learned *a lot*.

You may already be familiar with the basics of the Chandra X-Ray Observatory, a space telescope launched by NASA in July 1999 to study the high-energy X-ray universe. Chandra's working life began after its deployment from the space shuttle Columbia into an orbit some 86,500 miles above the Earth. (Space telescopes enable astronomers to detect wavelengths that never make it through Earth's atmosphere.) Since first light — NASA released Chandra's first images of the supernova remnant Cassiopeia A on August 26, 1999 — Chandra has functioned as a "cosmic X-ray machine," gathering observational data in the form of high-resolution X-ray images of the hottest regions of our universe, such as galaxy clusters, black holes, and supernovae. Chandra's images supplement those we receive from other space telescopes (most notably the Hubble Space Telescope, which observes near-infrared, optical, and ultraviolet radiation, and the Spitzer Space Telescope, which observes in the infrared). Adding X-ray data to the picture gives astronomers a more complete vision of the universe, allowing them to model our past and future more accurately.

In *Chandra's Cosmos*, Wallace H. Tucker, Science Spokesperson for the Chandra X-Ray Center at the Smithsonian's Astrophysical Observatory, takes on the tremendous task of interpreting the X-ray universe for the layperson. It's not an easy or enviable job. For instance, to interpret an X-ray image of the galaxy cluster Abell 383 for the reader, first Tucker has to explain dark matter (hot, cold, and warm), dark energy, and competing theories of gravity (Einstein is still the best thing going). To clarify Chandra's contributions to the study of supernovae remnants, parts of which are only detectable in the X-ray, Tucker has to first walk the reader through a course in stellar chemistry and nuclear physics.

Sound complicated? It is. But luckily, the combination of Tucker's lucid prose and Chandra's high-resolution imagery makes it seem less so. I admit: I had to read some of the dark matter discussion a few times over, and the physics of black holes can be truly mind-blowing, but the deeper I got in the book, the more it all made sense.

Tucker groups Chandra's triumphs under three headings: The Big (think cosmology, especially questions of dark matter and dark energy); The Bad (black holes, Seyfert galaxies, and quasars); and The Beautiful (supernovae, their remnants, and neutron stars). Each section focuses on a big question in astronomy (How does a black hole merger happen? How do stars die?) and includes a "reading" of Chandra images that astronomers use as part of their answer. I appreciated the inclusion of the controversies and the arguments. Tucker frequently leads with the most accepted solution to a problem but includes evidence from its detractors as well.

Chandra's Cosmos is an attractive volume with illustrations weighted toward the purple end of things, as you might expect from a book on X-ray astronomy. Tucker decodes each image, sometimes using supplemental diagrams, to explain what we're seeing and show how astronomers are using the colorful data. Initially, the matte finish of the pages disappointed me, but once I began following Tucker's arguments through the images, I began to appreciate the book's resilience to fingerprints.

If you have a quiet space nearby and a little time for thinking, don't hesitate to pick up *Chandra's Cosmos*. This is one book that will change the way you see our universe.

■ Observing Editor **S. N. JOHNSON-ROEHR** likes her astronomy to stretch across the electromagnetic spectrum.

The Zhumell Z130

This remarkably inexpensive tabletop Dob is an outstanding performer.

◀ The Z130 is very solidly built, which makes it considerably bigger and heavier than other one-arm 130-mm Dobsonians.

Zhumell Z130 Portable Altazimuth Reflector

U.S. Price: $199
Available at telescopesplus.com

What We Like:

Good optics

Rotatable tube

Tube rings attach directly to most commercial mounts

What We Don't Like:

Requires tools for collimation

Base unusually large and heavy

TO MY MIND, the perfect beginner's telescope should be inexpensive and easy to use, yet sufficiently capable to remain a prized possession even after one acquires a great deal of experience and possibly additional telescopes. One design that meets these criteria is the Dobsonian reflector. But full-sized Dobs are heavy, bulky, and clumsy-looking, which is a psychological deterrent for many beginners and a practical problem for people who can't lift much or have limited storage space.

A new alternative has become available in recent years: the 130-mm (5.1-inch) f/5, single-arm, tabletop Dobsonian. These gather almost as much light as traditional 6-inch f/8 Dobs, but in a much lighter, more compact package. And with prices around $200, they offer unparalleled bang for your buck. We have reviewed two of these scopes in the past: the Astronomers Without Borders OneSky (in February 2014 and December 2015) and the Meade LightBridge Mini 130 in December 2016. The latest entry in this field is the Z130 Portable Altazimuth Reflector from Zhumell.

I've been looking for a portable telescope to complement my 12½-inch Dobsonian, so I decided to purchase a Z130 in July 2016 and put it through its paces. The first thing that I realized, even before unpacking it, is that the Z130 is very big for its class. At 18 pounds (8.2 kg), it's about 30% heavier than the other two 130-mm tabletop Dobs I've used, and it also has a much wider footprint.

The other striking difference is that the tube is held by rings that attach to the mount using a standard Vixen-style dovetail bar. That gives the telescope unparalleled versatility. When the tube is on its native mount, you can loosen the rings and rotate it to put the eyepiece at the perfect height. Or you can pop the rings and tube assembly off the tabletop base and put them on most commercial telescope mounts without purchasing any additional hardware.

Reflecting telescopes, especially ones like the Z130 that have relatively short f/ratios, only deliver sharp images when properly collimated. Some designs hold collimation better than others, but all reflectors need to be collimated sooner or later. It's helpful to beginners if a telescope arrives reasonably well collimated right out of the box.

ALL PHOTOS BY SEAN WALKER

Collimation requires some kind of tool, which can be as simple as a reflective cap with a hole in the center or as high-tech as a laser. It also requires the center of the primary mirror to be marked in some way, preferably with a white donut.

The Zhumell Z130, like the other 130-mm tabletop Dobs I've looked at in recent years, is shipped with a center-spotted mirror. That's a great convenience for experienced astronomers and a huge benefit for beginners. While it's not really very hard to remove a mirror, center-spot it, and re-install it, the process is intimidating for beginners. However, the Z130 does not include a simple collimation tool. That's a non-issue for an experienced astronomer, who is likely to own at least one collimation tool already, but purchasing a collimation tool is an added inconvenience for a beginner who buys a Z130.

The primary mirror of my Z130 was fairly badly out of collimation when it arrived, and collimating it proved surprisingly complicated. Most reflectors have large thumbscrews to adjust the primary mirror's tilt. With the Z130, you first need to remove a thin metal plate from the back of the scope, which serves no obvious purpose besides blocking access to the collimation screws and preventing the mirror from cooling down as fast as it might.

▲ Collimating the main mirror requires removing a metal plate, then loosening three locking screws with an Allen wrench and turning the collimation screws with a Phillips-head screwdriver.

Once the plate was removed, I discovered two sets of screws were required for adjusting the primary mirror. An Allen wrench (not supplied with the scope) is needed to loosen the 3 locking screws, along with a Phillips-head screwdriver to turn the collimation screws. Fortunately, the telescope has remained in perfect collimation ever since the first time I adjusted it.

The telescope is shipped with two Kellner eyepieces, with focal lengths of 25 and 10 mm, yielding 26× and 65× respectively. Those are excellent magnifications for deep-sky observing, and the 10-mm eyepiece together with a 2× Barlow lens shows fine planetary images at 130×. But the telescope is capable of much more. A 32-mm Plössl or 24-mm wide-field eyepiece yields low-power images that are significantly wider and somewhat sharper at the edges than the 25-mm Kellner. And I found 162× using my own 4-mm eyepiece just about ideal for planetary observing.

The plastic focuser included with the Z130 is rather coarse, so focusing at such high magnifications requires a little fiddling. Fortunately, the heavy-duty mount is very stable, so vibrations from twisting the focuser knob die away rapidly. The optical tube works even better

◀◀ The optical tube is held in rings that attach to the mount with a Vixen-style dovetail plate. That makes it easy to attach to most commercial telescope mounts.

◀ The red-dot finder is simple but effective. The plastic focuser, however, is only marginally adequate at high magnifications.

▲ The center of the primary mirror is marked by a white circle. But users must supply their own collimation eyepieces or lasers.

at high power when placed on a sturdy equatorial mount, but that loses the benefit of portability; the combination is as heavy as a standard 8-inch Dobsonian and considerably less capable.

When used with its tabletop mount, the scope needs — or at least deserves — a custom-built support to raise it to an appropriate height. If you place it on a conventional table, the eyepiece is too high for use while sitting in a conventional chair and a bit low for a standing adult. Also, few portable tables are sturdy enough to permit the scope to be used at high power. Unlike many tabletop scopes, the Z130's base is too big to fit on a chair or stool.

If you're handy with tools and have a saw that can make accurate angled cuts, a support with splayed legs like the one under "DIY Improvements" at **eyesonthesky.com** is ideal. Having only hand tools, I built a small table with vertical legs from a scrap of ¾-inch plywood, a length of 2×2 lumber, and six angle irons to keep the structure rigid. It works very well indeed when I'm sitting in a conventional chair, and when I turn the table upside down, the scope nests inside it for storage. But the combination of table and scope, while much lighter than a 6-inch Dob, is right at the limit of what I consider to be easily portable in a single trip.

Once it's set up, this telescope is a joy to use. When I set the eyepiece angle appropriately, I can view all the way from the horizon to the zenith in perfect comfort. My head is above the eyepiece when it's at its lowest and level with the eyepiece when it's highest, and the two effects cancel out almost perfectly. My only complaint is that it's a little hard to rotate the tube in azimuth when it's pointing near the zenith. This is an issue with all Dobs, but the short tube exacerbates the problem. I found that the best solution was to get more leverage by grabbing hold of the turntable base rather than the tube.

Star-testing indicates that my Z130's mirror has a slight turned-down edge. That's probably responsible for the fact that Jupiter appears somewhat soft. Although the Z130 provides good views of the Great Red Spot at 130× during moments of excellent seeing, these moments are rarer and less sharp than in my premium-quality 7-inch Dob when I set the two up side by side. Still, the scope shows Cassini's Division in Saturn's rings with ease, and at 162× on one night of unusually steady seeing, I got a good view of Mare Erythraeum on Mars when the planet was just 11 arcseconds across. That's impressive for a mass-produced mirror of this aperture!

As for deep-sky observing, the scope shows all the Messier objects with ease under dark skies, and it has enough aperture to resolve dozens of stars in the brightest globular clusters. The improvement over a 114-mm scope is bigger than you might guess from the numbers alone. The Zhumell 130 is an outstanding performer for its amazingly low price.

■ *S&T* Contributing Editor **TONY FLANDERS** is a long-time fan of simple, inexpensive telescopes.

▲ The author built a low table to support the telescope out of scraps of wood. When the table is turned upside down, the telescope nests inside it during transport.

Sky Guide

Here's a great app for casual and experienced stargazers alike.

▲ The planetarium app *Sky Guide* for iOS devices incorporates several all-sky survey mosaics into the appearance, including coauthor Nick Risinger's own Photopic Sky Survey (left). Users can switch between several wavelength "skins," including infrared from the WISE survey (right).

Sky Guide by Fifth Star Labs

U.S. Price: $1.99, and $9.99 per year for SUPERMASSIVE in-app subscription

Available from the Apple App Store

64-bit device recommended.

What We Like

Excellent graphics

Ease of use

What We Don't Like

Only available for Apple devices

Doesn't permit free rotation

THESE DAYS THE MARKET for smartphone planetarium apps is pretty crowded. Simply go on your Android or Apple app store, search for "planetarium," and you'll be presented with dozens of options, each with a dizzying array of looks and features. While many have specific uses for observers or imagers, it can be hard to find one that quickly shows you the sky without sorting through a lot of bells and whistles.

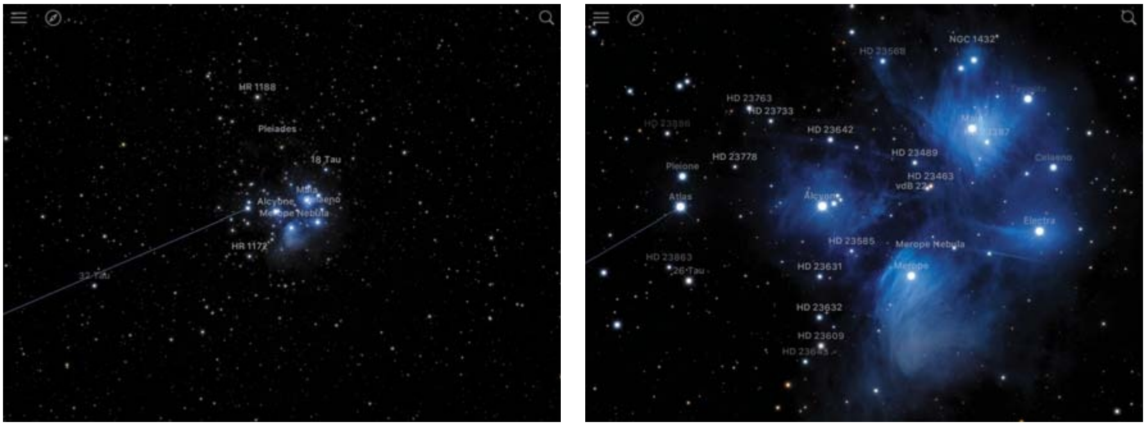
Sky Guide by Fifth Star Labs is a planetarium app for Apple devices (including an alert function for the Apple Watch) that sets itself apart from the crowd in a number of ways. Produced by photographer Nick Risinger and software developer Chris Laurel, the app features Risinger's seminal all-sky color Photopic Sky Survey (*S&T:* Feb. 2012, p. 70) as the base for the sky map. Like many other planetarium apps, *Sky Guide* will match the field of view when your device is held up to the sky, and it includes the Sun, Moon, and planets as well as the brighter moons of Jupiter, Saturn, and Mars (though none around Neptune and Uranus). But unlike other planetarium apps I've used, objects are represented by their appearance — or at least as a camera would see them in a moderately deep exposure — giving me a better appreciation for where objects really are in the sky in relation to other targets. The brightness of the stars and the background sky is adjustable by sliding two fingers up or down on the screen, allowing you to match the conditions at your location. This feature is very realistic and even imparts the familiar reddish-brown cast of urban light pollution along the horizon.

The app is unencumbered by a multitude of controls; there are only three tiny icons at the top of the screen. One brings you to a menu of options, another turns on or off the accelerometer that matches the view to the sky. The third at the top right is the search icon, which allows you to quickly find many objects, including those in the Messier and Caldwell catalogs, plus many other bright targets arranged by type.

Sky Guide has a nifty option that lets you change the appearance of the sky to different wavelengths in the electromagnetic spectrum based on other all-sky survey data. Holding your finger in one place for two seconds opens the filter window, which you use to reposition the pointer to select your desired wavelength filter. These include gamma ray, X-ray, ultraviolet, visible light (the default), hydrogen-alpha, infrared, microwave, and radio wavelengths. I found this feature particularly useful when hunting for astrophotography targets, especially nebulae.

Another feature within the app is its real-time tracking of 250 bright satellites. *Sky Guide* can send you a 5-minute advance alert when a particularly bright event, such as the appearance of the International Space Station or an Iridium flare, is about to occur. You can disable this setting in the menu, or set time periods when you'd prefer not to receive notifications.

Comets are another neat feature of *Sky Guide*. It looks like a lot of time went into presenting their appearance, and it was well worth the effort. Most bright comets visible at the time are displayed similar to their predicted photographic



◀ Users of *Sky Guide* can zoom into an area of an object like M45 (far left), though with the "SUPERMASSIVE" add-on, you can continue to zoom in to reveal even smaller features and fainter stars (left).

appearance, based on their solar position and our Earth-based viewing angle.

The depiction of the major planets incorporates the latest skins available from NASA and accurately shows their illumination. I was particularly impressed that the central meridian of Mars and Mercury both are properly displayed to match the local observation time, as are Great Red Spot transits on Jupiter. Several bright minor planets and the dwarf planets are also included.

Among the basic settings within the app, constellations can be represented as classic lines or as stylized "mythology" renderings. These tastefully appear only on the constellation at the center of the field, and fade away as you move on to a different part of the sky. You can disable the horizon to see the entire sky, though your view will still be "north up" no matter where you're pointing. You can show the ecliptic as a series of tiny Suns spanning the sky.

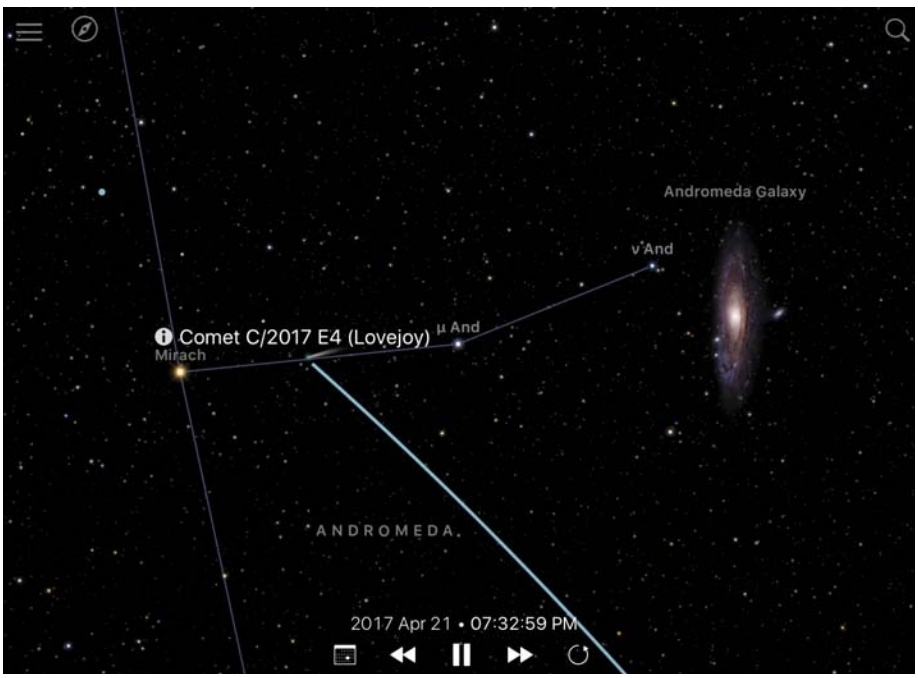
Subscription Content

A recent addition in *Sky Guide* is the subscription-based add-on of the "SUPERMASSIVE" feature ($9.99 per year). This increases the internal database; the entire NGC/IC catalogs are included, and the app's stellar database expands to more than 114 million stars. What's particularly captivating with the add-on is its high-definition feature.

The basic app lets you zoom in to an area of the sky to show the positions of some smaller objects, such as planetary nebulae, galaxies, and globular clusters. SUPERMASSIVE allows you to zoom into thousands of these objects in great detail, often incorporating Hubble and other high-resolution images (as well as the Moon). It's particularly fascinating to zoom into a galaxy such as M81 at high resolution and then search for M51, which cinematically zooms you out of M81 and into M51 to reveal tiny HII regions in this popular target. Occasionally, the limited number of galaxies in the SUPERMASSIVE database was noticeable; some galaxies in the Virgo Cluster surrounding M87 were notably absent even though they were labeled.

The SUPERMASSIVE add-on also includes an expanding collection of cinematic tours. My favorite is the depiction of several famous comet apparitions throughout the past three centuries, showing their swing through the inner solar system.

Sky Guide is billed as an app for astronomy enthusiasts of any level. And while I consider myself an advanced amateur who likes to image obscure targets, I often find myself opening this app rather than more-detailed planetarium programs. At $1.99 for the standard version, it's well worth the price.



▲ Comets are rendered to show the position angle of a predicted tail based on the object's position from the Sun and Earth at the time of observation. You can speed up the time and track comets as they swing through the solar system.

■ *S&T* Equipment Editor **SEAN WALKER** has filled the memory of his iPad Mini with several planetarium apps.

ASTRONOMY BINOCULARS ▶

Nikon introduces the WX series of super-wide-angle binoculars. The WX 10×50 IF ($6,399.95) features a proprietary field-flattener lens system to correct for field curvature and other optical aberrations across its entire 76.4° apparent field of view, providing pinpoint stars to the edge of the periphery. The binoculars use high-transmission Abbe-Koenig prisms and three ED lens elements to provide bright, razor-sharp views of stars and daylight targets free of color fringing. Each eyepiece individually focuses, each uses a turn-and-slide eyecup to block stray light. Its inter-pupil adjustment ranges from 58 to 78 mm, and the binoculars provide a generous eye relief of 15.3 mm. Each purchase includes a hard case, neck strap, and tripod adapter.

Nikon
Nikonsportoptics.com

◀ TELESCOPE CONTROL

New from Astrometric Instruments comes the PrimeTCS-i telescope controller for equatorial or alt-azimuth telescopes (starting at $3,495). The PrimeTCS-i is an ASCOM-compliant Go To system designed to minimize wiring and connectors in your mount, and it interfaces with most preexisting motors. Features include dynamic pointing and tracking, refraction correction, and user-definable slewing limits. PrimeTCS-i makes exclusive use of extended temperature-rated components, including military-grade connectors and tough high-flex cables. The base system includes two PrimeTCS-i drive units (one for each axis on your mount), *Maestro* control software for Windows, a hand paddle and a power supply. Additional motor and encoder options are available.

Astrometric Instruments, Inc.
508-836-3970; astrometric.com

OBSERVATORY CONTROL ▶

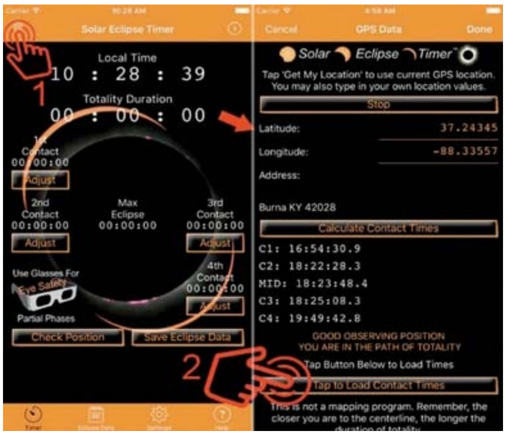
Lunático Astronomía now offers the Dragonfly, a remote observatory control box (450 €). The unit works in conjunction with a smartphone app, *Dragonfly Observatory Controller* (available for both Apple and Android devices), to remotely monitor and control multiple switches in an observatory. Dragonfly is well-shielded from electronic noise and can be used to initialize the power on telescopes, cameras, and mounts, as well as monitor the roof position in your facility. The controller is ASCOM-compliant and manages 8 control relays (4 double NO/NC and 4 NO) and also includes 8 overload-protected input sensors. It connects directly to the internet via an Ethernet port and can be powered using 12-to-24V DC. Each purchase includes 16 banana plugs. See the manufacturer's website for a list of international dealers.

Lunático Astronomía
+34 918 595 567; tienda.lunatico.es

PICKUP TENT ▶

Just in time for star party season, Napier introduces the Backroadz Truck Tent ($189.99). The truck-bed tent is designed to fit within the cargo area of your pickup truck to provide a clean, dry camping area that sets up on short notice. The Backroadz SUV fits most mid-sized to large pickup beds and attaches using two tie straps. It provides 5½ feet of headroom and includes a carry bag, 4 collapsible tent poles, and a removable rainfly. Specific sizing will depend on your vehicle dimensions; choose the one for your truck on the manufacturer's website.

Napier
Napieroutdoors.com



◀ ECLIPSE TIMER

Now available for observers preparing for this month's total solar eclipse is the *Solar Eclipse Timer* ($1.99). This smartphone app for Android and Apple devices works in conjunction with your device's GPS to automatically calculate the exact duration of each major phase of the eclipse. The app will provide spoken countdowns leading to the times of first, second, third, and fourth contacts, as well as alerts for when it's safe to remove eclipse shades and when to put them back on. The app also includes announcements of interesting occurrences during the eclipse, such as temperature changes, wildlife behavior, and where to look for shadow bands. A demo total eclipse movie, synchronized with timers, is included to help users practice their photographic technique well before the event.

Solar Eclipse Timer
Available on both the iTunes App store and Google Play.

BIG DOBS ▶

Sky-Watcher unveiled its Stargate Truss-Tube Dobsonian Telescopes at NEAF. These large 18- and 20-inch f/4 reflectors (starting at $5,999) are constructed around conical fused-borosilicate primary and cellular secondary mirrors with 94% reflective aluminum coatings. The modular truss design divides the total weight of each scope into manageable sections that assemble quickly in the field. The base model includes a 2-inch dual-speed Crayford focuser, 9×50 finder scope, as well as 28- and 10-mm LET eyepieces. Additional accessories include three 2.3 lb. counterweights, a truss shroud, and tool-free truss clamps. Both scopes are also available with motorized Go To and a SynScan hand controller at additional cost, featuring dual encoders that permit manual slewing without losing alignment. See manufacturer's website for additional details.

Sky-Watcher USA
310-803-5953 ext. 306; skywatcherusa.com

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

Low-Tech Eclipse Viewing

What to do if you're caught without optics on eclipse day.

IN PREPARATION FOR this month's total solar eclipse, my last two columns were about making solar filters and solar finders so you could observe the partial phases with a telescope. But what if you don't have a telescope or didn't get your filter material in time? Are you totally hosed?

Not at all! Observing the eclipse safely can be as easy as poking a hole in a piece of aluminum foil. No, don't look through the foil at the Sun! That would still damage your eyes. Use the hole to project an image of the Sun on a screen a few feet away.

A pinhole acts like a tiny lens, creating a focused image. It doesn't let much light through, so it only works well for bright objects like the Sun, but it works great for that. With a pinhole projection you can watch the Moon slide in front of the Sun on eclipse day, taking a bigger and bigger bite until mid-eclipse, then slide away again.

The biggest problem with a pinhole projector is that the image is small and dim. Moving the screen farther away from the pinhole will make the image larger, but because the light is spread out more, it will get dimmer. Making the hole bigger will let more light through, but the image will get blurrier.

How small is it? Pretty small. The Sun is only half a degree across, so the projected image will only be half a degree across, too, from the perspective of the pinhole. You'll get about 1⁄10 of an inch of image diameter per foot of distance. So if your screen is three feet away, your image will only be about a third of an inch across. If you want the image to be an inch across, you would need to put your screen 10 feet away. That's just not practical.

Fortunately there's another way: Use a mirror to reflect an image of the Sun onto a shaded wall. If you mask down the mirror to half an inch or so, it'll act like a pinhole and create a fairly good image. It'll be blurrier than an actual pinhole but much brighter, so you can cast its light a lot farther and get a bigger image. For viewing the crescent shape of partial eclipse phases, it will work just fine.

▲ You can cast a fairly bright image of the Sun on a wall with a small mirror. The smaller the reflective spot, the sharper (but dimmer) the image will be.

If you want a sharper, brighter, bigger image yet, there's one more good trick: You can use a pair of binoculars to project an image of the Sun onto a screen. The binoculars act as a complete optical system, using the entire front aperture to gather light and focusing it into a collimated beam that comes out the eyepieces. You can put a screen anywhere behind the eyepieces and project a crisp, clear image onto that screen, and the image will be much larger and brighter than with a pinhole or small mirror. You might have to adjust the focus of the binoculars, but you can get it crisp enough to see sunspots if there are any big ones.

You need to be careful about a couple of things if you use binoculars. First of all, don't ever look through them at the Sun without a proper filter, not even for a second. And make sure nobody else can, either. That means setting them up in such a way that no curious children can get their heads between the screen and the eyepieces.

▲ A simple pinhole projector made from wrapping-paper tubes serves the purpose of projection well. Use a round toothpick to poke a hole in the aluminum foil at the end.

JERRY OLTION (2)

Second, don't use a good pair of binoculars. While you're aiming them at the Sun, the intense beam of focused sunlight will be dancing around inside the eyepiece housing, heating up the field stop and melting any plastic parts it stays in contact with for too long. This is a project for a pair of Goodwill binoculars, not that fancy pair of Celestron 15×70s.

If you have none of the above methods at hand, nature gives you one for free: Just stand under a tree and look down at the dappled pattern of light filtering through the leafy canopy onto the ground. The gaps between leaves act as tiny pinholes, casting hundreds of crescent-shaped spots of light during the eclipse's partial phases.

And during totality? Look up! It's safe to look at totality (but *only* totality) directly. Remember to close your mouth or flies will buzz in!

Contributing Editor **JERRY OLTION** plans to use all of the above on eclipse day in addition to a solar-filtered scope.

JERRY OLTION

▲ You can use cheap binoculars to project an image of the Sun onto a screen. Don't use binoculars you care about for this, and don't let anyone look through the binoculars at the Sun.

SHARE YOUR INNOVATION
Do you have a telescope or ATM observing accessory that *S&T* readers would enjoy knowing about? Email your projects to Jerry Oltion at **j.oltion@gmail.com**.

"The Moon is up . . . . . . A Single Star is at her side"

Lord Byron's famous evening yields up its mystery: He wrote what he saw.

JEFF SULLIVAN, BELOW: COLLECTION OF DON OLSON

Exactly 200 years ago in August, the British Romantic poet Lord Byron described an evening twilight in Italy with spectacular colors filling the sky. To this celestial scene he devoted three stanzas of the poem that made him famous. Readers for two centuries may have assumed that he made it up. However, Byron's lines note that the Moon is visible and that a "Single Star is at her side." We've dug through his biography, letters, diaries, and other clues to show that actual events, in the sky and on the other side of the Earth, inspired these stanzas.

The poet George Gordon Byron (1788–1824), better known as Lord Byron, achieved a fame in the early 19th century comparable to that of Elvis Presley or the Beatles in the

▲ **MOON AND NOT-STARS** The two brightest "stars" that ever accompany the Moon are, of course, the two brightest planets: Venus and Jupiter. Both are caught in this dawn scene at California's Mono Lake on August 23, 2014. Jupiter is just above the title (and under the Beehive Cluster). Venus is dimmed and reddened by thick atmosphere near the horizon. They leave glitter paths on the water of different colors and widths.

▶ **WHEN POETS WERE SUPERSTARS** Lord Byron (1788–1824), in a 19th-century engraving based on a portrait by Thomas Phillips.

20th. Perhaps you were assigned his poetry in school. Before recorded music or TV, families read aloud his long, rhythmic poems in the parlor as standard evening entertainment.

The work that first brought him recognition and renown was a lengthy poem titled "Childe Harold's Pilgrimage," published in four sections called *cantos*. The first two cantos appeared together in 1812 to great acclaim; Byron later recalled, "I awoke one morning and found myself famous." He brought out the third and fourth cantos in 1816 and 1818, respectively, to meet popular demand.

A Memorable Twilight

Byron wrote the fourth canto in Italy during the summer of 1817. An intriguing astronomical passage running for three stanzas described a spectacular scene just after sunset, as the glow of twilight produced dramatic colors.

Stanza XXVII.
The Moon is up, and yet it is not Night –
Sunset divides the sky with her – a Sea
Of Glory streams along the Alpine height
Of blue Friuli's mountains; Heaven is free
From clouds, but of all colours seems to be
Melted to one vast Iris of the West,
Where the Day joins the past Eternity;
While, on the other hand, meek Dian's crest
Floats through the azure air – an island of the blest!

Stanza XXVIII.
A Single Star is at her side, and reigns
With her o'er half the lovely heaven; but still
Yon sunny Sea heaves brightly, and remains
Rolled o'er the peak of the far Rhaetian hill,
As Day and Night contending were, until
Nature reclaimed her order – gently flows
The deep-dyed Brenta, where their hues instil
The odorous Purple of a new-born rose,
Which streams upon her stream, and glassed within it glows,

Stanza XXIX.
Filled with the face of Heaven, which, from afar,
Comes down upon the waters; all its hues,
From the rich sunset to the rising star,
Their magical variety diffuse:
And now they change; a paler Shadow strews
Its mantle o'er the mountains; parting Day
Dies like the Dolphin, whom each pang imbues
With a new colour as it gasps away –
The last still loveliest – till – 'tis gone – and All is gray.

These lines refer to three locations in Italy and make two mythological references of astronomical interest.

The waters of the "deep-dyed Brenta" refer to a canal between Padua and the lagoon of Venice; wealthy families constructed more than 200 grand villas along the banks of

▲ **DIANA THE HUNTRESS** Poetry aficionados of the 19th century would immediately recognize "Dian" as romantic-speak for the Moon. The Roman lunar goddess was often depicted in paintings and statues with a crescent over her forehead.

PAINTING: ANTONIO CORREGIO / WIKIMEDIA COMMONS

the Brenta Canal as summer homes. During the summer of 1817 Byron rented the Villa Foscarini in the town of La Mira, about seven miles west of the Venetian lagoon.

"Blue Friuli's mountains" were peaks northeast of La Mira and Venice, while the "far Rhaetian hill" referred to the Rhaetian Alps along the Italy-Switzerland border northwest of Byron's location, in the direction of sunset.

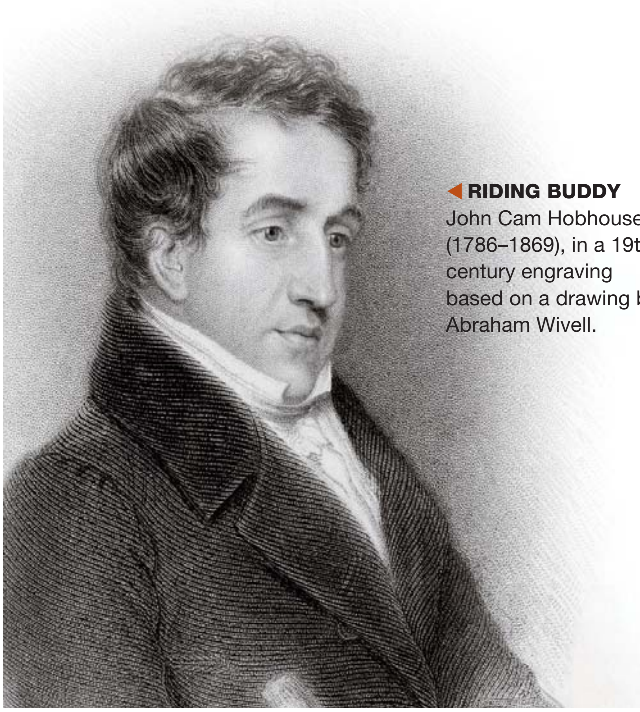
Iris was the goddess of the rainbow in Greek mythology, and Byron's phrase "Iris of the West" thus provided a poetic description of vivid colors in the twilight sky.

In addition to the explicit lunar reference ("The Moon is up"), the phrase "meek Dian's crest / Floats through the azure air" refers to the Roman lunar goddess Diana. Byron's readers would be familiar with paintings and sculptures identifying her by attributes including hunting dogs or a deer, a crescent-shaped bow, and a crescent Moon as a diadem or crest above her forehead.

But what about the "Single Star is at her side"? Its identity has been unknown for two centuries. Our Texas State University group wondered whether it might be possible to identify the "Single Star" near the Moon in this dramatic

▲ VACATION SPOT The Villa Foscarini today is the wide white building behind the end of the footbridge spanning the Brenta Canal in La Mira. The scene was surely more rustic 200 years ago. A plaque on the wall reads, in Italian, "Lord Byron lived here 1817."

▶ PILGRIMAGE Don and Marilynn Olson retraced the route of Lord Byron and John Hobhouse (on bicycles rather than horses) along the south bank of the Brenta Canal between La Mira and Dolo.



◀ RIDING BUDDY John Cam Hobhouse (1786–1869), in a 19th-century engraving based on a drawing by Abraham Wivell.

and colorful twilight. Could history, letters, diaries, and other clues allow us to find an actual event that inspired these stanzas?

Summer in La Mira

Byron left a rather detailed account of his life in his letters. He moved to the Villa Foscarini on the Brenta Canal in La Mira on June 14, 1817, and he began writing the fourth canto of "Childe Harold's Pilgrimage" by June 26th. One of his close friends, John Cam Hobhouse (1786–1869), joined him as a houseguest on July 31st, and the two began a custom of almost-daily rides together at sunset along the Brenta. They left La Mira on November 13th to spend the winter season in Venice. On January 8, 1818, Hobhouse departed for England and carried with him the manuscript of the fourth canto, which he delivered to John Murray, Byron's publisher in London. Thus the letters show that the celestial scene must have

PORTRAIT: COLLECTION OF DON OLSON, PHOTOS: DON OLSON (2) occurred sometime between June and November 1817.

In the first edition of the poem, published by Murray, a note by Byron appears to provide a precise date of August 18th for the spectacular twilight:

> *A single star is at her side, and reigns*
> *With her o'er half the lovely heaven.*
> The above description may seem fantastical or exaggerated to those who have never seen an Oriental or an Italian sky, yet it is but a literal and hardly sufficient delineation of an August evening (the eighteenth) as contemplated in one of many rides along the banks of the Brenta near La Mira.

However, this date may not be exactly correct. Byron scholars have published reproductions of the poet's manuscripts that show he first wrote the date as August 19, then crossed it out and changed his recollection by writing "18th." The exact date matters, as we shall see.

Remarkably, an even better source for the correct date exists. Byron and Hobhouse frequently made trips on horseback from La Mira to the town of Dolo and back. A biography of Byron noted, regarding the fourth canto, that "Stimulated by his rides at sunset along the Brenta, Byron added more stanzas." Hobhouse himself later recalled that "part of it was begot as it were under my own eyes . . . some of the stanzas owe their birth to our morning walk or evening ride at La Mira." Hobhouse kept a diary in the summer of 1817, and the relevant entry shows that the memorable twilight occurred on August 20th:

> Wednesday August 20th 1817: Ride with Byron. Return over the other side of the river from Dolo . . . . Riding home, remarked the moon reigning on the right of us and the Alps still blushing with the gaze of the sunset. The Brenta came down upon us all purple — a delightful scene, which Byron has put in three stanzas of his "Childe Harold."

The Moon and Jupiter

For a location between Dolo and La Mira along the Brenta Canal path, astronomical planetarium programs give the time of sunset on August 20, 1817, as 7:00 p.m. Local Mean Time (LMT). At sunset the Moon, a day past first quarter, stood 20° above the scene's southern horizon, and it was still 18° high an hour later when deep twilight would have matched Byron's description. And we see that Byron's "Single Star . . . at her side" was not a star at all. The planet Jupiter shone brilliantly 10° to the right of the Moon in the twilight — close enough that the pair would be memorable.

Antares was closer to the Moon, only 5° to its lower right, but Antares was only a twentieth as bright as Jupiter was that night and not nearly as eye-catching.

Volcanic Twilights

Byron's twilight rhapsodizing has another aspect of scientific interest. The spectacular colors he observed were likely to have been genuinely abnormal, stemming from the greatest volcanic eruption in recorded history.

In a previous *Sky & Telescope* article, our Texas State University group identified the blood-red sky in Edvard Munch's most famous painting, The Scream, as likely a depiction of a "Krakatoa twilight" (*S&T:* Feb. 2004, p. 28). For several years after the 1883 eruption of Krakatoa, in what's now Indonesia, dust and sulfate aerosols in the upper atmosphere produced remarkable red hues in twilight skies worldwide.

But much more powerful than the Krakatoa event was the April 1815 eruption of Mount Tambora (also in Indonesia). In 1984 Richard Stothers wrote in *Science* that the Tambora "eruption stands out as being an order of magnitude bigger in volume of discharged pyroclastics than the Krakatau eruption in 1883. . . . In fact, it exceeds any other known eruption, historical or otherwise, during the past 10,000 years." Stothers noted that in 1815, "prolonged and brilliantly colored sunsets and twilights were frequently seen . . . the twilight

▲ **SKY PAINTER** The 1815 explosion of Mount Tambora on Sumbawa Island, Indonesia, blew away an estimated 160 cubic kilometers (38 cubic miles) of rock, wiped out the area's population, and left a summit caldera about 6 km (4 miles) wide, seen in these USGS Landsat images. The eruption was heard more than 2,000 km (1,200 mi) away, and its global atmospheric aftermath lasted for several years.

TOP: NASA LANDSAT7, BOTTOM: NASA / PD-USGOV glows appeared orange or red near the horizon, purple or pink above." He noted that "Two and a half years after the eruption, some haze still remained."

Readers may remember the similarly spectacular worldwide volcanic twilights following the 1991 eruption of Mount Pinatubo in the Philippines — a much lesser event that, even so, turned clear twilight skies around the world from their normal deep blue to a spectacular reddish purple, or even clear, bright red as in the photo below.

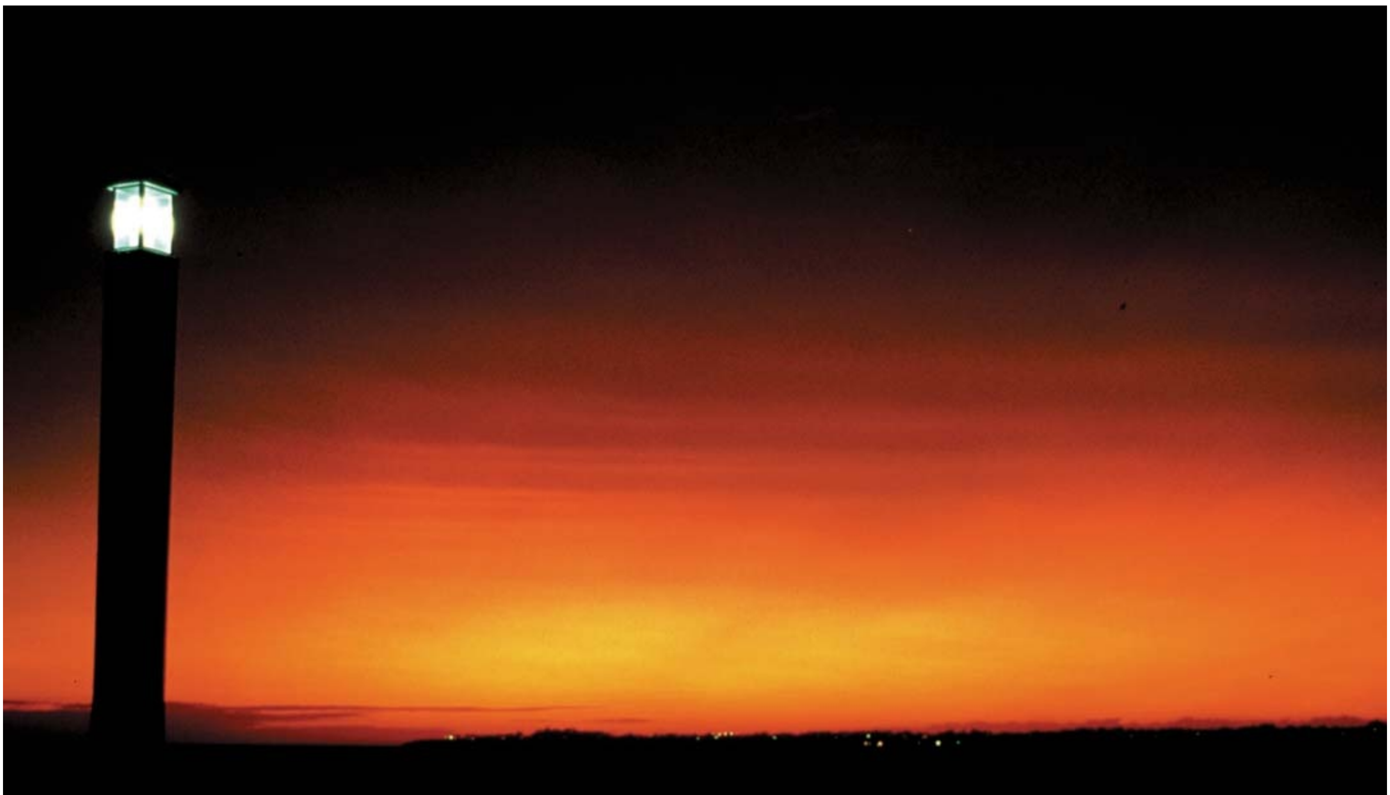
Tambora's global ash haze also dimmed the daytime Sun, causing 1816 to become known as the "year without a summer." In Switzerland, the cold and rainy weather forced Byron and a group of other vacationing authors, including Mary Shelley, to remain indoors. They invented tales of horror around the fireplace of Villa Diodati, the house near Geneva that Byron rented that summer. In another article our Texas State University group used the position of the Moon relative to a window there to determine a precise date and time for Mary Shelley's "waking dream" that became the inspiration for her novel *Frankenstein* (*S&T:* Nov. 2011, p. 68).

Byron himself wrote a short apocalyptic poem called "Darkness" with a line describing how "The bright sun was extinguish'd." The American artist William Edward West transcribed a conversation with Byron about the poem: "I asked him one day how he could have conceived such a scene as he had described in his 'Darkness' — said he wrote it one day in 1816 in Geneva when there was a celebrated dark day — that the fowls went to roost at noon and the candles lighted as at night."

Christos S. Zerefos and coauthors have analyzed "volcanic sunset paintings," defined as "those that were created within a period of three years that followed a major volcanic eruption." Their list of works with enhanced reddening in the sky includes paintings by J. M. W. Turner and Caspar David Friedrich in 1816–18. To examples like these we can add another effect of the Tambora eruption: the spectacular sunset Byron observed in Italy on August 20, 1817. As Byron and Hobhouse rode eastward on the bank of the Brenta Canal, a "Tambora twilight" set the stage for the Moon and Jupiter.

On several evenings in the summer of 2017 the celestial scene will reproduce, at least in part, the sky that inspired Byron's stanzas in 1817. It's unlikely that a sudden arrival of volcanic dust and aerosols will be turning twilights spectacular by the time you read this. But a roughly first-quarter Moon will again shine a roughly similar distance to the left of bright Jupiter during twilight on July 1st and again on July 29th.

■ **DON OLSON**, author of *Celestial Sleuth* (Springer, 2014) and the forthcoming *Celestial Sleuth: Further Adventures* (Springer, 2018), teaches physics and astronomy at Texas State University. He is grateful for research assistance from Margaret Vaverek at Texas State University's Alkek Library.



PINATUBO SUNSET Not just brilliant reds but parallel dark bands of dust were distinctly visible in twilights worldwide during the months of the greatest effects. And deep-sky observers had to wait about three years for faint clusters and galaxies to return to normal visibility.

ATMOSPHERIC RESEARCH / CSIRO

ASTRONOMERS NOW ALIVE remember three standout episodes, each lasting many months, when clear-sky twilights were purple or red, cloudless daytime skies were milky white rather than deep blue, and astronomical objects appeared too dim — worsened by extra light pollution reflecting down from the sky. These episodes followed the 1963 eruption of Mount Agung in Indonesia, the 1982 eruption of El Chichón in Mexico, and especially the 1991 Mount Pinatubo eruption in the Philippines, the largest in the last 100 years.

To cause these effects, a volcanic blast has to be large enough to send large amounts of material above the troposphere into the stratosphere. The troposphere is where weather occurs, so particles there wash out within a few weeks. The stratosphere is much slower to self-cleanse, allowing the material to spread around the world.

Although the most spectacular part of an explosive eruption is rock dust, seen above, the eventual stratospheric haze consists mostly of sulfate aerosols derived from sulfur dioxide gas (SO_2). These stay aloft for 1 to 3 years.

El Chichón and Pinatubo dimmed the Sun and stars by up to about 10% in tropical and north temperate latitudes. But most of the Sun's missing brilliance was forward-scattered down to the ground anyway; "clear" blue skies became brighter blue-white. This kept Earth from cooling more severely than it did, but it was no help at all to astronomers.

We've been blessed with mostly clear upper air for a quarter century, but there's no telling when the next big volcanic episode will begin.

—Alan MacRobert

▲ **LITTLE SKY PAINTER** The 1991 eruption of Mount Pinatubo in the Philippines ejected roughly 5 cubic km (about 1 cubic mile) of material. Enough of it reached the stratosphere to turn twilights around the world bright smoky red, to dim the Sun and other astronomical objects, and to cool the Northern Hemisphere by about 1° F for two years. This photo, taken June 12th from Clark Air Base 9 miles away, is of a small, preliminary eruption of Pinatubo three days before the main one began.

U.S. GEOLOGICAL SURVEY

△COSMIC CONTINENT

Terry Hancock

The iconic North America Nebula (NGC 7000) and nearby Pelican Nebula (IC 5070) are parts of an enormous interstellar cloud of ionized gas situated about 1,600 light-years away in Cygnus.

DETAILS: *Takahashi Epsilon-180ED astrograph and QHY11 CCD camera used with Chroma Hα, S II, and O III filters. Total exposure: 9 hours.*

▷TRAILS OF FIRE AND STARLIGHT

Dario Giannobile

An eruption of Sicily's Mount Etna on March 16, 2017, provided a Dantean foreground for this time-lapse composite showing circumpolar stars in Cepheus and a moonlit landscape.

DETAILS: *Canon EOS 7D DSLR at ISO 400 and 70-to-200-mm zoom lens at 200 mm. Individual exposures: 25 seconds.*

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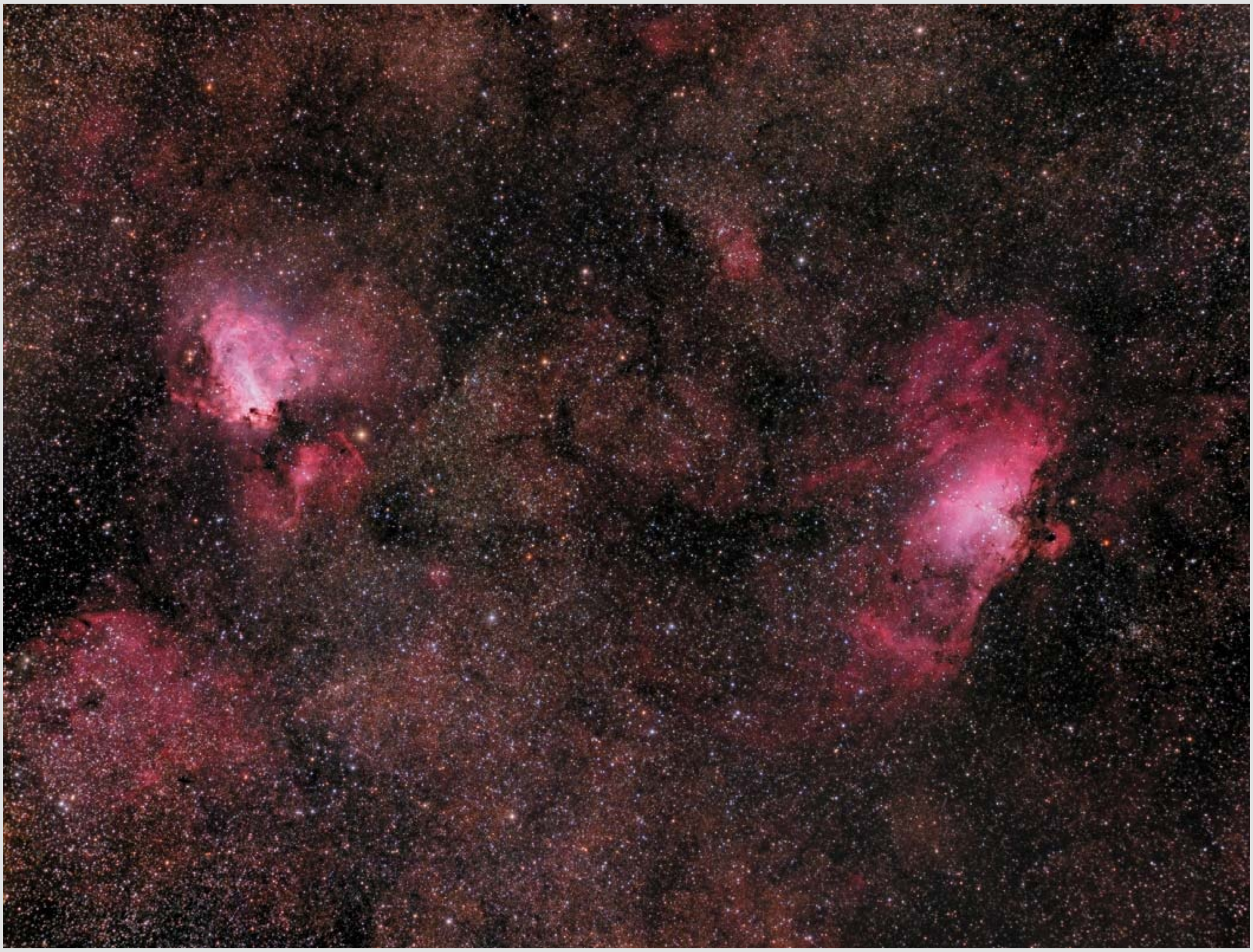
◁ GHOSTLY GLOW IN GEMINI

Keith B. Quattrocchi

Once thought to be the remains of a supernova, the Medusa Nebula (Sh 2-274) is a large but very dim planetary nebula some 1,500 light-years away.

DETAILS: *RC Optical Systems 16-inch Ritchey-Chrétien astrograph with SBIG STL-11000 CCD camera and Astrodon Hα-RGB filters. Total exposure: 24 hours.*

Visit **skyandtelescope.com/gallery** for more of our readers' astrophotos.



△BIRDS IN FLIGHT

Joel Short

Nestled 2½° apart at the junction of Sagittarius, Scutum, and Serpens, the Omega or Swan Nebula (M17, left) and Eagle Nebula (M16, right) are easy targets for visual telescopic viewing.

DETAILS: *Stellarvue SV80ST apochromatic refractor and Moravian Instruments G3-16200 CCD camera with Astrodon Hα and RGB filters. Total exposure: 8 hours.*

▷WILD DUCK CLUSTER

Ron Brecher

A third bird, not far away in Scutum, is the rich, compact, open cluster Messier 11. Its 2,900 stars look fine at low power or even in binoculars.

DETAILS: *ASA 10N astrograph and SBIG STL-11000M CCD camera with Baader LRGB filters. Total exposure: 1.6 hours.*

HEART OF THE EAGLE

Steve Mazlin

Buried deep in Messier 16 (see facing page) are elongated dark fingers dubbed “Pillars of Creation” in a celebrated 1995 Hubble image. This composite includes images taken over 8 years.

DETAILS: *RCOS 16-inch Ritchey-Chrétien astrograph; Apogee Alta U47, U9, and FLI ProLine PL16803 CCD cameras; and six filters. Total exposure: 38.5 hours.*

◁ BODE'S GALAXY

Joe Petrick

Messier 81 is among the largest and brightest spiral galaxies in the sky. Located 12 million light-years away in Ursa Major, it shows detail even in modest telescopes.

DETAILS: *Meade LX200-ACF 16-inch aplanatic Schmidt-Cassegrain telescope with SBIG STT-8300M CCD camera and Baader LRGB filters. Total exposure: 3 hours.*

▽ PERSEIDS IN 2016

Michael Krypel

A waxing gibbous Moon lights the foreground in this 61-image stack taken the night of August 11–12, 2016. The composite reveals several dozen Perseid meteors. Bright moonlight will also compromise this year's show.

DETAILS: *Canon EOS 6D DSLR camera at ISO 6400 and 24-mm lens. Individual exposures: 15 seconds.*

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AD INDEX

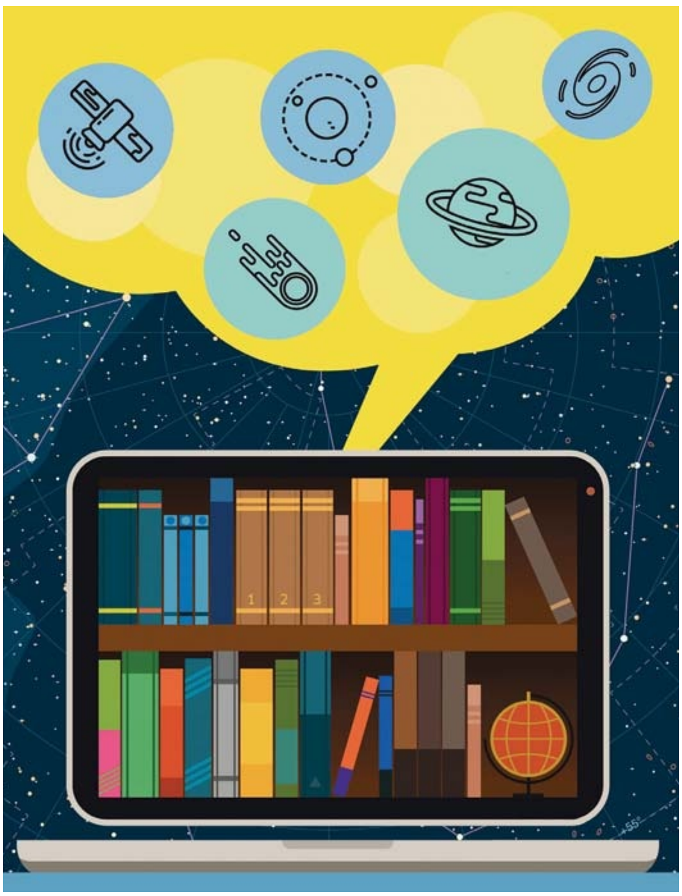
Student Aid

With the cost of college textbooks soaring, the author helped create an introductory astronomy textbook that's free for anyone to use.

IN FEBRUARY 2016, after surveying nearly 5,000 American college students, the U.S. Public Interest Research Group concluded that the retail cost of textbooks had increased over the past decade by 73%. While experts fiercely debate the exact figures in such studies, no one disagrees that textbook prices have become a major concern, especially at community and state colleges where students count on lower costs to make college affordable.

With recent mergers of college textbook publishers — some claim that only five large corporations control 80% of the market — it's easy to blame the lack of competition for the steep rise in prices. But culpability also lies both with the relentlessly efficient used-textbook market and with college bookstores, many of which are themselves owned by large corporations.

When students resell books after their course ends and these copies are resold, those who created the book get nothing. All the profit goes to the bookstores; none of it returns to the publisher, authors, or editors. Thus, publishers must squeeze their entire income from a textbook's first year on the market. This helps explain why publishers bring out new editions so often and charge an arm and a leg for them. Typical introductory astronomy textbooks retail for between $100 and $200, and even used copies at bookstores can be pricey.



Recently, a group of charitable organizations, including the Gates and Hewlett foundations, decided to do something about this situation. They formed a nonprofit organization called OpenStax, based at Rice University, with the mandate to bring at least one high-quality, professionally edited, *free* textbook to each subject area in which college students take introductory courses.

OpenStax began with science and math books, then expanded to economics, psychology, and history. Students mainly use the books in electronic form, though they can generate printed copies at cost.

When astronomy's time came, I and my co-authors, David Morrison (NASA Ames Research Center) and Sidney Wolff (National Optical Astronomy Observatory), were delighted that OpenStax turned to us. We'd been writing introductory astronomy textbooks since 1995 that explained astronomy in everyday language while using clear analogies, examples from students' own experiences, and touches of humor.

Starting in 2015, we began to assemble an updated and significantly revised textbook — cleverly entitled *Astronomy* — that would fit with the needs of today's students. For example, with so much useful material about astronomy now on the web, we could include links to short videos, apps, interviews, animations, and even music or fiction related to astronomy. Also, we can more easily revise and update an electronic book when (and only when) the need arises.

With the help of about 70 astronomers and educators, we finished the book in October 2016. *Astronomy* is now freely available to anyone, not just college instructors and their students, at **openstax.org/details/astronomy**. A hub of free, shared resources resides on the same webpage. In the end, we hope it all makes the cost of cracking the books on astronomy a tad less, well, astronomical.

ANDREW FRAKNOI chairs the Astronomy Department at Foothill College near San Francisco and was the 2007 California Professor of the Year. For 14 years he served as Executive Director of the Astronomical Society of the Pacific.