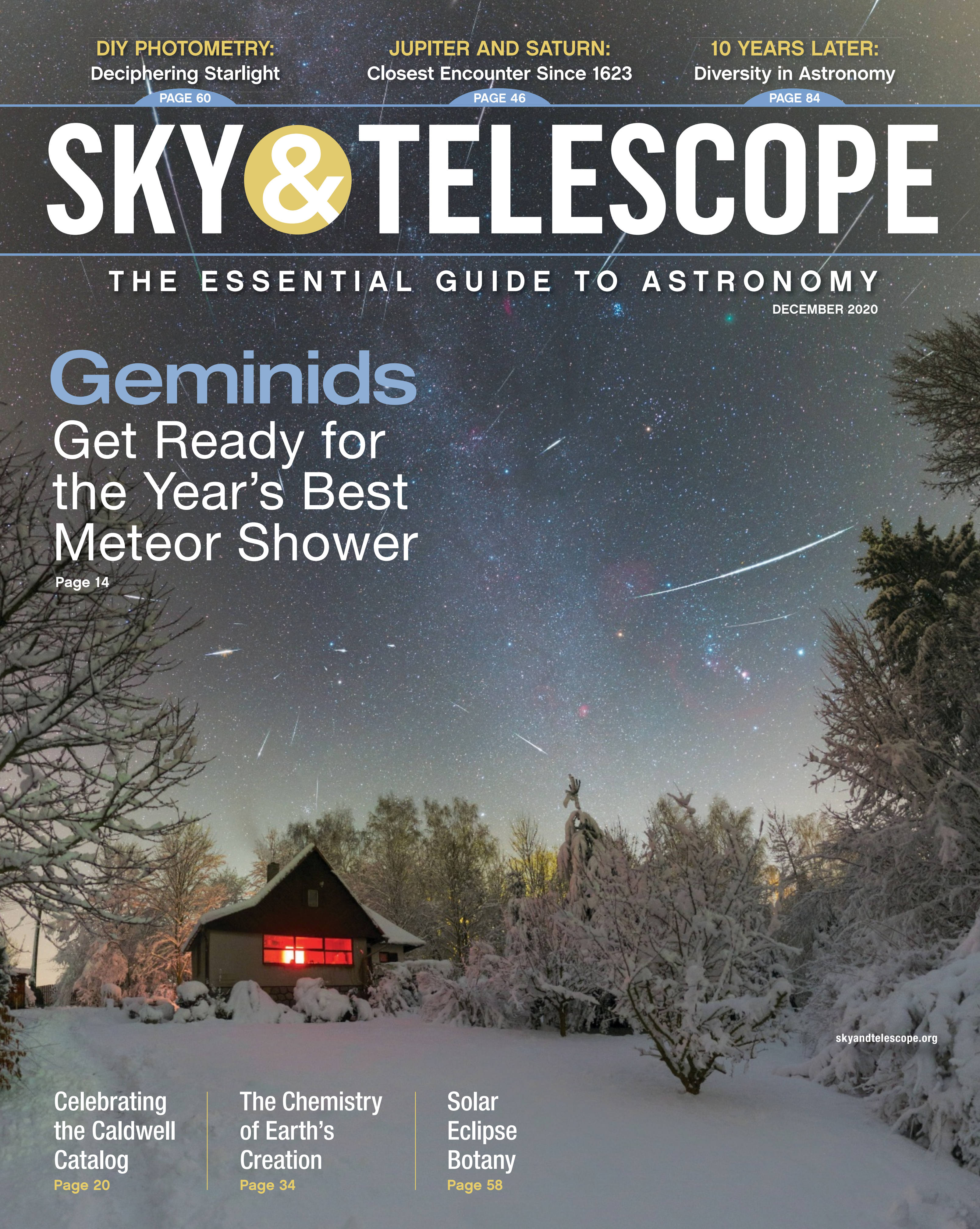

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SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

DECEMBER 2020

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USGS / NASA / LANDSAT 7

ON THE COVER

Composite image of the 2018 Geminid meteor shower

PHOTO: PETR HORÁLEK

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Rising Like the Phoenix

NEXT YEAR *SKY & TELESCOPE* turns 80. In a human life, that might be the time to start slowing down, resting on your laurels, settling into tried-and-true routines. As we approach this milestone at *S&T*, it's been the opposite. Over the past year or so since the American Astronomical Society brought us under its wing, we've done so many new things you'd think *S&T* had just fledged.

In a sense, we have. The AAS's purchase of *S&T* on July 3, 2019, gave us a new lease on life. The moribund feeling we'd had in the months after our previous owner's bankruptcy filing in March, when *S&T*'s future seemed uncertain, gave way overnight to a fresh sense of optimism, excitement, and renewed determination. Suddenly, we weren't staring at the end but celebrating a beginning.

S&T took its first new steps that fall. We hired our webmaster, Scilla Bennett, then our editorial assistant, Sabrina Garvin. We also brought in Gary Seronik as a consulting editor. As many of our readers know, Gary was most recently editor in chief of *SkyNews*, Canada's leading astronomy magazine, and before that was a long-time *S&T* associate editor. We're delighted to have all three of these talented individuals in our midst.

Sky & Telescope's new digs: One Alewife Center

In 2020 we further flexed our wings. In February, we launched our revamped website, **skyandtelescope.org**. Not long after that, we resumed putting out new *S&T* products. These include an eclipse globe, new editions of the *Pocket Sky Atlas* and its jumbo version, and the *2021 Observing Calendar*. Watch this fall for our annual publication *SkyWatch 2021*.

One new step we took last spring none of us had anticipated: On March 23rd, in the face of the ballooning coronavirus pandemic, the staffs of AAS and *S&T* went into full-time work-at-home mode; we've been there ever since. Fortunately, both organizations were able to make the transition without major hiccups, including no disruption in publishing *Sky & Telescope*.

A major leap forward occurred this past August. After 14 years at 90 Sherman Street in Cambridge, Mass., we moved about a mile away to a newly built office space. This spanking new suite epitomizes our renewal, and we look forward to working there once the AAS and *S&T* offices safely reopen. Here's our new address: **One Alewife Center, Suite 300B, Cambridge, MA 02140**.

Finally, beginning with next month's issue, we'll introduce a number of new editorial components in the magazine. I'll tell you about those then. But for now, know that they're the culmination of a bevy of enhancements that have arisen out of the happy rebirth of *Sky & Telescope*.

Peter

Editor in Chief

PETER TYSON / *S&T*

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The Essential Guide to Astronomy

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▲ Members of Troop 12 proudly display their new telescopes.

BERNARD VALLEJOS

DIY Refractors

The students of Scout Troop 12 in our town were determined not only to earn their Astronomy merit badges but also to build their own telescopes. Using the plans described by Jerry Oltion in "The STEM Spyglass Project" (*S&T:* July 2020, p. 74), they deconstructed binoculars, removed the eyepieces, and transplanted them into optical tube assemblies using a lot of tape. Then they secured and glued the objective lenses into place. They brought their telescopes to our socially distanced scout summer camp to fine-tune their instruments. Bad weather almost ruined the possibility of using their scopes, but at the last minute the skies cleared. They got to see Jupiter and its moons as well as Saturn.

The scouts earned their Astronomy merit badges and formed lifelong memories. The adult leaders became enthusiastic partakers of the night sky and created one of the best star parties I've ever attended. Troop 12 expresses its gratitude to the Wootens and to *Sky & Telescope*'s editors for sharing their encouragement and expertise. We hope that others will be inspired to make their own telescopes in the near future.

Thomas C. Rushton
Huntington, West Virginia

A Horn for Every Home

I enjoyed reading Diana Hannikainen's article "The Radio Sky" (*S&T:* Aug. 2020, p. 12) and the overview of radio astronomy that it provided. I'm an amateur radio astronomer, and I teach high school physics. For the past four years, I've been involved in the Digital Signal Processing in Radio Astronomy program developed by West Virginia University and Green Bank Observatory.

A main focus of this program is to help teachers build radio telescopes and develop curriculum for their classrooms. We developed a website **wvurail.org/dspira-lessons** that provides instructions and lessons on building and operating a horn radio telescope that is similar in design to the one used by Harold Irving Ewen and Edward Mills Purcell to detect 21-cm radio waves from neutral hydrogen. The spectrometer uses GNU Radio, which is a free and open-source toolkit for software radio.

We would greatly appreciate any feedback. Our ultimate goal is to have "a horn in every backyard" that can be linked as one big interferometer!

John Makous
Charlotte, North Carolina

Spacetime Disturbances

Your excellent article, "The Radio Sky," made me wonder if events that cause gravitational waves also produce an electromagnetic signal with a similar frequency spectrum. It would arrive after the gravitational wave.

Ward Halverson
Cambridge, Massachusetts

Diana Hannikainen replies: *Indeed, astronomers have detected radio emission after events that have given rise to gravitational waves, such as the neutron star merger recorded in 2017. They don't understand the origin of the radio emission completely, but one scenario proposes that the merger event creates a narrow, collimated, bipolar jet. As the jet plows outward, it shocks the interstellar medium, and scientists receive this as radio emission — this behavior is akin to the radio jets from quasars and microquasars.*

Inspirational Eclipses

Nicole Nazzaro's Focal Point (*S&T:* Aug. 2020, p. 84) about the total lunar eclipse on July 6, 1982, brought back memories. I was 13 years old and living in Michigan at the time. I too loved science and was a misfit — except in my backyard under the stars.

I loved astronomy in high school and considered it as a career. In college, I studied aerospace and mechanical engineering, leaving astronomy behind. Through the '90s, I built my career, got married, and did other hobbies. Then I also started a family and dusted off my old gear. In hindsight, astronomy never really left me. It was one of the main influences that steered me toward my technical vocation.

It is amazing how much a simple hobby can influence a person's life. If children enjoy a scientific activity, we need to feed it. Even if they later lose interest, the experience may spark future achievements.

Michal Warzecha
El Dorado Hills, California

Just like Nicole Nazzaro, I was influenced by an eclipse and a couple of science-fiction TV shows. But in my case, it was the 1970 eclipse of the Sun. I had a 60-mm refractor with the solar filter that no one uses anymore, and many people from my neighborhood came over to watch it. I found several deep-sky objects with that little telescope. As I grew older, I wanted to be an astronomer, but I soon realized that I didn't have the math skills for it. So I got married and joined the Army. I've been in and out of astronomy ever since, but I never lost interest. Now I have three telescopes. I've looked at many galaxies, nebulae, and, my personal favorite, open clusters since, but that eclipse was the first event that really inspired me to start looking at the sky.

Ed Bailey
Daniels, West Virginia

Remembering Saegmuller's Refractors

"Navy Gazing" is not how the U.S. Naval Observatory (USNO) has utilized its Saegmuller refractor, which was mentioned in Ted Rafferty's "Saegmuller's Forgotten Refractors" (*S&T:* Aug. 2020, p. 26), over its century of noble service.

Until the 1970s, its duties included observing interesting and difficult double stars, lunar occultations, and asteroids. After USNO astronomers rescued and restored this Saegmuller in 1980, it has been included in public tours demonstrating the USNO's long and continuing mission in national defense and scientific research, Smithsonian education programs, and observing by staff and authorized visitors.

In 1994, this Saegmuller, along with the USNO's 26-inch refractor, gave Comet Shoemaker-Levy 9 (D/1993 F2) codiscoverer and long-time *S&T* contributor David Levy his first view of the comet fragments' impressive impact scars on Jupiter's cloudtops. In 1996, friends of this Saegmuller gave it a 100th birthday party, complete with a birthday cake and poetry. So, this Saegmuller has not been forgotten.

Daniel Costanzo
Locust Grove, Virginia

In 1964, I was in fourth grade. That fall, my science teacher took us to Chamberlin Observatory on a field trip. Among other things, the staff showed us Saturn. I was absolutely floored.

Later in 1965, I ground a 4.25-inch Edmund Scientific mirror and made a beautiful f/5 Newtonian. I joined the Denver Astronomical Society and, while in high school, was trained along with a few friends to use the 20-inch Saegmuller refractor. It was a joy to operate. The sound of that big old dome grinding around to point at an object and the ease of moving that monster telescope with the hand wheels were intoxicating. The views were amazing. Sometimes, if the Saegmuller was available and our parents and school cooperated, we'd spend all night there observing.

John Gubbins
Littleton, Colorado

FOR THE RECORD

● In the red-plate mosaic depicting V Aquilae (*S&T:* Aug. 2020, p. 55), the bright star labeled η (right) is 12 Aquilae.

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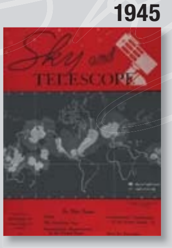
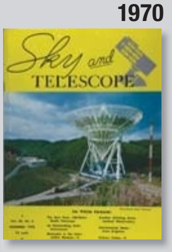
75, 50 & 25 YEARS AGO by Roger W. Sinnott

1945



1970



1995

◖ December 1945

Meteorite Picker-Upper "Dr. Lincoln La Paz, president of the Society for Research on Meteorites, describes an electromagnetic cane which facilitates discovery of meteorites near the surface of the ground and eliminates many a stoop-over backache.

"A small coil of enameled wire wound on a brass tube about two inches long can be made to slide up and down a light but strong iron rod. Using the electromagnet connected to a 6-volt Burgess Uniflex battery, carried in a knapsack, Dr. La Paz found that his cane could readily pick up an Odessa iron meteorite weighing more than a pound, and caused 'smaller fragments to jump an inch or more to the collecting tip.'"

◖ December 1970

Lunar Magnetism "When Apollo 12 landed on the moon on November 19, 1969, one of the instruments erected by Alan L. Bean and Charles Conrad, Jr., was a magnetometer . . . It is located on the eastern edge of Oceanus Procellarum, [and] the first 20 days of operation revealed a steady magnetic field of 36 ± 5 gammas at the magnetometer site. (One gamma is 0.00001 gauss, and the earth's surface field is somewhat less than one gauss.)

"By moving the three sensors of the magnetometer appropriately, it is possible to test for a horizontal gradient in the measured field. The observed gradient is negligibly small, demonstrating that the source of the field cannot be some magnetized artifact left by the astronauts.

"[However,] the Explorer 35 satellite . . . detected no dipole field [of the moon as a whole]. Therefore, the 36-gamma field is due to a localized source near the Apollo 12 site . . . of uncertain origin."

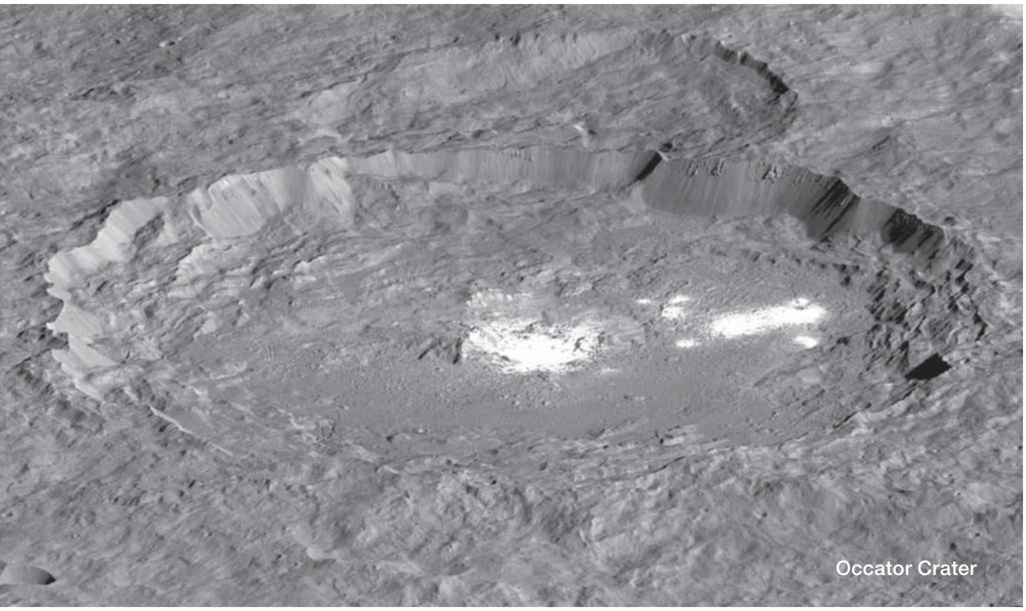
◖ December 1995

Exoplanets "What may be the first discovery of a planet orbiting a normal, Sun-like star other than our own has been announced by astronomers studying 51 Pegasi, a type G5 main-sequence object only 42 light-years away.

"At an early October conference in Florence, Michel Mayor and Didier Queloz (Geneva Observatory) explained that they found 51 Pegasi's line-of-sight velocity changing periodically by some 70 meters per second every 4.2 days. If due to orbital motion around a center of mass shared with another body, such values suggest that a planet lies some 7 million kilometers from 51 Pegasi . . . and has a mass at least half that of Jupiter. . . .

"Other astronomers are racing to confirm the discovery. The only other planets known to lie beyond our solar system are two Earth-size bodies orbiting a pulsar in Virgo."

This decisive find launched the modern era of exoplanet hunting. Some 4,200 planets of other stars are now confirmed, more than half thanks to NASA's Kepler spacecraft.



▲ This simulated perspective view based on Dawn images shows salty white spots on the crater floor of Occator.

SOLAR SYSTEM

Asteroid Ceres Is a Water World

SINCE NASA'S DAWN SPACECRAFT arrived at Ceres, the largest main-belt asteroid, scientists have thought that the world once hosted water (*S&T:* Dec. 2016, p. 16). But new analyses of Dawn's data, presented on August 10th in seven papers in *Nature Astronomy*, *Nature Geoscience*, and *Nature Communications*, indicate that the world might still have an ocean, underground.

Dawn's first images of Ceres revealed what turned out to be reflective salts on the floor of Occator, a fresh-looking crater 92 km (57 miles) across. But scientists continued to question how the spots had remained so bright in the 22 million years since Occator's creation, rather than being darkened by micrometeorite impacts over time.

Then, as Dawn mapped the asteroid's surface and topology, attention turned to Ahuna Mons, an oddly shaped mountain some 4,000 meters (13,000 feet) tall. Its wide top and steep sides marked it as a likely cryovolcano, spewing briny ice rather than lava.

Global density estimates also indicate a crème brûlée world, with a tough shell surrounding a mushy interior.

All this evidence at first hinted at an ancient subsurface ocean that had long frozen over. But new analysis of data that Dawn collected in the last phase of its extended mission, from June to October 2018, indicates that the ocean is still there, feeding cryovolcanism and other geologic activity.

The first line of evidence comes from Dawn's Visible and Infrared Mapping Spectrometer, which mapped minerals across the asteroid's surface. Maria Cristina De Sanctis (National Institute of Astrophysics, Italy) and colleagues report in *Nature Astronomy* the discovery of hydrated sodium chloride among the salts in the bright spots of Occator. Geological processes must have exposed this mineral recently, because it's not stable on Ceres' surface.

A second line of evidence comes from low-altitude gravity measurements made when Dawn flew as close as 35 km from the surface. In *Nature Astronomy,* Carol Raymond (JPL) and colleagues demonstrated negative density variations in and near Occator. In other words, material below the surface is less dense than it ought to be.

To explain the anomaly, Raymond's team suggests that a brine-rich reservoir lies under the surface, melted millions of years ago by the impact that created the crater. The reservoir has stayed fluid due to the presence of salts and other minerals, which lower water's freezing point and also provide a layer of thermal insulation.

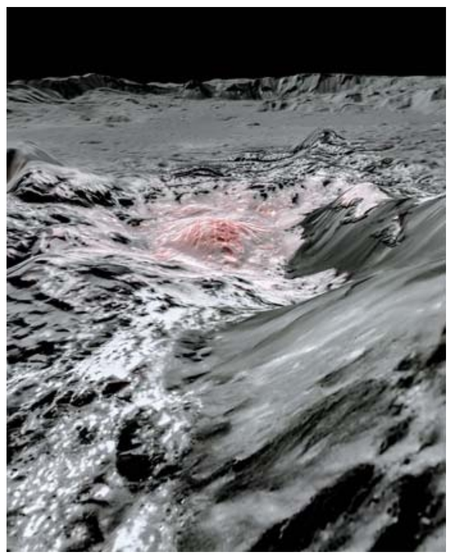
Analysis of the gravity data supports the idea that not only did the impact melt water in an underground chamber, but it also likely created fractures connecting Occator's floor to a larger, deeper, and older reservoir, one that is capable of driving very recent or even current activity.

The results place Ceres in the realm of ocean worlds, says Dawn project scientist Julie Castillo-Rogez (JPL). But she notes that the asteroid's underground ocean is unique among the solar system's other ocean worlds, such as Jupiter's moon Europa and Saturn's Enceladus. Ceres' "ocean" is more of a slurry, Castillo-Rogez explains: 25–30% saltwater mixed with a high concentration of rocky particles.

Whether such an ocean would be habitable is still an open question, but a fascinating one to consider. As Castillo-Rogez writes, the new data show that Occator is "an obvious target for a future mission."

■ **MONICA YOUNG**

● **See more images at https://is.gd/Cereswater**



▶ Recently exposed brine, pushed up from Ceres' depths, is highlighted in red in this false-color view.

NASA / JPL-CALTECH / UCLA / MPS / DLR / IDA (2)

SOLAR SYSTEM

Early Mars Was Wet — But Not Warm

ACCORDING TO NEW RESEARCH, early Mars was wet but rarely warm.

Ancient Mars might have had ice sheets advancing and retreating across its surface, says lead researcher Anna Grau Galofre (Arizona State University). She and colleagues report in the August 3rd *Nature Geoscience* that rivers, which cut channels across the Martian surface long ago, mostly flowed underneath these glaciers.

Before now, scientists have largely thought that these channel networks were carved by water flowing on the surface between 3.5 billion and 3.9 billion years ago. But three-dimensional climate models have been unable to reproduce the "wet and warm" Mars required for this to happen.

Grau Galofre and her team examined subglacial channels on Devon Island, a harsh, uninhabited place in the Canadian Arctic Archipelago that has served previously as a Mars analog. The researchers developed metrics to classify four possible origins for the valley networks: surface rivers, glacial meltwater, subglacial flows, and seeping flows from groundwater sources. Then they applied these metrics to trace the origins of more than 10,000 Martian valleys making up 66 valley networks.

Of these networks, 22 showed the hallmarks of fluid erosion under the pressure of thick glacial ice sheets. Another 9 networks exhibited features associated with retreating ice sheets. Seventeen valley networks looked like surface flows: 14 that were cut by open rivers and three formed from groundwater sapping. The model couldn't pin down the origins of the remaining 18 networks.

▲ Subglacial channels carved on Devon Island, shown here, share features with many Martian valley networks.

An icy Mars need not be lifeless, Grau Galofre says. She points out that a subglacial environment would hover around the freezing point for an extended time, which would protect any life from dramatic temperature variations as well as intense solar radiation.

Jeffrey Kargel (Planetary Science Institute), who was not involved in the study, praises the team for a "great quantitative analytical approach." However, Victor Baker (University of Arizona), who was also not involved in the study, points out that other phenomena on Mars dating back to the same time period are consistent with warm conditions.

NASA's Perseverance rover, now on its way to Mars, will hopefully cast more light on how warm Mars was in its early days.

■ JEFF HECHT

SUN

Radioactive Aluminum Sheds Light on Young Solar System

▲ Artist's illustration of the young solar system

ASTRONOMERS THOUGHT aluminum-26, a short-lived radioactive isotope that flooded the early solar system, could only be made in supernovae or around giant stars. Now, research shows that Sun-like stars could produce it themselves, right after they're born.

Calcium-aluminum-rich inclusions (CAIs), tiny white specks found in larger meteorites, were one of the first solids to condense in the protostellar disk of dust and gas around the still-forming Sun. Studies of CAIs have shown that the early solar system was awash in aluminum-26, a quickly decaying radioactive isotope that only forms in extreme environments. Researchers had suggested that the isotope might have blown into the solar system from a nearby supernova or via winds from extremely massive stars. Either scenario would make our Sun's birthplace busy.

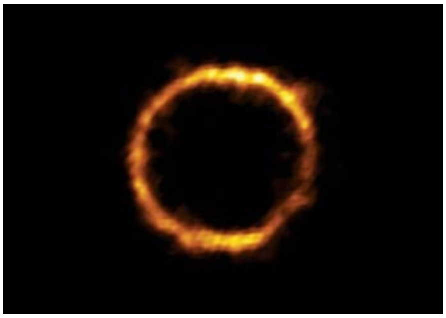
New research points to a simpler explanation: The Sun itself might have helped produce aluminum-26. Brandt Gaches (University of Cologne, Germany) and colleagues developed computer simulations, published in the July 20th *Astrophysical Journal*, which demonstrate that the young Sun would have sent more than enough energetic protons into the protostellar disk, where they would have collided with existing elements to make aluminum-26.

Gaches and his team propose that production peaks as the protostar's growth begins to slow and planets start forming. For the solar system, this corresponds to about 4.6 billion years ago, when meteorites' CAIs formed.

Even if young stars' cosmic rays made aluminum-26, though, that doesn't explain the presence of other short-lived radionuclides; only supernovae can produce iron-60, for example. However, while nearby supernovae are still needed to explain some features of our solar system, the new findings relax constraints on those scenarios.

■ JAVIER BARBUZANO

DEVON ISLAND: A. GRAU GALOFRE / ARIZONA STATE UNIVERSITY; RADIOACTIVE ALUMINUM: NASA / JPL-CALTECH



◀ The ALMA radio observatory reveals a distant galaxy gravitationally lensed into a near-perfect ring of light.

GALAXIES

"Dead Ringer" for the Milky Way Found in the Early Universe

ASTRONOMERS HAVE USED a gravitational lens to investigate a surprisingly Milky Way–like galaxy that existed 1.4 billion years after the Big Bang.

The gravity of a massive foreground galaxy bends the light of the more distant galaxy, referred to as SPT0418–47, distorting its shape into a near-perfect Einstein ring. Francesca Rizzo (Max Planck Institute for Astrophysics, Germany) and colleagues used the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile to image the glow of this galaxy's cool dust, as well as emission associated with its star-forming gas. They then reconstructed the galaxy to show what it would look like without the distortions, publishing the results in the August 13th *Nature*.

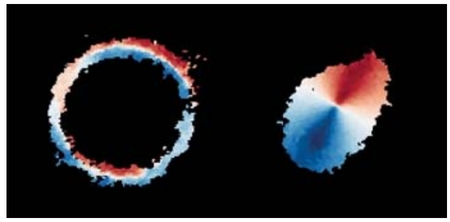
The digitally restored galaxy is roughly 10 times smaller than the Milky Way and furiously forming stars more than 100 times the rate in our own galaxy. But the young galaxy is surprisingly modern in its shape and behavior. Like our own, it's a rotating disk with a central bulge. And it's less chaotic than expected.

Cosmological simulations have taught astronomers to expect fluffy disks in the early universe, with forces other than rotation also contributing to the movement of gas. But in this galaxy, rotation dominates over random motions by about 10:1, similar to modern-day galaxies like the Milky Way.

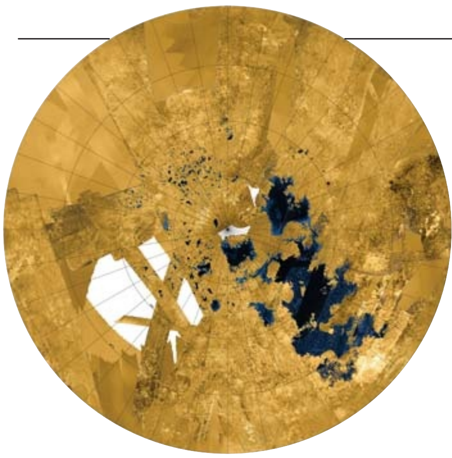
However, Marcel Neeleman (Max Planck Institute for Astronomy, Germany) cautions that comparing observations with cosmological simulations isn't so simple. Most simulations, including the one quoted in this study, do not model the cold gas that ALMA sees. That said, Neeleman thinks the implications could be profound if additional observations can replicate these findings in other early galaxies.

Cosmological simulations used to form too many stars early on, Neeleman explains. Current models solve that problem by including feedback, such as the blowback from newborn stars and supernovae or black hole jets. Feedback hinders gas from settling into stars — but it also produces turbulence. If astronomers find that other young galaxies also lack turbulence, Neeleman says, then they'll have to rethink the role, or at least the mechanisms of feedback in galaxy evolution.

■ **MONICA YOUNG**



▲ These images show motions within the galaxy as observed (left) and in the reconstructed version (right); blue and red represent gas moving toward and away from the observer, respectively. The galaxy is a rotating disk with a central bulge.



◀ This mosaic of radar images from Cassini's Titan flybys shows the various lakes and seas on Saturn's largest moon.

MOONS

Waves on Titan's Seas

SUNLIGHT GLITTERING OFF rough patches of a methane-ethane sea on Titan has provided the first solid evidence for abundant (albeit tiny) waves on Saturn's largest moon.

NASA's Cassini spacecraft previously detected the glare of sunlight reflecting off the smooth surfaces of the moon's lakes and seas, and in early years, scientists saw no signs of waves. But calculations suggested that winds would begin to rise as the northern hemisphere entered spring in 2010 and surface temperatures increased slightly. Subsequent observations found hints of a few, isolated instances of waves in two seas (*S&T:* Oct. 2014, p. 18).

Michael Heslar (University of Idaho) and colleagues have now dived into Cassini's data and found evidence of widespread wave activity on Titan's largest sea, Kraken Mare.

The team took advantage of high-resolution observations gathered during Cassini's later Titan flybys to look for *sun glitter*, when sunlight reflects off rougher seas. Sun glitter is weaker than the glare of direct reflection. Combining imaging and spectral data with radar surface maps, the team found several instances of sun glitter on Kraken Mare's surface, especially in and around two narrow straits, Bayta Fretum and Seldon Fretum. The sun glitter may indicate consistently agitated seas in the straits — unsurprising for coastal areas, the team notes in the September *Planetary Science Journal*.

Calculations and lab experiments suggest that weak winds and tides lead to waves up to 20 cm (8 inches) high — hardly a surfer's dream. But wave height is difficult to gauge without better knowledge of the seafloors.

■ **CAMILLE M. CARLISLE**

DISTANT GALAXY: ALMA / ESO / NAOJ / NRAO / RIZZO ET AL. / NATURE AUG. 12, 2020 (2); TITAN: NASA / JPL-CALTECH / ASI / USGS

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ASTEROIDS

Potential New Targets for Hayabusa 2

THE HAYABUSA 2 TEAM has laid out a proposal for an extended mission to one of two asteroids after the spacecraft's Earth flyby this December.

Launched in 2014, Hayabusa 2 arrived at Ryugu in 2018, collected samples, and deployed two rovers and a small lander, then departed in November 2019 (*S&T:* Mar. 2020, p. 10). The spacecraft will pass by Earth on December 6, 2020, dropping off its sample-return capsule in Australia.

With still about half of the xenon thruster fuel remaining and the spacecraft in good shape, Japan Aerospace Exploration Agency (JAXA) engineers are now looking at options for sending the mission to another target.

Possible asteroids, selected from an initial field of 354 candidates, include the oblong 2001 AV_{43} and the carbonaceous 1998 KY_{26}. They're each about the size of a baseball diamond, both circle the Sun outside of Earth's orbit, and both have a low enough speed relative to the spacecraft to put them within reach after December's flyby.

Both are also fast rotators, as evidenced by their light curves, each spinning on its respective axis once every 10 minutes. These asteroids are therefore likely solid objects, rather than loosely aggregated "rubble piles" like Ryugu and 101955 Bennu are (the latter is the target of NASA's Osiris-REX mission).

Hayabusa 2 could reach 2001 AV_{43} in late 2029 or 1998 KY_{26} in mid-2031, if the extended mission is approved.

Navigating to either asteroid would involve Earth flybys, but reaching 2001 AV_{43} would also require a pass by Venus. JAXA could use the Venus flyby to carry out observations that would complement data coming from the Akatsuki orbiter.

Visiting either space rock would give Japan the opportunity to test its technical capabilities of deep-space navigation and planetary protection technology.

■ DAVID DICKINSON

STARS

Magnetic Fields in Serpens South

NEW DATA SHOW the complex role of magnetic fields in star formation.

Thushara Pillai (Boston University) and colleagues used the HAWC+ instrument aboard the Stratospheric Observatory for Infrared Astronomy (SOFIA) to gauge magnetic field direction and strength in the Serpens South stellar nursery, publishing the results August 17th in *Nature Astronomy*.

▲ This composite image of the Serpens South star cluster shows magnetic field lines superimposed over an infrared background image.

Dense filaments of dust and gas permeate the cluster. Previous measurements have shown that the magnetic field tends to run parallel to lower-density filaments but perpendicular to higher-density filaments. Magnetism might moderate star formation by counteracting the pull of gravity.

However, the new HAWC+ measurements taken by Pillai's team indicate that along the densest, darkest filaments in Serpens South, such as the one at lower left in the image above, the magnetic fields once again run parallel. "In some dense filaments the magnetic field succumbs to the flow of matter and is pulled into alignment with the filament," Pillai explains. The weakly magnetized gas is feeding the growth of new stars like a conveyor belt.

■ MONICA YOUNG

IN BRIEF

Arecibo Observatory Damaged

The Arecibo Observatory in Puerto Rico, one of the world's largest radio telescopes, was damaged when one of its auxiliary cables snapped, bringing operations to a halt. No personnel were injured. The damage occurred on August 10th at 2:45 a.m. local time, when a 3-inch-thick cable snapped and fell, opening a gash 30 meters (100 feet) long in the 305-meter reflector dish. The cable is one of many extending from three towers, which support a metal platform over the dish. Among other things, the platform houses the Gregorian dome, a reflector system that focuses incoming radio waves. The dish points at the zenith, but thanks to the beam-steering mechanism in the dome Arecibo can aim at a swath 20° north or south of this point, expanding its view considerably. The auxiliary cables and Gregorian dome were added in an upgrade completed in 1997. What caused the cable to snap isn't immediately clear; engineers are still gauging the damage and the time needed for repairs.

■ DAVID DICKINSON

See images and drone video at https://is.gd/Arecibodamage.

Lick Observatory Survives Wildfires

As the Santa Clara Unit Lightning Complex fire swept east of San Francisco Bay in California in late August, flames threatened the historic Lick Observatory, founded in 1888 on nearby Mount Hamilton just outside San Jose. The fire, which had already burned nearly 400,000 acres, came dangerously close to the main domes around August 19–20. The fire came within meters of the domes and was clearly visible via the observatory's webcam. However, the main observatory complex escaped major damage and staff and residents are safe. A few historic residences — including the home of astronomer Edward Emerson Barnard on Kepler Peak — were lost in the conflagration.

■ DAVID DICKINSON

See how close the fire came at https://is.gd/Lickfire.

NASA / SOFIA / T. PILLAI / NASA / JPL-CALTECH / L. ALLEN

"It's the most wonderful time of the year . . ."
to see meteors!

Mark Sunday, December 13th, on your calendar as Night of the Shooting Stars. If skies are clear, you'll have a chance to observe the brightest, most reliable, and prolific annual meteor shower.

There was a time not so long ago when such accolades were reserved solely for the perennial midsummer performance staged by the August Perseids. But that was then, and this is now.

Fifty years ago, the Geminids were considered a strong second to the Perseids. But over the years the Geminids have slowly increased in intensity, and around the turn of this century they moved into top spot and show no sign of slackening any time soon.

Although the Geminids now surpass the Perseids, without doubt December's frequently cloudy weather and cold temperatures have worked against the display, at least from the perspective of skywatchers north of the tropics. There's no question that if the Geminid meteors occurred during a warmer month, they'd be as popular as the Perseids.

Relaxing on a reclining chair for a few hours is a wonderful way to enjoy the sight of shooting stars . . . so long as it's summer. However, it's a different story in mid-December when you might be subjected to blustery winds, fast-moving clouds, and frigid temperatures. Only a nut would forego a nice warm bed to be outdoors in such conditions. But I'll wager that the nuts will be out in force on the night of December 13–14 for a chance to catch a few "Gems."

Unlike 2019, viewing circumstances for the Geminids this year are nearly perfect. Last year, the display was "mooned out" by a waning gibbous that shone like a dazzling spotlight from the very constellation the Geminid meteors appear to radiate from. And the shower's peak took place during daylight hours in North America, ensuring that most observers missed the best part of the show. By contrast, this year the Moon will be new on December 14th (at 16:17 UT, 11:17 a.m. EST), so there won't be the slightest bit of lunar interference.

There's more good news. The shower's 2020 maximum is forecast to occur around 1^h UT on December 14th. That corresponds to the early evening hours of the 13th across North America. The Geminids, however, tend to remain close to their peak strength for about 8 to 10 hours both before and after maximum, meaning we'll have a front row seat for this year's presentation. And it should be good. According to the International Meteor Organization (IMO), rates of up to 150 per hour — more than two per minute — are possible from dark-sky sites.

How to Prepare

In his 1946 guidebook *A Primer for Stargazers*, Henry Neely wrote about observing the Geminids and offered this recommendation: "Take the advice of a man whose teeth have chattered on many a winter's night — wrap up much more warmly than you think is necessary."

How true!

No two observers prepare for a meteor vigil the same way. I find it helps to have had a late afternoon nap, a shower, and to wear all fresh clothing. Break out that summer recliner and either snuggle into an insulated sleeping bag or wrap yourself in a heavy blanket. When you sit quite still and close to the rapidly cooling ground, you can easily become very chilled. Be sure to bundle up evenly from head to foot, paying special attention to preventing air leaks around your face,

PETR HORÁLEK

DECEMBER GIFT The annual Geminid shower is the finest meteor display of the year, but observers need to be ready for cold temperatures to enjoy the show. This composite image portrays the 2018 Geminids as photographed from near Seč Lake, in the Czech Republic.

for the Geminids

neck, wrists, waist, and ankles. Some food and a warm drink will help keep you comfortable but stay away from alcohol — it impairs night vision!

Find a safe observing site that's as far from bright lights as possible and provides a wide-open view of the sky — you don't want trees, buildings, or streetlights intruding into your field of view.

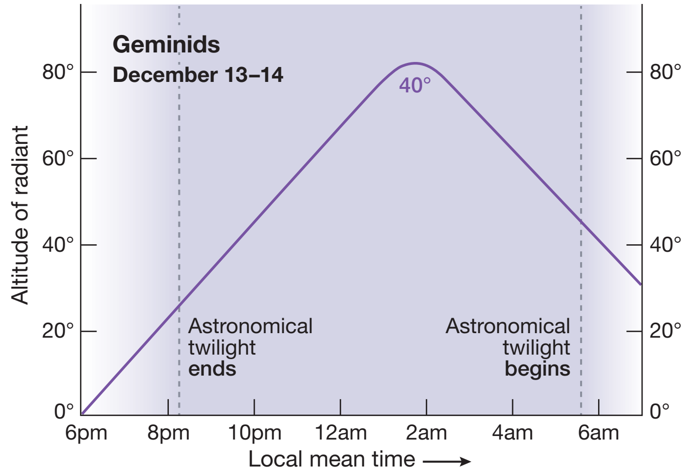
If you're not planning to make a full night of it and just want to do some casual viewing, make sure you allow at least 20 minutes for your eyes to adjust to the darkness. It's a rookie mistake to simply throw on a jacket, step outside from a brightly lit living room, stand around craning your neck for 5 or 10 minutes, then go back inside to declare that the shower was nothing more than a lot of media hype because you "didn't see a @#* thing!" Those crucial 20 minutes of dark adaption will let the pupils of your eyes open wide and allow you to see fainter objects.

Another reason to watch over an extended period is the "clumping effect." Meteors tend to arrive in groups — you'll catch two or three in less than a minute, then several minutes will pass before the sky again bears fruit. If your watch happens to occur during a lull in activity, your meteor count might be a little underwhelming. Viewing for a full hour or longer ensures that you'll see several peaks and valleys in shower activity.

What to Expect

Meteors belonging to the Geminid shower are identifiable because their paths appear to extend back to a small area near the bright star Castor in Gemini (as shown below). However, shower members can appear in any part of the sky, so it doesn't really matter which direction you face. If you concentrate on the radiant, meteors will appear to diverge in all directions, but they'll have short paths. Conversely, if you look in the opposite direction (toward the Great Square of Pegasus in the evening, or Boötes in the predawn) you'll see meteors darting along lengthy paths away from you.

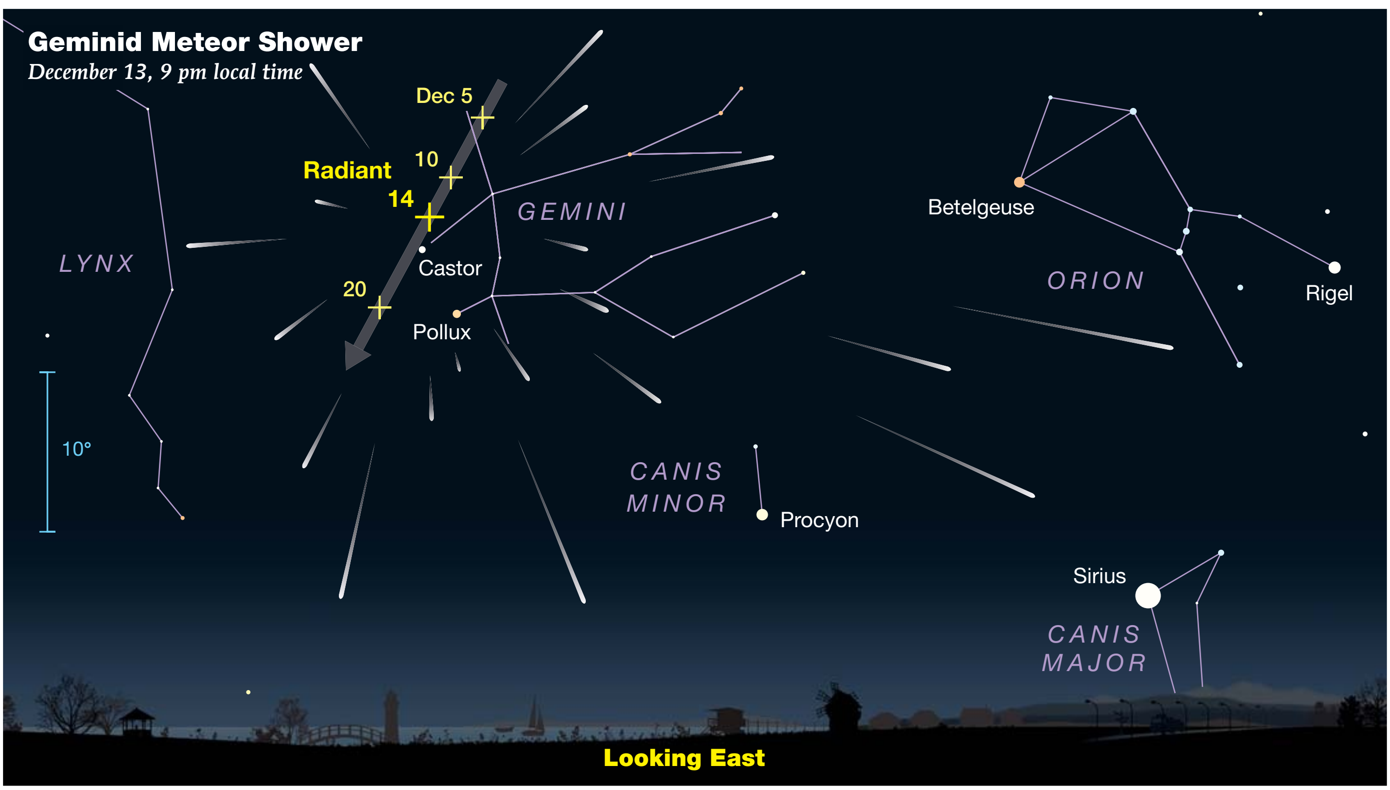
One of the best things about the Geminids — unlike most other meteor showers, including the Perseids — is that you needn't wait until the wee hours of the morning to enjoy a good show. In fact, you might spy a Geminid or two at nightfall. Any that appear that early (when the shower's radiant is hovering near the horizon) will sail majestically across the sky. These "earthgrazers" are bright meteors that enter our planet's atmosphere at very shallow angles and skim along the top layer of air, somewhat like a stone skimming across a lake. You need to be patient, but if you sight just one of these early evening beauties, you'll already feel well-rewarded.



▲ **PEAK OF THE PEAK** As this graph shows, the altitude of the radiant rises and falls throughout the night of the peak. Regardless of your latitude, the peak occurs around 2 a.m. local time.

Gemini will be rising in the east-northeast as the evening wears on, so the number of meteors that flash into view will markedly increase as the shower's radiant climbs higher. A "productive" Geminid watch can start as early as 9 p.m. local time, when the shower's radiant is already about 30° high, or

▼ **SHIFTING SHOWER** The Geminids appear to radiate from a region in northern Gemini, not far from the bright star Castor. As this chart shows, the position of the radiant shifts over the duration of the display. This year, the Geminids peak on the night of December 13–14, at 1^h UT on the 14th. (Positions are plotted for 0^h UT on the dates noted.)



GREGG DINDERMAN / S&T

one-third the distance from the horizon to the zenith.

But it's after local midnight when the radiant soars high in the sky and our side of the planet rotates to face the direction of Earth's orbital motion. That's when the numbers really begin to increase and approach the advertised two-per-minute rate that makes the Geminids so gratifying. And since the onset of dawn doesn't occur until around 5:30 a.m., we have 5½ hours of exciting meteor watching ahead of us.

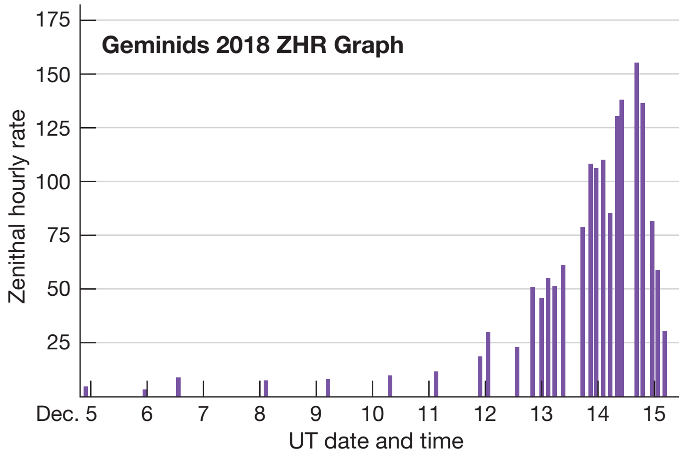
By 2 a.m. the radiant will be almost directly overhead so, if you are blessed with a very dark sky, you can see meteors at the oft-quoted *zenithal hourly rate* (ZHR) of 150. The ZHR is the predicted number of meteors that an experienced observer could see when the shower's radiant is directly overhead and the naked-eye limiting magnitude is 6.5. If your sky isn't quite that dark, or if part of your view is obstructed by trees or clouds (or if the shower is less active than expected), your count will be lower than the ZHR.

Shower Attributes

As the chart at right shows, Geminid activity is asymmetric — the shower features a slow rise, followed by a rapid decline. That means you can expect to see a few Geminids perhaps as early as December 4th. By December 10th, the ZHR is 10, and on the night before the peak (December 12–13) the rate reaches a very respectable 60 meteors per hour. But already 24 hours after the peak (December 14–15), the ZHR has fallen precipitously to around 30, and on the following night (December 16–17) it's back down to about 10. The display is all but over the very next night.

Geminid meteoroids strike Earth's upper atmosphere at around 35 km (22 miles) per second. That's about 40% slower than the average Perseid. Visually, the difference is fairly obvious. Where a Perseid flits across your field of view in a second or less, a Geminid might be visible for a couple of seconds or more. For this reason, many astronomy books refer to Geminid meteors as "slow and graceful."

Another difference between the two showers is that about a third of all Perseids leave persistent incandescent trains in their wake, yet only about 3% of Geminids do. This may have something to do with the fact that Geminid fragments are several times denser than average meteoroids.



▲ **A GOOD YEAR** Bright moonlight seriously hampered the Geminids in 2019, but in 2018 amateurs around the world followed the International Meteor Organization's standardized procedures and counted 10,674 meteors to produce this activity graph. The shower maintained a zenithal hourly rate of around 100 or more for about 22 hours, then, as usual, dropped off faster than it rose.

Curiously, prior to the shower's peak Geminids tend to be somewhat faint, whereas following the peak, for a dramatic 24 hours or so, they're considerably brighter. This may be due to solar radiation pressure separating lighter cosmic dust from larger and heavier meteoric particles. So, from the appearance of the first forerunners up until the peak, the preponderance of Geminids seen are generally in the range of 3rd or 4th magnitude. But at the shower's peak, Earth interacts with much larger fragments, of which 50% produce

▶ **SUMMER SPLENDOR** August's mild temperatures and frequent clear skies mean the Perseids are the best-known annual meteor shower, even though December's Geminids actually put on a better show. This composite photo taken by Petr Horálek shows the 2018 Perseid display and includes 407 meteors recorded over nine nights, between August 6 and 14, 2018.

ZHR GRAPH: IMO

meteors of at least 2nd magnitude and about 10% reach zero magnitude or brighter. A few become outstandingly bright meteors (fireballs) while others silently and spectacularly explode (bolides).

Geminids can also be colorful. About 90% appear yellowish-white, but the rest can appear red, orange, blue, and even green. Some observers report that the Geminids appear brighter and more colorful before midnight.

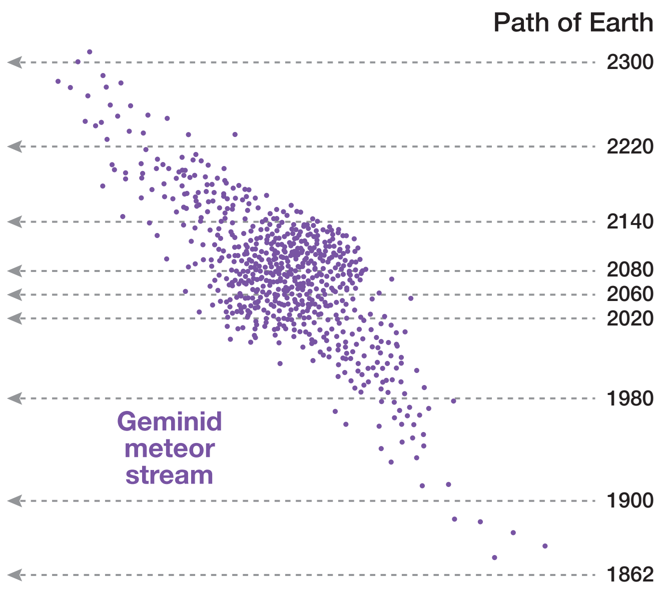
The Geminid "Rock"

Meteor streams in general are thought to comprise dusty debris released by comets. However, for many years the source of the Geminids was an enigma because no parent comet could be identified. In fact, up until the early 1980s, astronomers assumed that the original Geminid comet had disappeared centuries ago.

Then, on October 11, 1983, the Infrared Astronomical Satellite (IRAS) found an asteroid racing through the stars of Draco. The object was provisionally designated 1983 TB and turned out to be a most unusual find in more ways than one.

First, traveling in a highly elongated orbit, the 5-km-wide asteroid comes closer to the Sun than any other asteroid. Its perihelion distance is only 20.9 million km in its 1.43-year orbital period — nearly one-third Mercury's average distance, and 7 million km closer than the previous asteroid record holder, 1566 Icarus. The IRAS asteroid's surface heats up to about 700°C (1,300°F) — hot enough to melt aluminum. Appropriately, the object was christened 3200 Phaethon (pronounced "FAY-uh-thun"), after the son of Helios, the god of the Sun in Greek mythology.

Two weeks after its discovery, highly regarded comet expert Fred L. Whipple reported in IAU Circular 3881 that this asteroid's orbit was practically identical with the Geminid stream and was the long-sought parent body of these meteors. But how could an asteroid produce meteoroids?



▲ **A STREAM OF DEBRIS** A theoretical cross-section of the Geminid meteor stream. Imagine that this page represents the plane of the Earth's orbit. The Earth moves from right to left and the zone of intersection shifts over time, causing the Earth to pass through different parts of it.

In the November 2010 issue of *The Astronomical Journal*, astronomers David Jewitt and Jing Li suggested that Phaethon is essentially a "rock comet." Phaethon's short perihelion distance induces thermal fracturing of its rocky surface, which leads to the production of dust that is subsequently ejected into space.

Indeed, in 2009 and 2012 NASA's STEREO A spacecraft imaged Phaethon emitting a stubby tail of gravelly debris. But Jewett and Li also pointed out a problem: The amount of dust ejected during the asteroid's solar encounters adds a meager 0.01% to the mass of the debris stream — far less than needed

▼ **ECCENTRIC ASTEROID** (*Left*) In 2009 and again in 2012, David Jewitt, Jing Li, and Jessica Agarwal (University of California, Los Angeles) used NASA's STEREO A spacecraft to image Phaethon as it reached perihelion, and they detected a stubby dust tail pointing away from the Sun. Visible in this STEREO image is the southeastward extension of Phaethon's dust trail. (*Right*) Asteroid 3200 Phaethon is the source of the Geminid meteor shower. The object travels in a very eccentric orbit and passes closer to the Sun than any known asteroid. On December 16, 2017, it whizzed past Earth at a distance of 10.3 million km (6.4 million miles). It won't come this close again until 2093.

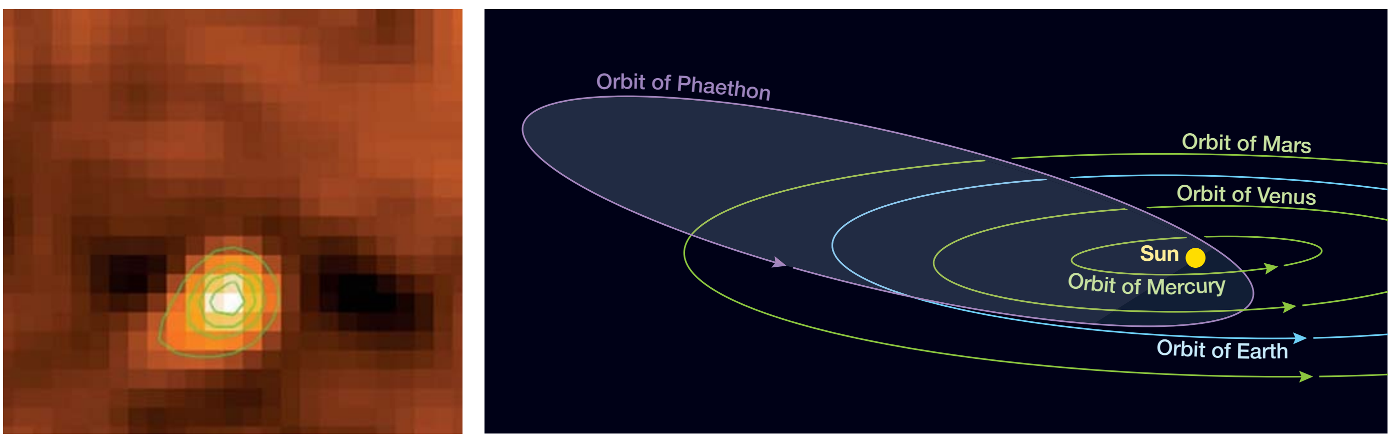


IMAGE OF PHAETHON: JEWITT, LI, AGARWAL / NASA / STEREO; PHAETHON ORBIT DIAGRAM: LEAH TISCIONE / S&T; METEOR STREAM DIAGRAM: JOE RAO to keep the Geminids sufficiently stocked for an annual display of shooting stars. So, if Phaethon currently isn't spewing enough dust to account for the Geminids, did it shed more material in the past? No one knows. It's yet another mysterious chapter in the story of the enigmatic Geminids.

The End Is Nigh (Maybe)

Unlike a number of other meteor showers whose historical records span centuries or even millennia, the first definitive appearance of the Geminids dates back just to 1862, making this display the new kid on the block. Are these mid-December meteors only a fleeting moment in the history of the solar system?

In the past, some theorists predicted that Earth would hit the densest part of the Geminid stream during the mid- or late-20th century, and thereafter the shower would start to decline and completely vanish by the end of the 21st century. But these studies were conducted before the discovery of Phaethon, and so far (thankfully) their dismal forecasts have yet to become reality as the Geminids continue to strengthen. But how long can we expect them to last?

To answer this question, I've done my own study with an orbit simulator. The Geminid stream intersects the ecliptic at two locations, but only one of these points (the stream's descending node) is in the vicinity of Earth's orbit. The Geminid stream is currently inside our planet's orbital track, but around 2080 the respective orbits of the stream and Earth should coincide. That could be when the shower plateaus with a ZHR easily topping 200!

Making It Count

If you'd like to be more than a casual spectator, check out how to report a scientific meteor count. You'll need to follow the International Meteor Organization's standardized procedures so that your counts can be meaningfully compared with others. To learn more, visit **imo.net/visual/major**.

But after that, all bets are off.

Once Earth exits the debris stream Geminid activity might end abruptly. However, if the amount of material left in the wake of Phaethon is symmetrically distributed, the Geminids would slowly diminish before finally disappearing completely by the end of the 23rd century.

No matter what the future holds, we should consider ourselves fortunate to be living at a time when we can enjoy such a wonderful celestial pyrotechnics display each December. Think of the Geminids as nature's free holiday gift — one well worth braving cold temperatures to receive!

■ **JOE RAO** is an eight-time Emmy-nominated broadcast meteorologist and has been an assiduous amateur astronomer for more than 50 years. He has served as an associate and guest lecturer at New York's Hayden Planetarium since 1986. He dedicates this article to his aunt and uncle, Irma and Ron Balzano, who allowed the young Joe to observe comets and meteor showers under the once-dark skies of Mahopac, NY, located 75 km north of New York City.

BRILLIANT BOLIDE This huge Geminid fireball was captured streaking past the stars of Orion on December 14, 2017, over Tucson, Arizona by Eliot Herman. He writes: "Amazing night – many meteors captured including quite a few bright ones – this being the best by far. A photo of a lifetime."

The Caldwell Catalog Turns 25

SPUR-OF-THE-MOMENT COMPILATION One evening's musings led to an observing catalog that first appeared in the pages of this magazine a quarter of a century ago.

This popular list of observing targets published in 1995 is marking its first quarter-century.

This month marks the 25th anniversary of the first publication of the Caldwell Catalog in the December 1995 issue of *Sky & Telescope*. In the past quarter-century the Caldwell Catalog has inspired further creations, provoked discussions and debates, and led thousands of amateur astronomers to observe objects that they might otherwise have overlooked. And yet, after all this time there are parts of the story of the Caldwell Catalog that aren't widely known. This anniversary seems like a fitting time to look back at the origin of the catalog, chart its history, and examine its current status in the landscape of astronomy.

Enter Patrick Moore

The story of the Caldwell list starts with Patrick Moore, the doyen of British astronomy from the 1950s until his death in 2012. Moore, an astronomical prodigy, became interested in the subject at the age of six, and by the age of 11 he'd joined the British Astronomical Association. At only 13 he published his first scientific paper, which was on craterlets on the Moon that he'd observed from home using a 3-inch refractor. Moore's first book, *Guide to the Moon*, appeared in 1953, and he'd go on to write many more, mostly nonfiction astronomy titles. Working with Hugh Percy Wilkins, Moore mapped the Moon in unprecedented detail, and both the early Russian and American lunar programs would rely on the maps and data generated by these visual observers. Starting in 1957, Moore hosted the monthly "The Sky at Night" television program for the British Broadcasting Corporation. He would continue to host the program the rest of his life, setting a world record for the longest-running television series with the same presenter.

For his contributions to astronomy and the popularization of science, Moore received many honors, including a knighthood in 2001. He always described himself as an amateur and, as a visual observer of the Moon and planets, a "dinosaur." Moore liked to joke that anything beyond the orbit of Neptune was a bit remote for him. Regrettably, he also held regressive views on immigration and gender roles. Our goal here is not to focus on his political opinions, but instead to celebrate his deep-sky observing list and the objects it highlights.

The Caldwell Catalog Comes into Being

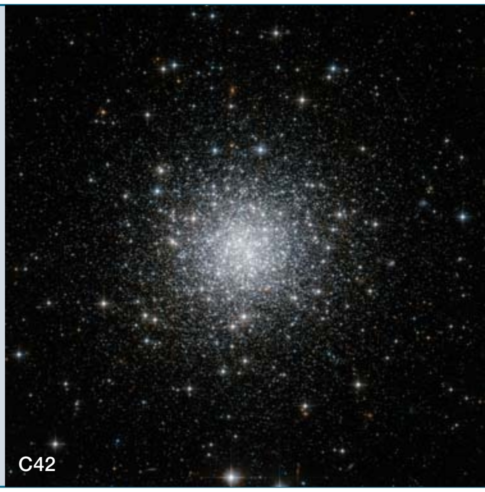
Although his primary interest was in the Moon and the planets, Moore was nevertheless an experienced deep-sky

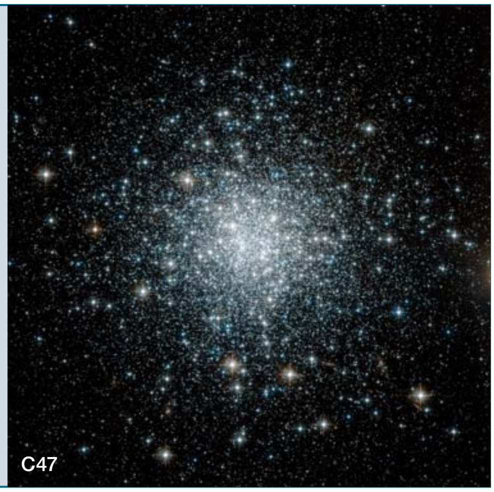
A Caldwell Tour

Whether you're an experienced deep-sky observer or just starting out, the selection of two dozen late-autumn Caldwell objects presented here will show you fine examples of every class of deep-sky object. Moore chose the Caldwells for their inherent interest. In that spirit, and to facilitate comparisons among objects, I've organized this tour by object type rather than by proximity in the sky.

C20: MASIL IMAGING TEAM; CHART: GREGG DINDERMAN / S&T

GLOBULAR CLUSTERS Start high in the west-southwestern sky with the tiny constellation Delphinus, the Dolphin, off the "nose" of Pegasus. Here you'll find two of the most northerly globular clusters in the Caldwell Catalog, C42 (NGC 7006) and C47 (NGC 6934). C42 is the dimmer of the two globulars, at least as seen from Earth, and with good reason: At 135,000 light-years, it lies more than two-and-a-half times as far away as C47, well beyond the disk of the Milky Way.


C42


C47

observer. One evening in 1995 he was struck by the fact that many worthy deep-sky objects were either never observed by Messier, or at least not included in his catalogs. As Moore wrote in the foreword to Stephen James O'Meara's *Deep-Sky Companions: The Caldwell Objects*, ". . . there are many other objects of equal or greater interest than those with 'M' designations. Many of these non-Messier sights are shamefully neglected . . . . Why not draw up a catalog to list objects not identified by Messier?"

The next morning Moore wrote up a list of 109 deep-sky objects spread across the entire sky, including challenges for those with large telescopes. He decided to arrange his list by declination, so that observers could quickly zero in on the most southerly (or northerly) objects available to them, and get an accurate tally of how many were within their reach. Since the 'M' designation was already taken by the Messier catalog, Moore invoked his full last name, Caldwell-Moore, called his list the Caldwell Catalog, and assigned 'C' numbers to the objects. Then, as he wrote, "Having completed my list, I put it in an envelope and sent it off to *Sky & Telescope*. To be candid, I thought very little more about it. Creating the list had been an interesting exercise, but would anyone else be interested in it?"

The editors at *Sky & Telescope* were indeed interested. Thanks to the widespread availability of Dobsonian reflectors and affordable Schmidt-Cassegrains, interest in deep-sky observing had been increasing since the 1970s. Moore's new list of deep-sky objects, chosen for their visual splendor and astrophysical significance, and composed for a global audience, seemed certain to capture readers' attention. As former editor in chief Rick Fienberg explains, "He [Moore] sent us his letter and list of objects and said we could do with it as we please. We responded by asking him to write an article explaining his rationale for compiling the list and for ordering it by declination from north to south. He responded by saying he was too busy to write such an article, but that we were welcome to adapt his letter for an article ourselves. That's why Barlow Pepin is the coauthor [in the December 1995 issue] — he was the editor assigned to turn what Patrick sent us into an article. Patrick approved the article before we published it and was thrilled at how it came out."

C42 & 47: ESA / HUBBLE / NASA; C22: MASIL IMAGING TEAM; C6: NORDIC OPTICAL TELESCOPE / ROMANO CORRADI / ISAAC NEWTON GROUP OF TELESCOPES, SPAIN

PLANETARY NEBULAE A large swath of the western sky offers no fewer than five Caldwell planetary nebulae. Start in the northwest with C6, the Cat's Eye Nebula (NGC 6543), in Draco, just about halfway between Delta and Zeta Draconis. A little more than 20° to the southeast, in the western wing of Cygnus, the Swan, you'll find C15, the Blinking Planetary (NGC 6826). Another sweep almost twice as much farther east takes you to Andromeda and C22, the Blue Snowball (NGC 7662), flying near the zenith on late-autumn evenings. Now pivot south and swoop down low to Aquarius to find C55, the Saturn Nebula (NGC 7009). The planetaries listed so far are small, but with high surface brightness, so they hold up surprisingly well under moderate light pollution if you use high magnification. But you'll want the opposite — dark skies and low magnification — to pick up the fifth and final Caldwell planetary on this tour: C63, the Helix Nebula (NGC 7293). The large apparent size and low surface brightness of the Helix are due to its proximity: At a little more than 500 light-years away, it's much closer than the other planetaries listed here, which range from 1,400 to 3,200 light-years away.


C22


C6

C4

C27

DIFFUSE NEBULAE The Caldwell Catalog includes diffuse nebulae of every level of brightness, from naked-eye visible to darned near impossible. But at least a couple should be easy to find at this time of year. Start in Cepheus with C4 (NGC 7023), a small reflection nebula that benefits from moderate magnification. Then scan a little more than 20° south on the same line of right ascension to find C20, the North America Nebula (NGC 7000; page 20), which is visible to the naked eye under sufficiently dark skies, and a fine target for binoculars and rich-field telescopes. If you're up for a challenge, proceed to the heart of Cygnus, the Swan, to attempt C27, the Crescent Nebula (NGC 6888) — at least the brightest portion of the loop should be visible as a bar of light projecting southwest from a 7th-magnitude star.

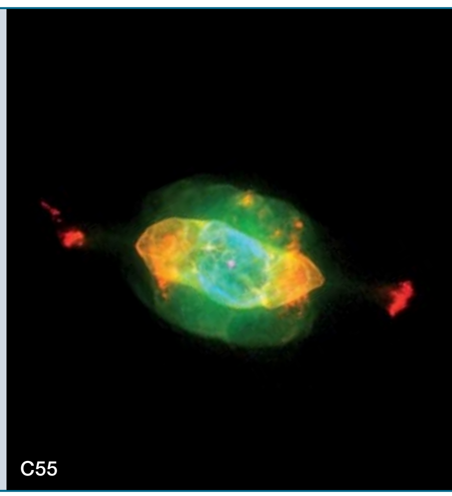
C27 & C4: MASIL IMAGING TEAM; C15 & C55: BRUCE BALICK / JASON ALEXANDER / ARSEN HAJIAN / YERVANT TERZIAN / MARIO PERINOTTO / PATRIZIO PATRIARCHI / NASA / ESA; C63: NASA / ESA / C. R. O'DELL / VANDERBILT UNIVERSITY / M. MEIXNER / P. MCCULLOUGH / G. BACON / SPACE TELESCOPE SCIENCE INSTITUTE

Caldwells Go Global

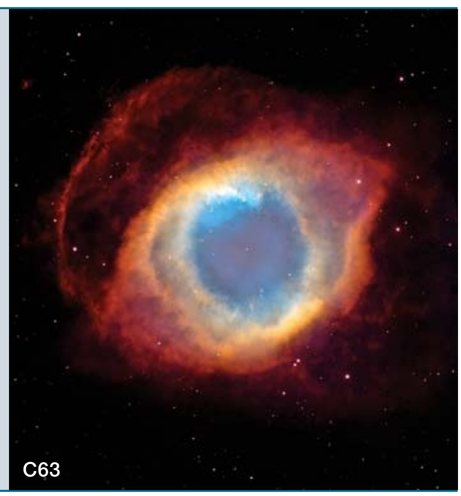
The response to the article was more than anyone had anticipated. "The Caldwells came along at the right time," in the words of Dennis di Cicco, who was an associate editor in 1995. "It was a deep-sky list at a time when deep sky was really taking off. We thought it would be an interesting article, but we were surprised when it caught on as much as it did. We didn't initially think that it would be something that people would write books about." In fact, to this date there have been at least three books about the Caldwells: the aforementioned volume by O'Meara; *Observing the Caldwell Objects* by David Ratledge; and *The Caldwell Objects and How to Observe Them* by Martin Mobberley. In 2001, the Astronomical League (AL) launched a Caldwell Observing Program, with a silver award for observing at least 70 Caldwells, and a gold award for those who can travel to the opposite Hemisphere to catch all 109. In addition, the databases of Go To telescopes usually include a list of the Caldwells.

Perhaps inevitably the Caldwell Catalog has also had its detractors. Some people criticize the list because it was originally published with a few errors (since corrected by O'Meara), or because it includes some very difficult objects and some outright stinkers, or because it's not a "true" astronomical catalog published for scientific purposes. I'd counter that some of these criticisms apply to the Messiers as well (anachronistically, M108 and M109 were added in an article by Owen Gingerich in *Sky & Telescope* in 1953!), and that pushing for purity tests in our amateur observing catalogs is a lost cause, not to mention a bit silly. The Caldwell list exists, and it seems it's here to stay.

C15



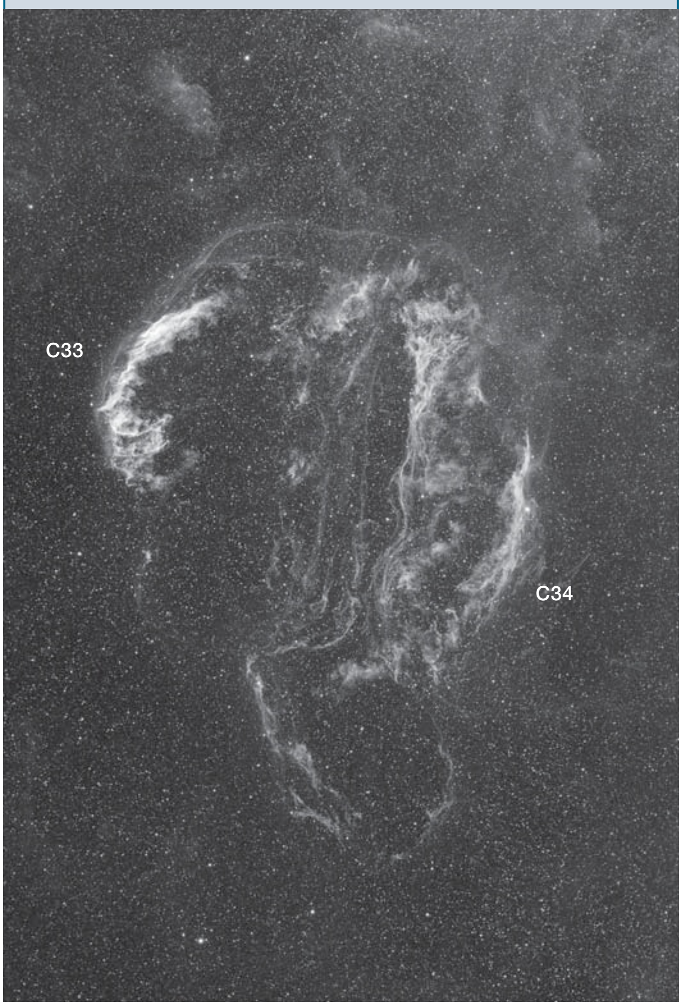
C55



C63

Could much of the criticism of the Caldwell Catalog stem from a misunderstanding about its purpose? It's not supposed to be a list of the 109 best and brightest deep-sky objects beyond the Messiers, nor the 109 easiest, and Moore never claimed otherwise. Instead, he wrote that ". . . there are many other objects of *equal or greater interest*" (emphasis mine) than the Messiers, which in his opinion hadn't received enough attention from amateur astronomers, including some challenging ones. Among them are the Milky Way's largest and brightest globular clusters Omega Centauri (C80) and 47 Tucanae (C106), colliding galaxies NGC 4038 and 4039 (C60 and C61), a vast, dark molecular cloud called the Coalsack (C99), not to mention variable nebulae, open clusters, supernova remnants, dwarf galaxies, and more planetary nebulae than you can shake a horizontal branch at.

SUPERNOVA REMNANT While you're in Cygnus, examine the area southwest of a line connecting Epsilon and Zeta Cygni for a supernova remnant, C33 and C34, the eastern and western parts of the Veil Nebula (NGC 6992/5 and NGC 6960, respectively). Dark skies, low magnification, and good dark adaptation will all help to bring these vast arcs of exploded star-stuff into view.

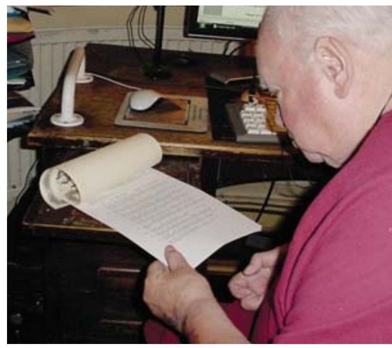


The Caldwells: A Personal Quest

Going after the Caldwells has pushed me to become a better observer. To this day I've never seen the notoriously dim Cave Nebula (Sharpless 2-155, C9), but searching for it sent me farther into the deserts of southern California and western Arizona. Under those inky-dark skies I was able to make out the Bubble Nebula (NGC 7635, C11) and the dwarf galaxy IC 1613 (C51), which even O'Meara — one of the most skilled visual observers of our time — considers to be challenging objects. I learned to be zealous about dark adaptation, to observe objects when they culminate, to optimize averted vision, and to breathe deeply before attempting a difficult detection. All these skills paid off when I started work on the Herschel 400 and other deep-sky observing lists.

From my regular observing site on the shore of the Salton Sea, Omega Centauri (C80) is naked-eye visible — barely — and it's the most southerly Caldwell I've seen from California. There are 29 more at or below my horizon. I got a crack at the remaining southern Caldwells in the summer of 2010, when I attended a scientific conference in Punta del Este, Uruguay. At night I'd go down to the beach with binoculars and a tiny travel telescope, and cruise the skies, which were deliciously dark and clear. Despite my modest instruments I was able to log 91 southern celestial gems, including 23 Caldwell objects. That trip pushed my Caldwell tally over 70 — enough to qualify for the Astronomical League's silver award for the Caldwell program.

Why am I telling you all this? Because my story is about to intersect with Moore's. When I returned from Uruguay I dutifully sent my observing log to Susan Rose, coordinator for the AL's Caldwell Observing Program. Shortly thereafter, Rose embarked on her annual pilgrimage to Moore's home in Selsey, on the south coast of England, bearing the Caldwell program logs. A month later I got a wonderful surprise in the mail: my Caldwell program certificate and a letter of congratulations, both signed by Moore himself. The certificate, the letter, and the photo (at right) are among my most treasured mementos to this day.



▲**COUNTING CALDWELLS** Every year, the Astronomical League's Susan Rose would bring a batch of observing logs to Moore at his home in England. If the observer tallied the requisite 70 objects, they'd earn a silver award; the full list of 109 would garner them the gold award. Moore enjoyed the interaction with amateurs chasing "his" targets. In this photo, Moore is reviewing Matt Wedel's observing notes, and ascertained that Wedel had indeed observed at least 70 Caldwell targets.

C33 & C34: MDW SKY SURVEY; COUNTING CALDWELLS: SUSAN ROSE

Legacy — the Caldwells Today

In his later life, Moore always seemed both pleased and humbled that his list had caught on. For as long as he was physically able, he enjoyed personally reviewing the observing logs of those who had completed the AL's Caldwell program. As Rose told me, "He was very pleased that people thought enough of his list to tackle it and always appreciated all the comments people sent him. I had the honor of giving him the first Caldwell awards, and he hung them up over his desk. He signed all the certificates personally until his severe arthritis prevented him from doing so. I then used a scan of his signature, but I still took pictures of him holding the certificates until he passed away." It's very fitting that someone who gave so freely of his time, energy, experience, and wisdom should have gotten enjoyment in return from seeing his catalog inspire other amateur astronomers — for that's how Moore always described himself: as an amateur.

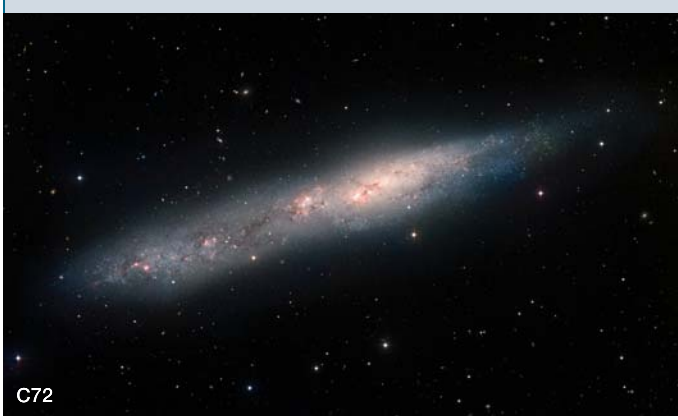
A quarter of a century on, people are still finding new ways to use the Caldwell Catalog. Noted observer Stephen Saber enjoys running Messier Marathons and chasing Caldwell objects, and he's combined both pursuits to create the Messier-Caldwell Marathon: an attempt to see all 110 Messier

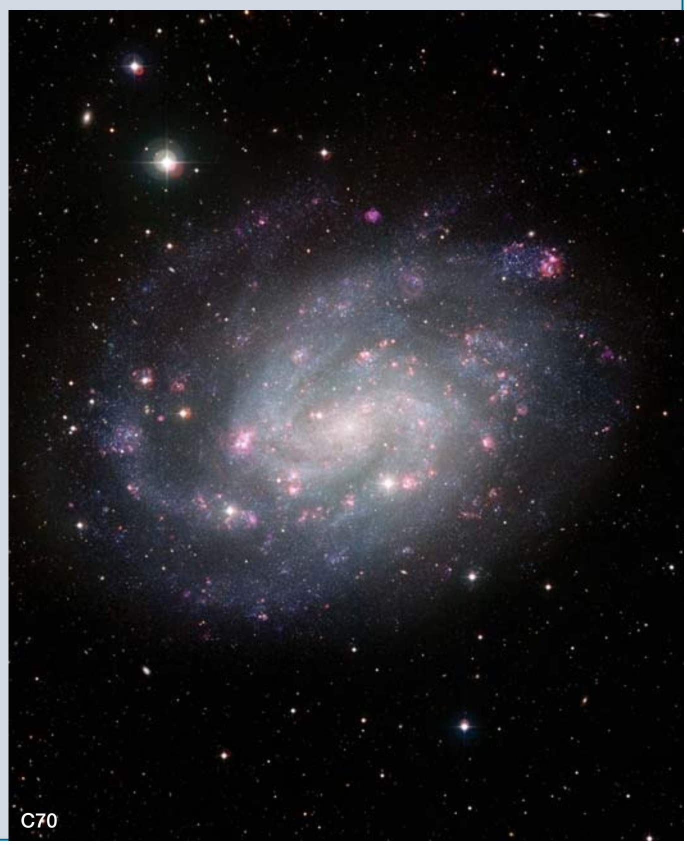
GALAXIES Now let's go deeper, into intergalactic space. The magnificent spiral galaxy C7 (NGC 2403) in Camelopardalis, the Giraffe, never sets at mid-northern latitudes, but you may have to wait a bit for it to rise above the near-horizon murk. While you're waiting, scan north-northeast of Eta Pegasi for C30 (NGC 7331), a vast spiral galaxy larger than our own Milky Way. An even more stunning galaxy waits far to the south and east: C65, the Silver Coin (NGC 253), at the northern edge of the constellation Sculptor. If you have a clear southern horizon, drop down another 12° to the southern reaches of Sculptor, to hunt for two more galaxies: At 7th-magnitude, C70 (NGC 300) and C72 (NGC 55) are both fairly bright, but they're in a region of the sky that many Northern Hemisphere observers visit infrequently.


C7

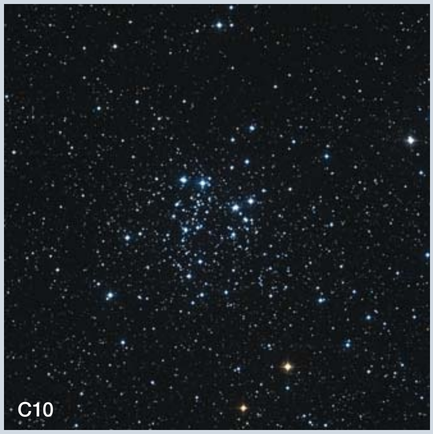

C65

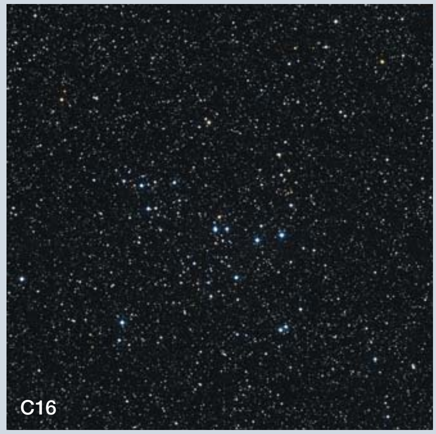

C30


C72


C70

C65: ESO / INAF-VST; C7: NASA / ESA / A. V. FILIPPENKO / UNIVERSITY OF CALIFORNIA, BERKELEY / P. CHALLIS / HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS; C30: MASIL IMAGING TEAM; C72 & C70: ESO





POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY (5); C14: MASIL IMAGING TEAM; C41: AKIRA FUJII

Choice Caldwells for Late Autumn

Caldwell No.	Object	Type	Common Name	Constellation	Mag(v)	Size	RA	Dec.
C42	NGC 7006	Globular Cluster	—	Del	10.6	3.6′	21^h 01.5^m	+16° 11′
C47	NGC 6934	Globular Cluster	—	Del	8.8	7.1′	20^h 34.2^m	+07° 24′
C6	NGC 6543	Planetary Nebula	Cat's Eye Nebula	Dra	8.1	24″ × 18″	17^h 58.6^m	+66° 38′
C15	NGC 6826	Planetary Nebula	Blinking Planetary	Cyg	8.8	30″ × 24″	19^h 44.8^m	+50° 31′
C22	NGC 7662	Planetary Nebula	Blue Snowball	And	8.3	30″	23^h 25.9^m	+42° 32′
C55	NGC 7009	Planetary Nebula	Saturn Nebula	Aqr	8.0	42″ × 24″	21^h 04.2^m	–11° 22′
C63	NGC 7293	Planetary Nebula	Helix Nebula	Aqr	7.3	12′ × 10′	22^h 29.6^m	–20° 50′
C4	NGC 7023	Reflection Nebula	—	Cep	7.7	10′ × 8′	21^h 01.6^m	+68° 10′
C20	NGC 7000	Emission Nebula	North America Neb.	Cyg	5.0	100′ × 60′	20^h 58.8^m	+44° 20′
C27	NGC 6888	Emission Nebula	Crescent Nebula	Cyg	8.8	18′ × 13′	20^h 12.0^m	+38° 21′
C33	NGC 6992/5	Supernova Remnant	Eastern Veil Neb.	Cyg	7.5	60′ × 8′	20^h 56.4^m	+31° 43′
C34	NGC 6960	Supernova Remnant	Western Veil Neb.	Cyg	7.9	70′ × 6′	20^h 45.7^m	+30° 43′
C7	NGC 2403	Spiral Galaxy	—	Cam	8.4	24′ × 13′	07^h 36.9^m	+65° 36′
C30	NGC 7331	Spiral Galaxy	—	Peg	9.5	9.7′ × 4.5′	22^h 37.1^m	+34° 25′
C65	NGC 253	Spiral Galaxy	Silver Coin	Scl	7.6	26′ × 6′	00^h 47.6^m	–25° 17′
C70	NGC 300	Spiral Galaxy	—	Scl	8.1	20′ × 15′	00^h 54.9^m	–37° 41′
C72	NGC 55	Spiral Galaxy	—	Scl	8.1	34′ × 6′	00^h 15.1^m	–39° 13′
C8	NGC 559	Open Cluster	—	Cas	9.5	7′	01^h 29.5^m	+63° 18′
C10	NGC 663	Open Cluster	—	Cas	7.1	15′	01^h 46.3^m	+61° 13′
C13	NGC 457	Open Cluster	ET Cluster	Cas	6.4	20′	01^h 19.5^m	+58° 17′
C14	NGC 869/884	Open Cluster	Double Cluster	Per	5, 6	18′, 18′	02^h 20.5^m	+57° 08′
C28	NGC 752	Open Cluster	—	And	5.7	75′	01^h 57.6^m	+37° 50′
C16	NGC 7243	Open Cluster	—	Lac	6.4	30′	22^h 15.0^m	+49° 54′
C41	Melotte 25	Open Cluster	Hyades	Tau	0.5	5.5°	04^h 26.9^m	+15° 52′

Table data are from Stephen O'Meara's book cited in the text. 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.

OPEN CLUSTERS Open star clusters, the final class of deep-sky objects, are my seasonal favorites, perhaps because their glittering concentrations of bright stars remind me of holiday lights. The Caldwell Catalog doesn't disappoint. Start at the eastern end of the W in Cassiopeia, where C8 (NGC 559), C10 (NGC 663), and C13 (NGC 457) all sit within 5° of each other — easily framed together in most finder scopes and low-power binoculars. From there, follow the line from Gamma Cassiopeiae past Delta and onward about twice that distance to find C14, the famous Perseus Double Cluster (NGC 869 and 884). Now scan south-southeast nearly 20°, past Gamma Andromedae, to find C28 (NGC 752), which sprawls over more than 1° and contains stars that are two billion years old. Then go back to the Milky Way and follow it westward to Lacerta, the Lizard, to pick up C16 (NGC 7243), which is only about 1½° west-northwest of 4 Lacertae. Note that C16 sits in the middle of a shoal of stars that spreads across nearly 10°, from NGC 7296 in the northeast to NGC 7209 in the southwest. The last Caldwell object on this tour scarcely needs an introduction. The Hyades (C41), the closest open star cluster to Earth (other than the Ursa Major Moving Group), is one of the true highlights of autumn and winter skies. Explore this stellar wonderland with naked eyes, binoculars, and your favorite telescope — you'll find new things to enjoy at every magnification.

objects and as many Caldwells as possible in a single night. You can find his search sequence for 40°N at **https://is.gd/mescald**. Or why don't you create your own challenge, for your latitude and observing interests?

The Caldwell Catalog is a reminder that astronomical observation is a participatory pursuit. For those of us who enjoy exploring the deep sky, familiar objects always reward another visit while overlooked targets await our attention. Every clear night, the adventure begins anew.

■ Contributing Editor **MATT WEDEL** thanks Dennis di Cicco, Rick Fienberg, Tony Flanders, Stephen James O'Meara, Susan Rose, Stephen Saber, and Roger Sinnott for sharing their thoughts and memories.

FURTHER RESOURCES: NASA's own Caldwell Catalog is a collection of photos of more than 50 Caldwell objects taken by the Hubble Space Telescope; see **https://is.gd/hubble_caldwell**. The link to the Astronomical League's Caldwell Challenge is at **https://is.gd/al_caldwell**.

Specks Betwee

When thinking about cosmic wonders, we often sweep interstellar dust under the rug. But these humble particles play a huge role in the universe.

At the mere mention of dust in space, Karl Gordon's face lights up. "I love talking about interstellar dust," he says.

Interstellar dust, a cornucopia of microscopic flecks of solid debris, doesn't usually grab headlines. It's not as flashy as a supernova nor as exotic as an alien planet. It doesn't blaze like a star, nor does it bend the imagination like a supermassive black hole.

But for Gordon (Space Telescope Science Institute) and many other astrophysicists, interstellar dust is a fascinating puzzle, a playground of physics that ties together the cosmos.

"When I started, people were like, 'Ohh, you're going to have to find something else — I mean, you can't make a career out of this,'" Gordon recalls. "It turns out, you can!"

Gordon spends much of his time measuring the light from stars, both in our galaxy and others, not in order to understand the stars themselves but to learn more about the stuff between them. To him, "the stars are like a nuisance parameter," astronomer Julianne Dalcanton (University of Washington) said of Gordon during her lecture at the January 2019 meeting of the American Astronomical Society. "It's pretty adorable."

Although dust usually lurks in the background, it's essential for understanding the universe. Despite making up just a tiny fraction of all matter in the cosmos, dust helps build stellar nurseries, ferries newly forged elements from one generation of stars to the next, and lays the seeds for newborn planets. It's also a tool. Astronomers use dust to map the magnetic architecture of our galaxy, pinpoint the locations of nearby star-forming regions, and unlock secrets about the peak of cosmic star formation 10 billion years ago.

Even astronomers who aren't drawn to dust's vibrant life need to know something about its properties. Nearly every sightline to any celestial object, within or beyond our galaxy, runs through dust that interferes with observations. There

AKIRA FUJII

▶ **THE GREAT RIFT** Dusty clouds in the Milky Way block starlight from reaching Earth, creating the illusion of regions of empty space along our galaxy's disk.

n the Stars

are few cosmic investigations that interstellar dust doesn't impact in at least one way.

"If you want to understand everything from the space between stars, the envelopes of stars, [to] the circumstellar disks that form planets around stars, you need to know what the dust is doing," says astronomer Sarah Sadavoy (Queen's University, Canada). "You need to know what it is. You need to know how it's changing. And by doing that, you'll be able to better understand the universe and everything that you're using to probe it."

The Milky Way's disk, by mass (baryonic)

91%	9%	0.09%
Stars	Gas	Dust

Fine Galactic Soot

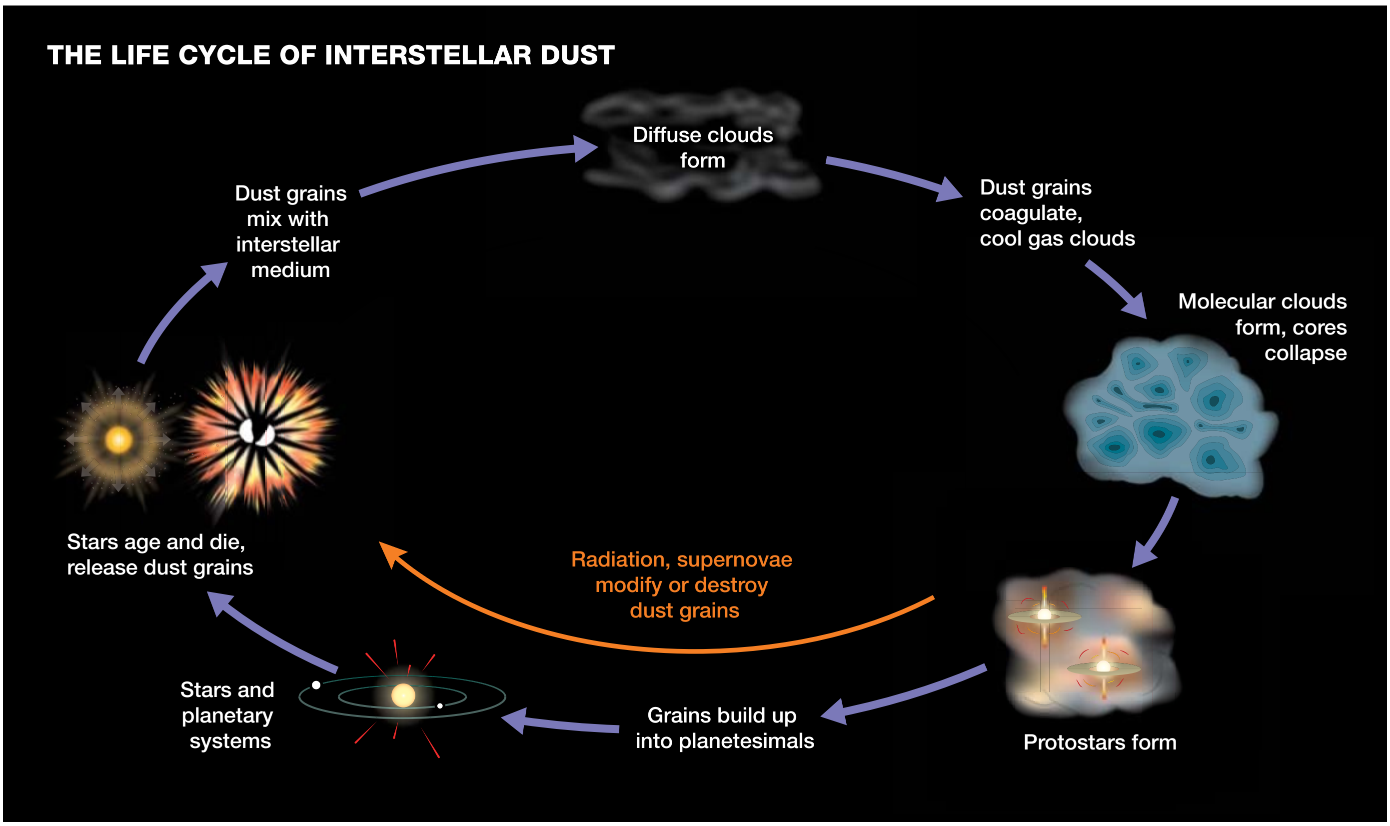
In early evenings, during late summer, the plane of the Milky Way arcs overhead, divided by a dark lane known as the Great Rift: a band made of clouds of solid particles in space that block distant starlight.

Long ago, people saw stories in those dark patches. To the Quechua people of Peru, these *dark cloud constellations* represented a menagerie of animals that recirculated Earth's water. The Milky Way was a great celestial river, and when it rose above the horizon, the animals ferried water into the sky and released it as rain.

Quechuan storytellers weren't far from the truth: The particles in those clouds do circulate elements through the cosmos and are even a breeding ground for molecules of water. Today, astronomers know the clouds are loaded with solid grains, which appear not only in the Great Rift but in many cosmic environments, including the exhaust from dying stars, the majestic wakes of supernovae, and nascent planetary systems.

Interstellar dust grains are microscopic, ranging roughly in size from several to a few hundred nanometers, giving them the consistency of fine soot. Some grains are made of silicates, minerals composed of mostly silicon and oxygen. Carbonaceous, or carbon-laden, dust comes in an assortment of types, ranging from organic macromolecules to nuggets of graphite or diamond. Some dust grains are also coated with a veneer of frozen water and other types of ice.

Astronomers learned this largely by observing how clouds of dust filter starlight. The size, composition, and shape of dust particles affect how they absorb and scatter particular wavelengths of light. Dust also offers up some secrets via thermal emission of infrared light or, for the coldest dust just 30 or so degrees above absolute zero, emission at submillime-



DUST TEXTURE: SERGIO34 / SHUTTERSTOCK.COM; DUST LIFE CYCLE: GREGG DINDERMAN / S&T

ter and millimeter wavelengths, a part of the electromagnetic spectrum only detectable with equipment akin to radio dishes (*S&T:* Aug. 2020, p. 12).

"Our only way of understanding what interstellar dust is will be through making inferences from what we see and asking ourselves, what kind of physical stuff can make the world look the way it does," says dust researcher Bruce Draine (Princeton).

Interstellar dust clouds didn't get a modern astronomical treatment until the early 1900s. Astronomer E. E. Barnard, along with his contemporary Max Wolf, spent the first decades of the 20th century photographing some of these dark regions and concluded that something in space was blocking the light from more distant stars.

"I did not at first believe in these dark obscuring masses," he wrote in the January 1919 *Astrophysical Journal*. "[My] own photographs convinced me . . . that many of these markings were not simply due to an actual want of stars, but were really obscuring bodies nearer to us than the distant stars."

About a decade later, astronomer Robert Trumpler took a stab at dissecting these obscuring bodies. "Most likely the absorbing medium is made up of particles of various sizes, ranging from free electrons and atoms, small solid dust particles, up to larger meteoritic bodies," he wrote in the October 1930 *Publications of the Astronomical Society of the Pacific*.

Trumpler came to that conclusion after noting that stars in distant clusters were dimmer than expected for their distance and appeared redder than nearby stars of the same spectral type. He attributed this to fine particles permeating the galaxy that, much like Earth's atmosphere, preferentially scatter blue light and let red light pass. This reddening effect is a cornerstone of dust research to this day.

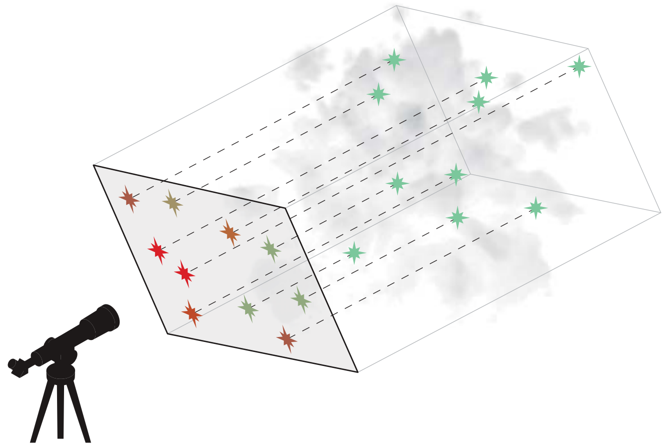
While astronomers quibble over the details, most agree that interstellar dust comes from dying stars, which spend their lives forging progressively heavier elements in their cores. At the end of their lives, stars release those elements into space via stellar winds (in the case of most stars) or powerful supernova explosions (for the stellar heavyweights). Regardless of how these atoms get into space, once there, and far enough from a star's radiation, they find each other and start to link up, forming ever larger conglomerates.

Dust contributes little to the overall mass of a galaxy. By mass, the Milky Way is composed mostly of stars and dark matter, plus a relatively small amount of gas. The total mass of the dust is just one percent that of the gas. And yet it plays an outsized role in the formation of stars and planets.

"Without dust, it would be a very different galaxy and universe," Gordon says.

Stars form in dense pockets of gas, which gravitationally attract even more gas, building up to a critical mass, at which point the gas collapses and, eventually, ignites nuclear fusion. But to get under way, this birthing process needs a cloud of mostly hydrogen molecules, and it needs that cloud to be cold. If the gas is hot, the molecules whiz around too much for gravity to take hold.

Dust takes care of both requirements. It provides a surface upon which a hydrogen atom can alight, pair up with another hydrogen atom, and then pop off as a full-fledged molecule. (That surface is also critical for interstellar chemistry: The terrain provides a place where, for example, hydrogen atoms can meet up with hydroxide ions to form water molecules.) Dust is also an efficient cooling agent. It shields molecular



▲ **INTERSTELLAR REDDENING** Dust suffusing the galaxy preferentially scatters short wavelengths, making distant stars appear redder than they actually are. The farther or dustier the distance, the redder the star looks.

▶ **BARNARD 68** One of the dark nebulae that E. E. Barnard cataloged, B68 is a Bok globule: a dark, dusty cloud that blocks starlight at visible and near-infrared wavelengths *(left)*. But when seen in longer infrared wavelengths (*right*), the cloud largely disappears and background stars shine through.

INTERSTELLAR REDDENING: GREGG DINDERMAN / S&T; DARK NEBULA: ESO (2) gas by absorbing high-energy ultraviolet light from stars and reradiating it as lower-energy infrared light.

For some astronomers, the inner life of dust is more than enough to keep them busy. But for others, dust is a means to an end — or sometimes even a decoy.

The Dirty Windshield of the Milky Way

In 2014, a group of cosmologists made a rather public blunder.

With much fanfare, the team of a project known as BICEP (Background Imaging of Cosmic Extragalactic Polarization) announced that they had found an elusive signal from the dawn of time. Imprinted on the cosmic microwave background, a remnant glow from a time when the entire universe was roughly 3000° Celsius (5000°F), this signal looked like one that theorists expected to have been made by the echoes of gravitational waves released during the epoch of inflation, a passing moment when the universe ballooned in size roughly a trillionth of a trillionth of a trillionth of a second after the Big Bang.

Early the following year, they issued a mea culpa: The signal was actually from interstellar dust in the Milky Way (*S&T:* May 2015, p. 12).

The BICEP flop was a cautionary tale on many fronts. But one takeaway is that if astronomers want to understand the cosmos, they need to understand the dust they're peering through to see it.

"One of the grad students I worked with in the past said, you have to look through the dirty windshield of the Milky Way to see anything," says Gordon.

Sadavoy echoes that sentiment. "Depending on what science you're interested in, you need to know the dust in order to disentangle it from your actual observations," she says.

But dust can also be a powerful tool for revealing things that might otherwise remain unseen. Take the BICEP saga: Dust grains filtered background light in a way that mimicked the sought-after signal because of how the grains aligned themselves to the magnetic field of the Milky Way. That means astronomers can use the grains to trace out our galaxy's magnetic structure.

In 1949, astronomers John Hall and Alfred Mikesell (U.S. Naval Observatory) discovered that some starlight was polarized: The lateral oscillation of the light waves had a preferred direction. What's more, they saw a connection between the degree of polarization and the amount of reddening. Raw starlight is not polarized, but dust was filtering it in such a way that preferentially allowed light waves of a particular orientation to pass.

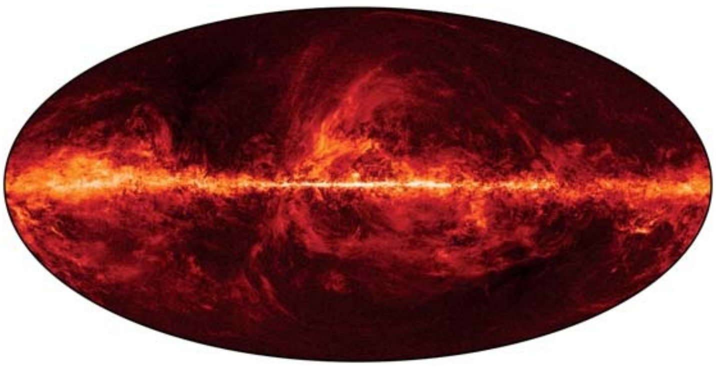
Since then, astronomers have recorded polarized light from all directions in the sky, which in turn provides sweeping vistas of our galaxy's magnetic field. Other galaxies have benefited from a similar treatment. In January, astronomer Enrique Lopez-Rodriguez (NASA Ames Research Center) and colleagues observed the polarized glow emitted by warm dust in the nearby galaxy NGC 1068 and found that the galaxy's magnetic field closely follows its spiral arms.

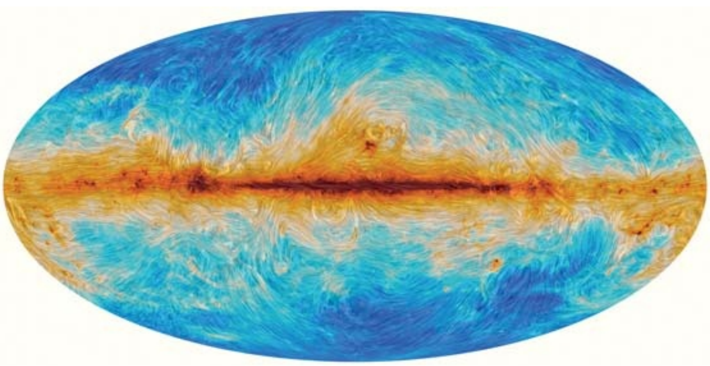
Astronomers are also using dust to discover large-scale structures in our galactic backyard. In January, João Alves (University of Vienna, Austria) and colleagues reported that many nearby star-forming regions are linked together in a coherent gaseous thread they dubbed the Radcliffe Wave, which bobs in and out of the plane of our galaxy (*S&T:* May 2020, p. 9).

Interstellar dust was the key to finding this structure. The team identified hundreds of stars in front of, within, and behind dust clouds that permeate these stellar nurseries. They then combined measurements of how much dust dims and reddens the starlight with new precision distances to those stars from the Gaia satellite to trace the 3D structure of the dust. Astronomers have started using the same idea to revise the distances to spiral arms in the Milky Way.

This 3D dust mapping is a relatively new tool, says Sadavoy. Historically, the distance to dust has been difficult to pinpoint, because background starlight reveals all the dust along a line of sight. "This 3D dust modeling tries to remove that challenge by taking into account the fact that you're not just measuring the extinction of stars, but you're measuring extinction of stars as a function of distance," she says. "That's the new element that we didn't really have before."

But using dust as a tool isn't just limited to the Milky Way and its neighbors. Dust is also revealing secrets about the peak of cosmic star formation, which occurred roughly 10 billion years ago.





▲ **MAGNETIC TRACER** Astronomers have used the emission from polarized dust grains *(top)* seen with the European Planck spacecraft to map the Milky Way's magnetic field *(bottom)*.

ESA / THE PLANCK COLLABORATION (2)

Dusty Star-Forming Factories

According to astronomer Caitlin Casey (University of Texas, Austin), the history of the universe as told through starlight is biased and inaccurate. The light from cold dust in distant galaxies, however, has revealed a major hidden character in this drama.

About 3 billion to 4 billion years after the Big Bang, the universe was populated with galaxies enshrouded in so much dust that no starlight escaped. Instead, the galaxies blazed with dustlight, the thermal glow of interstellar dust heated by massive crops of bright young stars.

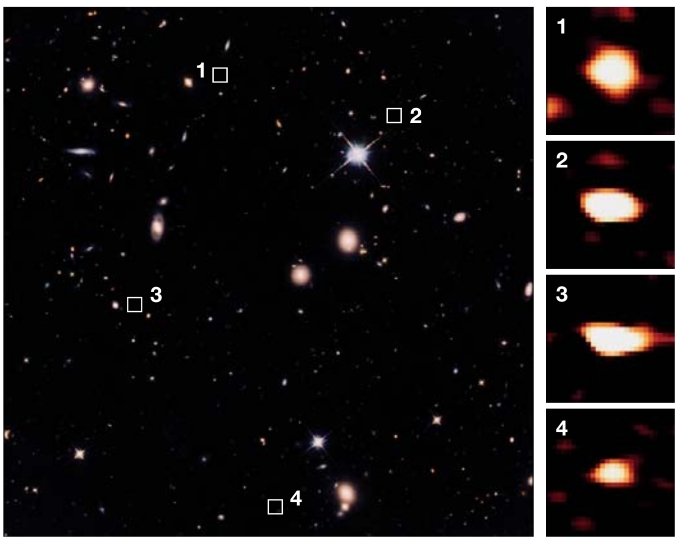
The dust goes hand-in-hand with the star formation, says Casey. Lots of new stars leads to lots of dust production as the most massive stars quickly age and die off.

With no starlight to guide them, astronomers can only find and study these early galaxies with telescopes sensitive to millimeter-wavelength light, which is emitted from brutally cold gas and dust. At these wavelengths, the galaxies glow brightly, whereas in images taken with visible light, they are nowhere to be seen.

Dustlight has revealed that these obscured galaxies dominated star formation at a time when the universe, on average, produced stars at a rate 10 times greater than it does today. Whereas the Milky Way churns out a few new stars per annum, Casey says, these stellar factories produced roughly 5,000 stars every year. And they have few modern parallels. While there are a handful of comparable galaxies in the modern universe, "they were a thousand-fold more common 10 billion years ago," Casey says.

It's not yet clear why these galaxies were so prolific. One potential culprit is galaxy collisions, says Casey, but it's uncertain how widespread such mergers were 10 billion years

Hubble **ALMA**



▲ **HIDDEN GALAXIES** Sections of sky that appear empty to the Hubble Space Telescope contain massive, star-forming galaxies when viewed in the submillimeter range with the Atacama Large Millimeter/submillimeter Array in Chile.

HIDDEN GALAXIES: UNIVERSITY OF TOKYO / CEA / NAOJ; DUST TEXTURE: SERGIO34 / SHUTTERSTOCK.COM

80%

Fraction of starlight in the Milky Way that is absorbed and reradiated by dust

ago. It's also possible that galaxies back in the day simply had more gas to fuel star formation than their modern counterparts. This mystery is driving Casey and colleagues to peer farther out into space — and hence further back in time — to pinpoint when these galaxies and their dust first came on the cosmic scene.

"We don't know if these are still very common in the universe's first billion years," she says. She envisions that, eventually, "we'll start to see galaxies that have very high star formation rates but that are not yet polluted by dust." Such galaxies would have existed in a brief window of time after the first generation of stars switched on but before enough of them (or the second wave that followed) dirtied up those pristine infant galaxies.

Pinpointing the onset of cosmic dust could thus provide a window into the fleeting yet foundational epoch of the first stars. The first stars had to have formed without any help from dust. With no dust to cool the primordial gas, the first stars were likely bloated monstrosities hundreds of times more massive than the Sun.

But getting that galaxy census will require instruments that can survey large swaths of the sky at once, something that current millimeter-wavelength facilities aren't good at doing. A new camera under development for the Large Millimeter Telescope in Mexico, she says, will be a boon to this kind of work and enable astronomers to continue a century of investigations that have shown dust to be crucial in moving elements around the cosmos and helping stars form.

Only dust could have revealed this hidden chapter in the story of cosmic evolution. It's a lesson that astronomers continue to be reminded of, from the far reaches of the visible universe to familiar stellar nurseries sitting right next door: Interstellar dust is everywhere, and to ignore it is to risk missing a vital element of where we come from.

■ **CHRISTOPHER CROCKETT** is a freelance science journalist living in Arlington, Virginia. Formerly an astronomer, he found research to be too tedious and now writes about it instead.

Follow the Carbon

When talking about habitability, we often talk about water. But there's another ingredient that's crucial to the recipe for life.

Looking around at our planet, we observe the signs of life everywhere. Life is found buried deep inside rocks, at the highest elevations, at the bottom of the ocean near vents that heat water to several hundred degrees, and in Antarctica, one of the driest places on Earth. This is a living planet.

But what were the conditions at Earth's planetary birth that set our world towards this destiny of life? We can characterize the conditions in various ways — a solid surface, a temperate climate — but one of the central requirements is a chemical one: A planet has to have the chemical materials that life needs readily available on the surface.

Our planet itself is mostly composed of silicate rocks, dominated by the elements silicon, oxygen, magnesium,

and iron — think of glass or sand, or just pebbles on the ground. But *life* is composed mostly of carbon, oxygen, hydrogen, and nitrogen. These four elements constitute some 97% of the mass of living beings. Other, less abundant elements are important in distinct ways — for example, phosphorous plays an important role in DNA, the molecule that holds life's genetic code. However, the chemistry of life is dominated by carbon, assisted by nitrogen, and facilitated by the liquid medium of water (hydrogen and oxygen). These elements therefore have to be present on the planetary surface.

We are, seemingly, a water- and carbon-rich world. But that's an illusion. Water makes up only about 0.1% of Earth's mass, even if we make a generous assumption about how much water lies buried in the planet's deep mantle. And based on the Sun's composition and the mass of material that must have been present to make Earth, we know that when Earth formed, it received less than 1% of the carbon available. Even this tiny amount is based on optimistic calculations. For nitrogen, the accounting is even less. We are a silicate rock sitting in space with a tiny sprinkling of carbon, nitrogen, and water.

But — life is here! How did this happen? Is this common? To begin to answer these questions, let's look deep into our planet's history and explore what carbon tells us must have happened to Earth to transform it from an insanely large number (10^{41}!) of tiny particles floating in space to a world that supports the chemistry of life.

BLUE BALL This image taken in 2014 from the International Space Station makes Earth look like a water world. But the elements that life depends on account for only a tiny fraction of Earth's makeup.

ALEX GERST / NASA

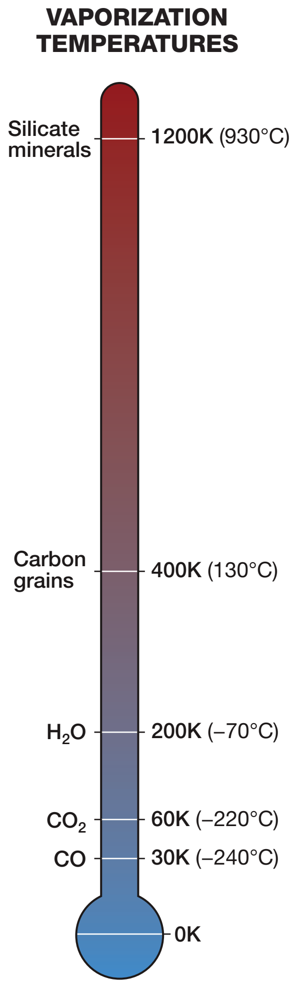
Volatile Chemistry

Carbon atoms — as well as many other elements — are created in the bellies of stars as products of nuclear fusion and thrown into space during the end stages of stellar evolution and death (*S&T:* June 2020, p. 58). Aging and dying stars also create stardust, the tiny particulate matter that provides the seeds of terrestrial worlds. We've observed carbon carried by grains, ice, and gas in space, and the form it takes affects how it's incorporated into forming planets.

This brings up a central aspect of the chemistry of space: *volatility*. Volatility is a general term describing how likely it is that a given molecular compound will transition to the vapor phase. Pressure and temperature determine when this transition happens. But in space, the pressures are less than a quadrillionth (that is 15 orders of magnitude) less than the air we breathe! And the temperature in a star-forming cloud is 20K to 30K above absolute zero, or about −250°C (−410°F) to me and you. Because of these extreme conditions, there is no liquid phase in space chemistry: Compounds transfer directly from solid rock or ice to the vapor phase.

Stardust, whether silicate or carbonaceous, is *refractory*, meaning it's hard to vaporize. Other common molecules, such as water and carbon monoxide (CO), are referred to as *volatiles*, as these species prefer to be in the gas phase and are harder to incorporate into rocks and ices.

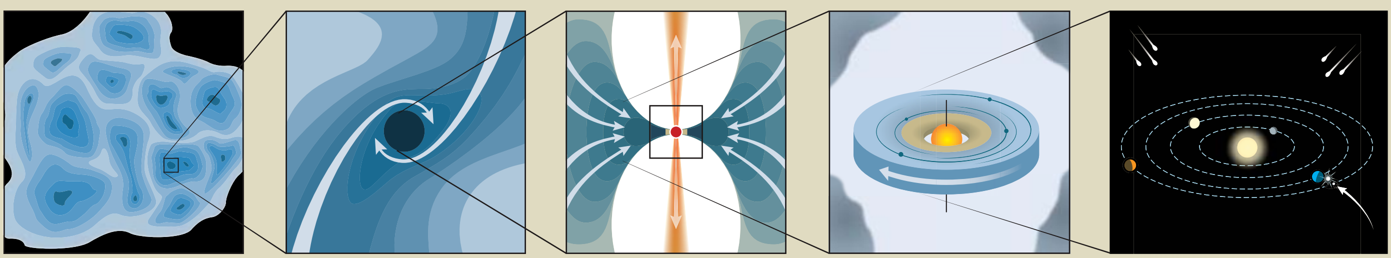
Thanks to instruments such as the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile, astronomers can detect a wide range of compounds in regions in our galaxy where stars and planets are being born today (*S&T:* May 2020, p. 34). We can also observe objects at different stages in the formation process. By doing so, we can pull together the distinct stages of planet growth and complete our story of what happens to carbon throughout a planet's creation.



Such studies essentially "tune in" to the frequencies of specific molecules around forming stars and planets, the same way you might tune the radio in your car to a local radio station. When a star is first forming, it heats gases and solids in close proximity to a couple hundred kelvin, depending on how dense the material is. Within this hot gas, molecules are moving around randomly, but they are also spinning or rotating. Molecules that are spinning faster "want" to spin slower, and they can spontaneously slow down their rotation by emitting a photon. This photon appears at microwave wavelengths and can be detected by telescopes such as ALMA.

From a spectrum of the gas around a young star, we can add up the carbon and determine what molecular form it's in. We find that just before the main phase of planet formation, carbon dominates the chemistry of space: The majority of detected molecules have carbon as a central element. This is likely not an accident, as the carbon atom has the highest number of available bonds of the cosmi-

HOW THE SOLAR SYSTEM FORMED



Molecular cloud — Stars are born in clouds of dust and molecular gas.

Dense core — Dense regions of the cloud collapse under the weight of their own gravity, rotating as they do so.

Protostar: 0-1 million years — Inside the core, a star forms surrounded by a disk, fed by material from the core as collapse continues. To conserve angular momentum, the protostar ejects material as outflows from its poles.

Protoplanetary disk: 1-10 million years — Radiation and outflowing material remove the planetary system's natal envelope and cut the link with the cloud. This is when planetary building blocks form — bodies the size of asteroids or even Mars.

Final assembly of terrestrial worlds: 10-50 million years — The disk dissipates and collisions continue, completing planet formation.

THERMOMETER: GREGG DINDERMAN / *S&T*; HOW THE SOLAR SYSTEM FORMED: GREGG DINDERMAN / *S&T*, SOURCE: K. PEEK cally abundant elements. Silicon has the same number of bonds, but in space all silicon is locked in rocks, unavailable to react with other elements and build up compounds. That is not the case for carbon: About 50% of the carbon is in the form of volatile compounds such as CO, CO_2, and a host of small organic ices. The remaining carbon is found in macromolecular forms of carbon locked in refractory stardust. This preponderance of available carbon may explain why we are carbon-based lifeforms.

Ice Marks the Spot

The next step in the story of carbon focuses on the formation of terrestrial worlds such as our own, a planet made from solids. Planets are born inside disks of gas and stardust, and the tiny dust particles of silicate and carbonaceous compounds that stick together to build these worlds are coated with layers of ice — not just water ice but also CO, CO_2, and CH_4 and other organic ices.

Which ices are present depends on how far the grains are from the forming star. Different carbon compounds have different levels of volatility. This means that particles that coagulate at successively greater distances from the Sun will have different amounts of carbon present and in different forms.

For example, out at Neptune's current distance from the Sun, where the planet-forming disk would have been a chilly 20K, bodies essentially wouldn't have lost any carbon to vaporization: They would contain both rocks and ices with the same fraction of carbon that is seen in the Sun. Cryovolcanism or other geologic processes can change the molecules carrying carbon over billions of years in large bodies such as Pluto, but in smaller bodies, such as comets, we think the molecules maintain their original form.

Slightly nearer the Sun, around Uranus's orbit, temperatures in the disk would have risen above 20K, and CO ice would have evaporated into the surrounding gas. Solids that formed at this point would have incorporated about 70% of the available carbon. Indeed, astronomers observe some comets that are CO-poor but rich in CO_2 and other compounds.

Within Jupiter's orbit at 5 astronomical units, we are inside the CO_2 and CH_4 snowlines, the minimum distances from the Sun where these compounds will exist as ice. These ices would sublimate into the gas, meaning any carbon taken up by growing rocky-icy bodies in this region would only appear in simple organic molecules or carbon rocks. Carbon-bearing ices aren't the only ices in the disk, however; these rocks would still have substantial amounts of water ice, as well as silicates.

At 1 a.u., we find an even warmer situation. There, the disk is 200K, and the only carbon available to form Earth is from the refractory (rocky) forms of carbon — no organic molecules — combined with the silicate rocks. There would

Organic

An *organic molecule* is one that contains at least one hydrogen atom bonded to a carbon atom. They're called organic because they're associated with living organisms.

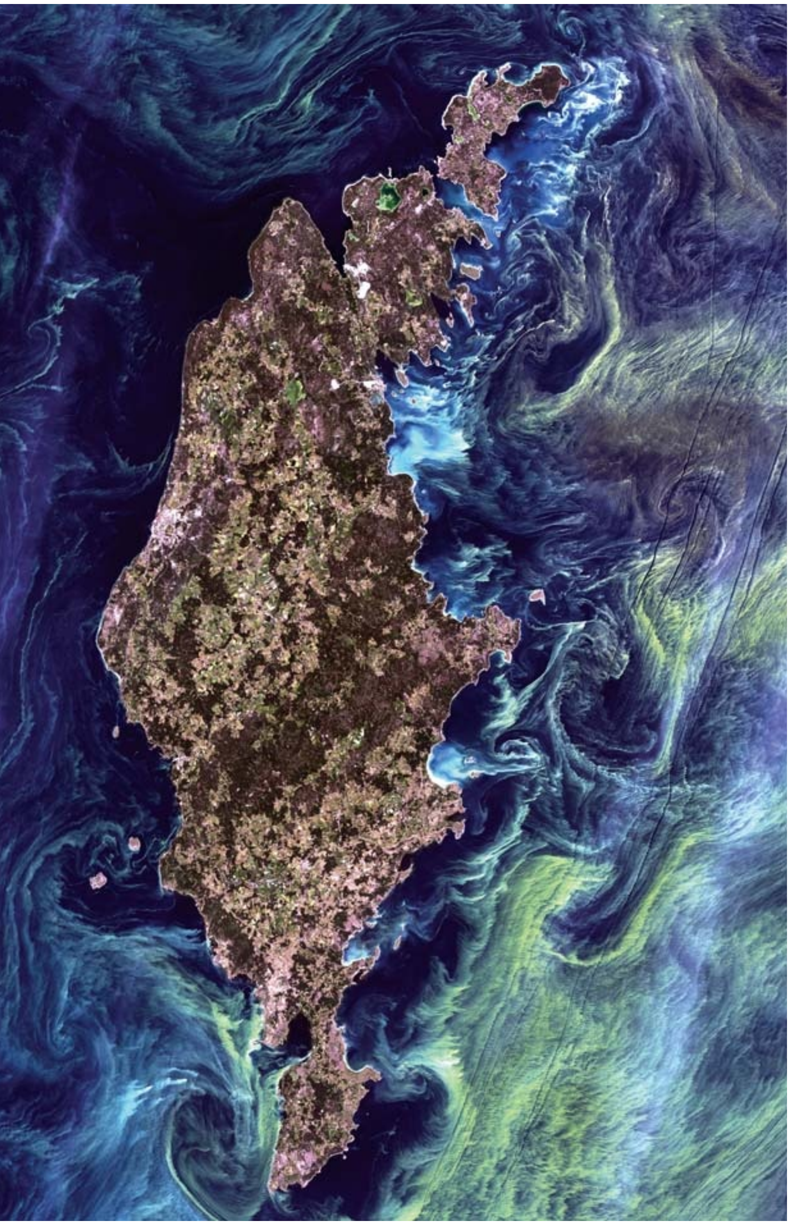
▶ **SHARPLESS 2-106** A young star blows out hot gas (blue) as it forms. A ring of dusty gas shapes the outflows into an hourglass. Ridges in the hot gas arise from interactions with the cooler surrounding medium.

have been no ices, not even water. As tiny particles here built up into pebbles and then larger, kilometer-size rocks and, ultimately, into entire worlds, the planets made would have been dry, rocky bodies.

Congratulations: We have just proved that Earth is made of rocks.

This seems trite, but we didn't do it from any assumptions based on what we see around us. Instead, we combined basic chemical principles with knowledge astronomers have gleaned about the conditions that exist in regions of incipient planets, all rooted in observations of the solid and gaseous chemical species in faraway planet-forming places.

▼ **LIFE AFLOAT** A phytoplankton bloom (green) swirls in the dark waters around the Swedish island Gotland, in the Baltic Sea. Plankton is one of countless lifeforms that incorporate carbon and depend on water.



USGS / NASA / LANDSAT 7

Losing Carbon

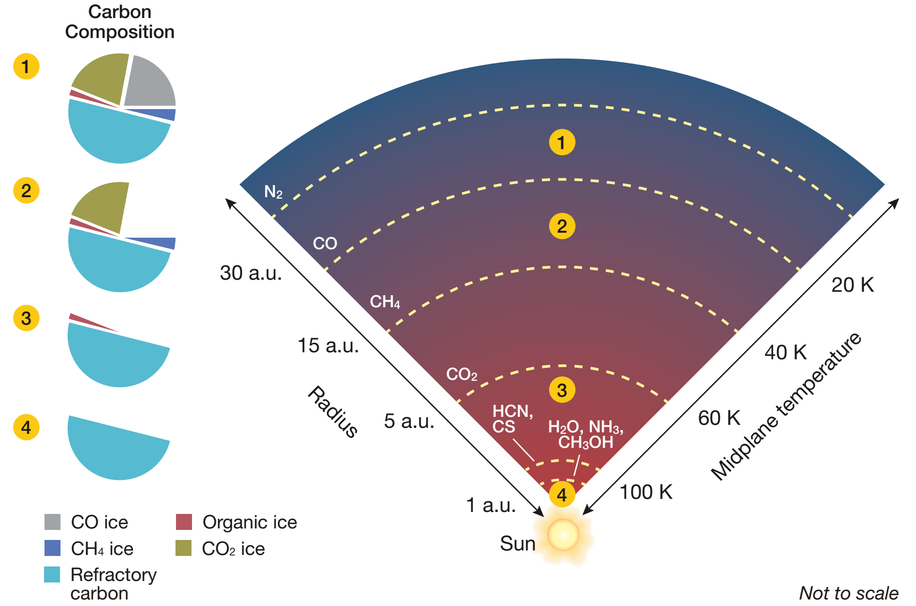
However, this method also leaves us with a problem: We have way too much carbon. Based on our chemical accounting, carbon should survive in the inner regions of the protoplanetary disk fairly well, and the relative amounts of elemental carbon to silicon in our planet's rocks should be a factor of 4. Instead, Earth's ratio of carbon to silicon is less than 0.001 — that is a factor of 4,000 off. We should be sitting on a carbon-dominated rock, not a silicate Earth with a tiny amount of carbon. What went wrong?

We think that at 1 a.u. in the disk, temperatures weren't hot enough to destroy carbon pebbles prior to their assembly into larger bodies. So all the carbon found in refractory or rocky form in space would make its way into forming terrestrial worlds. Yet based on Earth, this cannot be the case. Was there a time during the evolution of the solar system that the temperature was high enough to destroy most of these carbon rocks and not the silicate ones? If such a phase existed, then the main building blocks that combined to make Earth must have begun assembling during that time.

The temperature range we need is between 425K and 1200K. Based on observations of nascent planetary systems, we know that about 1 million years after the birth of the Sun, the disk at 1 a.u. would have been colder than that. So we are forced to look earlier, during the first 1 million years of evolution. During this stage, pebbles are actively forming from interstellar stardust in the disk. However, the Sun is still being assembled as it continues to accrete material from the cloud of molecular gas that served as its nursery. During this protostar phase, the Sun is more luminous than when the natal envelope later disappears, and the temperature of the surrounding material is warmer. If the main building blocks of Earth formed this early, within the first million years, then we have solved our problem: We can make a silicate Earth with essentially zero carbon.

However, this solution leaves us with yet more problems: We need *some* carbon, not zero, and we need the amount not to change drastically over time. The process of sublimation is sort of a one-way street — it irreversibly puts all the carbon into gaseous form. We need to keep some of it in rock form. And in the protoplanetary disk, pebble-size particles are not just sitting in place waiting to form a new planet: Differential forces cause them to drift inwards towards the highest pressure point in the disk. The point of highest pressure is the inner edge of the disk, right next to the star (inside today's orbit of Mercury). So even if we made carbon-poor rocks in the first million years, pebble drift would provide a continuous supply of carbon- and silicate-rich rocks from the outer solar system to the forming pre-Earth, upsetting the balance later.

We have to either stop or slow this supply within 1 million years, when the disk is still hot. How can that be done? The easiest way is to add a second pressure maximum in the disk — something with a big effect that will reverse the pressure gradient at a distance from the young Sun that is beyond Earth's orbit, such that drifting pebbles will just pile-up at



▶ **HOW TEMPERATURE AFFECTS COMPOSITION** In the first few million years of the solar system, gases and ice-coated pebbles combine to create a disk around the Sun, inside which planets begin forming. The disk grows hotter with decreasing distance from the star. Because different carbon-bearing compounds vaporize at different temperatures, some will be solid, others gas, at any given location. The pie charts indicate the composition of solid bodies that would form at each numbered location.

that distant location and never migrate into the inner solar system.

As it happens, Jupiter fits the bill. Indeed, scientists who study meteorites have found discrete differences in meteoritic composition that, based on radioisotopes, date back to around 1 million years after the formation of our star system. Astronomers and cosmochemists think the meteorites bear the imprint of Jupiter's creation and the subsequent chemical separation of the outer and inner solar system caused by its presence.

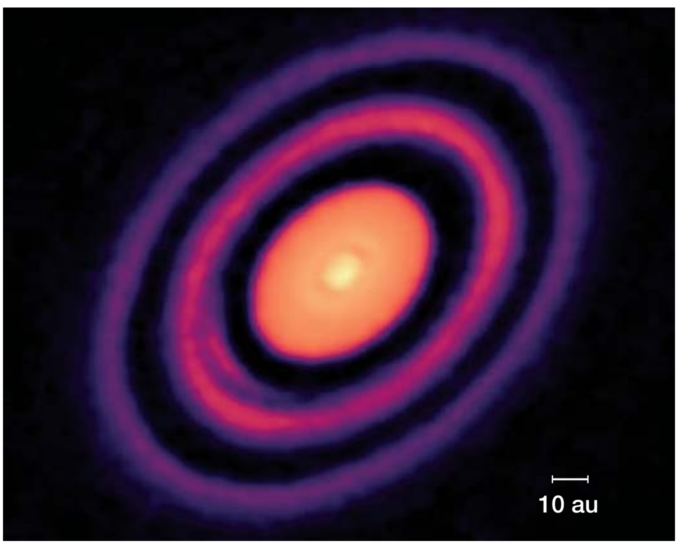
Amazingly, we can see this process happening in other systems. Emission from the millimeter-size pebbles in disks surrounding young Sun-like stars reveals that there's more material closer to the star than at greater distances, and that it's also warmer closer in. We also see dark gaps in the disks where these pebbles are absent, edged by bright rings. We think that these gaps exist because hidden young gas giants carve the gaps, creating bright regions of high pressure at the gap edges where pebbles pile up.

The Chemistry of Other Worlds

These insights allow us to complete our story of Earth's early formation and its initial supply of formative materials: Our planet's carbon was implanted in building blocks less 1 million years after the Sun's birth, and infant Jupiter kept the inner solar system's composition carbon-poor.

What is left to come in Earth's formation? Interactions between Jupiter and the large bodies in the asteroid belt will lead some of these kilometer-size rocks to crash-land on our planet — supplying additional carbon. This will set the stage for the formation of our planet as we know it — a silicate rock sitting in space with a tiny sprinkling of carbon. This sprin-

▼ **CORRALED PEBBLES** *Left:* This ALMA image of emission from millimeter-size pebbles in the disk around HD 163296 reveals multiple dark gaps where pebbles are absent. Yellower colors indicate higher emission. *Right:* An artist's illustration of planets forming in the HD 163296 disk gaps — astronomers' preferred explanation for why such gaps exist.



TEMPERATURE AND COMPOSITION: GREGG DINDERMAN / *S&T*, SOURCE: I. CLEEVES AND E. BERGIN; GAPS: ALMA: ALMA (ESO / NAOJ / NRAO), S. ANDREWS ET AL., N. LIRA; ILLUSTRATION: B. SAXTON / NRAO / AUI / NSF kling, accompanied by some water, was enough to transform the abiotic chemistry of interstellar space into the chemistry with memory that we call life.

Is this story unique? We don't know! We do know that planetary systems with a Jupiter-like planet at a Jupiter-like distance from its star are rare — encompassing about 10% of the known exoplanet systems. Our story would naively suggest that these 10% of systems have a different history and a different carbon story than the majority.

Our story would naively suggest that these 10% of systems have a different history and a different carbon story than the majority.

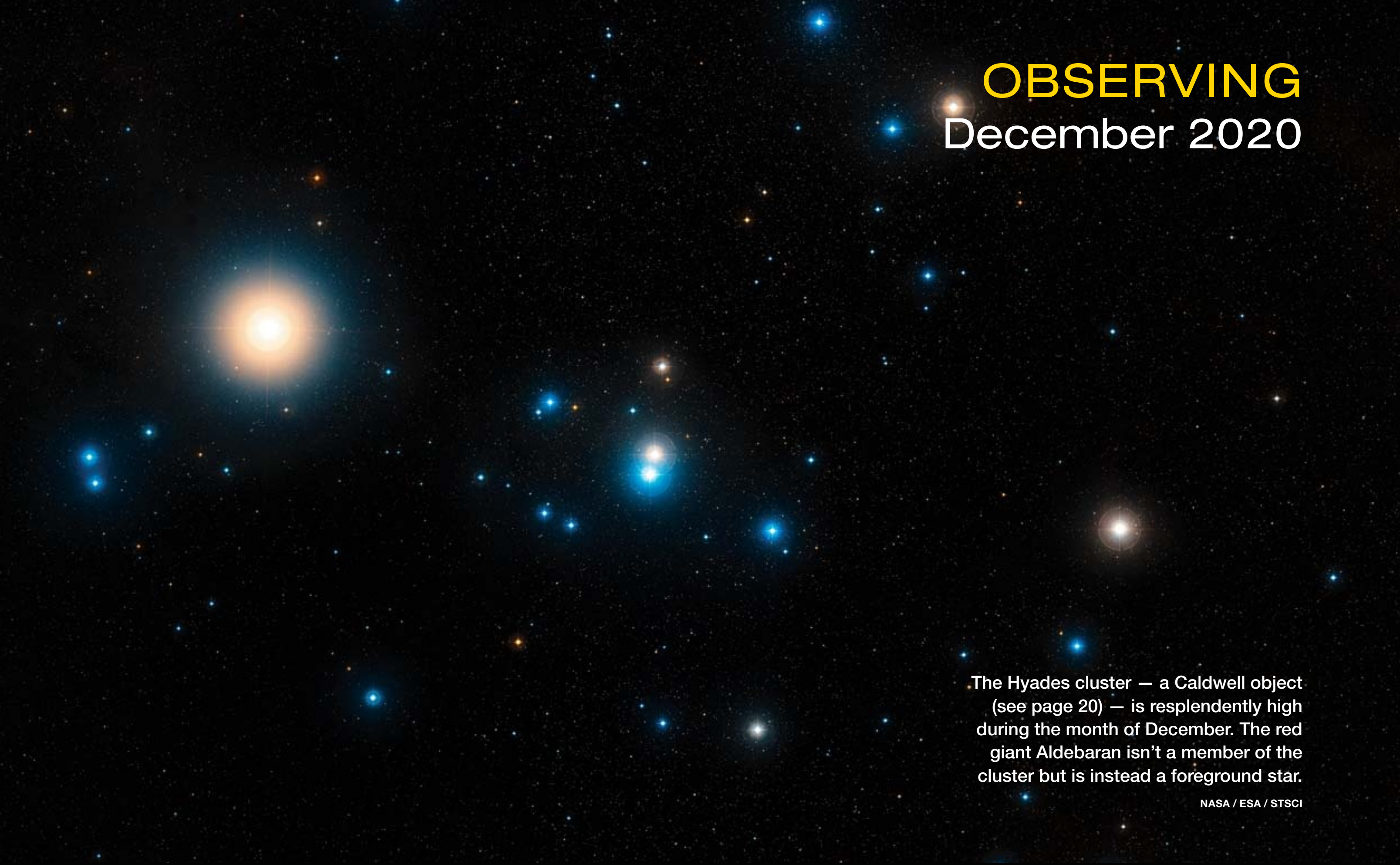
But confirming this theory will be immensely difficult. A large fraction of our planet's carbon is buried in rocks deep down, as part of a cycle powered by plate tectonics and volcanoes. Such deep carbon would be unobservable to astronomers. However, Venus has substantial carbon in its atmosphere, so much so that its surface temperature is above the boiling point for water. Since Earth and Venus were likely supplied similar amounts of carbon, perhaps this distinction is because of the lack of plate tectonics on Venus. If we can find worlds like Venus and Earth, we may be able to use them to find out if the carbon in their planetary systems followed the same journey as it did in the solar system. Clearly, understanding the carbon story of planet formation needs many more data points!

Over the next decades, we will embark on our journey of discovery in earnest by finding more and more Earth (and Venus) analogs. We will use new and sensitive telescopes to characterize their atmospheric composition to search for signposts of life such as methane and molecular oxygen, which were and are placed into our atmosphere by life. Alongside this amazing search for life, we will continue to characterize young star and planetary systems as they form — and ultimately witness, by proxy, the assembly of worlds such as our own.

■ **EDWIN "TED" BERGIN** is a professor of astronomy at the University of Michigan. In 2019 he received the Dannie Heinemann Prize in Astrophysics from the AAS and the American Institute of Physics.

EARTH TRANSIT Seen from the International Space Station, the Sun peeks through the thin line of Earth's atmosphere. Astronomers use similar alignments with exoplanets and their host stars to probe the planets' atmospheric compositions.

GRAINY TEXTURE: IRINA QIWI / SHUTTERSTOCK.COM; EARTH TRANSIT: ALEX GERST / NASA



OBSERVING
December 2020

The Hyades cluster — a Caldwell object (see page 20) — is resplendently high during the month of December. The red giant Aldebaran isn't a member of the cluster but is instead a foreground star.
NASA / ESA / STSCI

2 EVENING: Algol shines at minimum brightness for roughly two hours centered at 10:54 p.m. PST. See page 50 for a table of Algol minima.

3 EVENING: Look toward the eastern horizon to see the waning gibbous Moon hanging some 4° lower right of Pollux.

5 EVENING: Algol shines at minimum brightness for roughly two hours centered at 10:43 p.m. EST.

10 MORNING: A slender waning lunar crescent and Spica rise together in the east-southeast, with less than 7° separating the pair.

12 DAWN: An even thinner lunar crescent pairs up with Venus. The Moon occults the planet for viewers in western North America, Alaska, and Hawai'i, while those elsewhere will nevertheless enjoy the delightful sight of the two celestial bodies separated by mere degrees (see page 50).

13 NIGHT: The Geminid meteor shower is expected to peak in the evening — there will be no interference from the Moon, so take advantage of the long dark night to enjoy this event (see page 14).

14 NEW MOON (11:17 AM EST) A total solar eclipse will be visible along a narrow path that crosses Chile and Argentina. Much of South America will see partial phases (see page 48).

16 DUSK: Low above the southwestern horizon a two-day-old lunar crescent hangs 5° below the very close pairing of Jupiter and Saturn. Catch this delightful sight before the Moon sets.

21 THE LONGEST NIGHT OF THE YEAR in the Northern Hemisphere. Winter begins at the solstice at 5:02 a.m. EST (12:02 a.m. PST).

21 DUSK: Jupiter and Saturn are in a very rare, remarkably close conjunction, around 6′ apart. Take in this sight before the duo sets in the southwest.

23 EVENING: The waxing gibbous Moon and Mars are in Pisces, some 5½° separating the pair.

25 EVENING: Algol shines at minimum brightness for roughly two hours centered at 9:27 p.m. PST.

26 EVENING: A fatter Moon is about halfway between the Hyades and the Pleiades.

28 EVENING: Algol shines at minimum brightness for roughly two hours centered at 9:16 p.m. EST.

30 EVENING: The waning gibbous Moon has come full circle from the start of the month and is back in Gemini, about 4° right or lower right of Pollux.
— DIANA HANNIKAINEN

DECEMBER 2020 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		

LAST QUARTER
December 8
00:37 UT

NEW MOON
December 14
16:17 UT

FIRST QUARTER
December 21
23:41 UT

FULL MOON
December 30
03:28 UT

DISTANCES

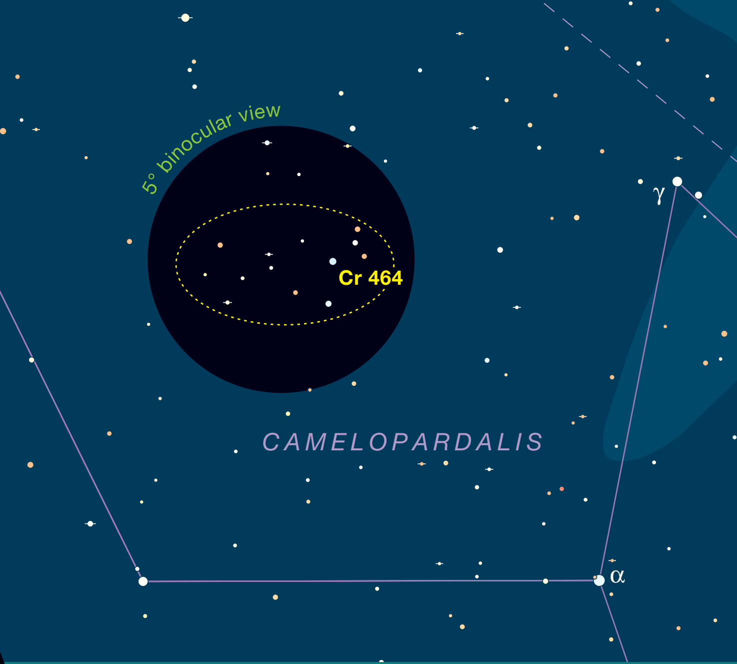
Perigee	December 12, 21^h UT
361,773 km	Diameter 33′ 02″
Apogee	December 24, 17^h UT
405,011 km	Diameter 29′ 30″

FAVORABLE LIBRATIONS

• Rydberg Crater	December 6
• Andersson Crater	December 8
• Vashakidze Crater	December 18
• Compton Crater	December 20

Planet location shown for mid-month

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



WHEN TO USE THE MAP

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

*Daylight-saving time

Binocular Highlight by Mathew Wedel

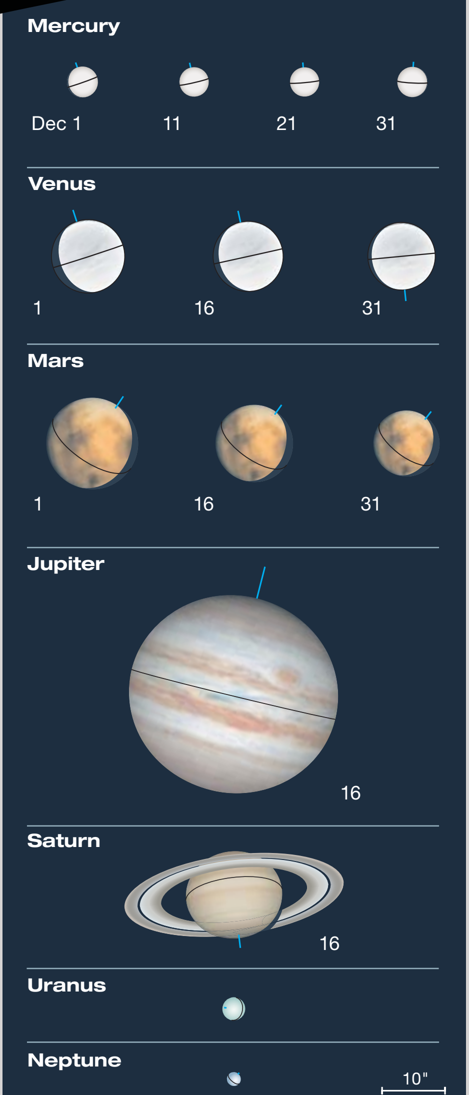
Tides of Light

Our target this month is the open cluster **Collinder 464** in the constellation Camelopardalis, the Giraffe. At first glance, it might not look much like a cluster, but rather a gaggle of moderately bright stars scattered across an ellipse almost 3° wide. Collinder 464 is pretty close as open clusters go, only about 400 light-years away. By comparison, most of the Messier, Caldwell, and showpiece NGC open clusters are between 1,000 and 7,000 light-years distant. Because it's so close, Collinder 464 is therefore spread out, so the challenge is not so much to see it, but to recognize it as a cluster.

Another oddity is that this big, diffuse cluster is not round, but instead elongated from east to west. If you imagine that line and extend it another 30° toward the heart of Cassiopeia, you'd find it intersecting the backbone of the Milky Way. And indeed, some astrophysicists hypothesize that Collinder 464 has been stretched toward the galactic plane by tidal forces.

In binoculars, Collinder 464 appears to contain about a dozen stars of 6th and 7th magnitude, and a host of dimmer ones. Some of the bright ones are cluster members, but others lie in the foreground or background, only coincidentally aligned with the cluster as seen from Earth. To me, the stars here seem to be hung in regular geometric arrangements: triangles, parallelograms, and 90° and 120° angles, like the skeleton of some great engineering project. Under sufficiently dark skies, a swarm of 8th- and 9th-magnitude stars fills in the picture, especially at the eastern and western ends of the cluster. I find that Collinder 464 rewards an unhurried survey. I hope it pulls you in as well.

■ **MATT WEDEL** is feeling the pull of the night sky right now, and he's headed outside at the end of this sentence.



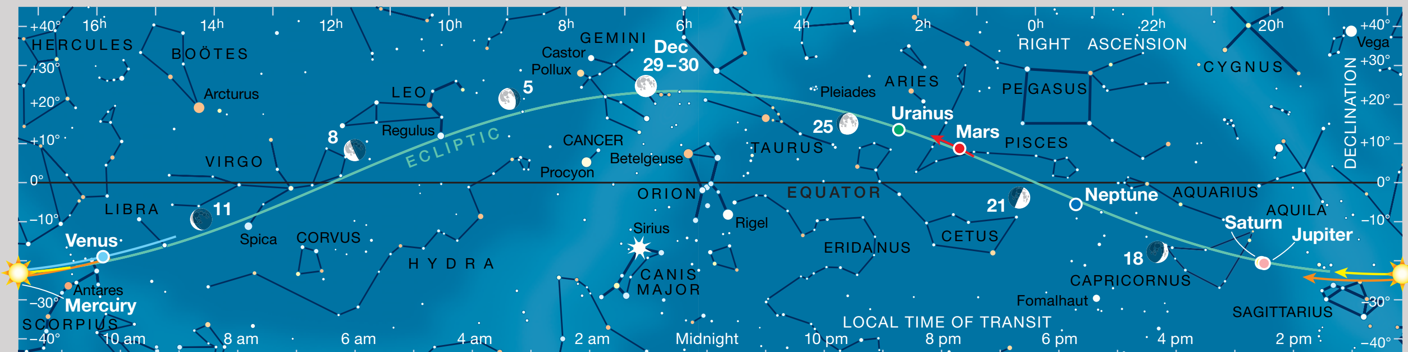
PLANET DISKS have south up, to match the view in many telescopes. Blue ticks indicate the pole currently tilted toward Earth.

PLANET VISIBILITY (40°N, naked-eye, approximate) **Mercury:** hidden in the Sun's glare all month • **Venus:** is the leading light at dawn • **Mars:** transits the meridian in the early evening and sets in the predawn • **Jupiter:** visible at dusk all month • **Saturn:** visible at dusk, sets in the early evening.

December Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	$16^h\ 29.0^m$	–21° 47′	—	–26.8	32′ 26″	—	0.986
	31	$18^h\ 41.2^m$	–23° 06′	—	–26.8	32′ 32″	—	0.983
Mercury	1	$15^h\ 45.3^m$	–19° 16′	11° Mo	–0.8	4.9″	96%	1.366
	11	$16^h\ 50.5^m$	–23° 04′	5° Mo	–1.0	4.7″	99%	1.436
	21	$17^h\ 59.0^m$	–24° 57′	2° Ev	–1.3	4.6″	100%	1.446
	31	$19^h\ 09.7^m$	–24° 34′	7° Ev	–1.0	4.8″	98%	1.398
Venus	1	$14^h\ 38.1^m$	–13° 41′	28° Mo	–3.9	11.7″	89%	1.431
	11	$15^h\ 27.4^m$	–17° 22′	25° Mo	–3.9	11.3″	91%	1.477
	21	$16^h\ 18.8^m$	–20° 18′	23° Mo	–3.9	11.0″	92%	1.518
	31	$17^h\ 11.9^m$	–22° 16′	21° Mo	–3.9	10.7″	94%	1.556
Mars	1	$1^h\ 01.9^m$	+6° 33′	128° Ev	–1.1	14.6″	92%	0.642
	16	$1^h\ 16.4^m$	+8° 36′	117° Ev	–0.7	12.3″	90%	0.759
	31	$1^h\ 37.6^m$	+11° 04′	107° Ev	–0.3	10.5″	89%	0.889
Jupiter	1	$19^h\ 51.8^m$	–21° 26′	47° Ev	–2.0	34.4″	100%	5.729
	31	$20^h\ 18.6^m$	–20° 08′	23° Ev	–2.0	32.9″	100%	5.988
Saturn	1	$20^h\ 01.2^m$	–20° 53′	49° Ev	+0.6	15.7″	100%	10.609
	31	$20^h\ 14.2^m$	–20° 16′	22° Ev	+0.6	15.3″	100%	10.894
Uranus	16	$2^h\ 18.5^m$	+13° 21′	133° Ev	+5.7	3.7″	100%	19.095
Neptune	16	$23^h\ 17.4^m$	–5° 46′	84° Ev	+7.9	2.3″	100%	30.018

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. equals 149,597,871 kilometers, or 92,955,807 international miles.) For other timely information about the planets, visit skyandtelescope.org.



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

A Long Night's Journey Into Day

The dark of winter offers plenty of time for skygazing and quiet contemplation.

Only that day dawns to which we are awake. There is more day to dawn. The sun is but a morning star.
— the concluding lines of *Walden*, by Henry David Thoreau

This year has brought a deadly pandemic along with social and economic upheaval. The prevalence of COVID-19 has kept most of us from sharing telescopic views with the public and each other. As we near the end of 2020, perhaps we can gain inspiration from the words of Thoreau.

But first, let's bolster ourselves by touring the longest nights of the year.

The long night's journey. For observers at mid-northern latitudes, the span from sunset to sunrise around the winter solstice is more than 14 hours, and astronomical darkness (when the Sun is more than 18° below the horizon) persists for nearly 11½ hours. Few of us have the endurance to take advantage of the entire night for a marathon, non-stop observing session, but we can sample this mighty span over the course of several nights.

For a first starry sample, look in the west as night falls. There you'll spot the Summer Triangle, not yet gone, beckoning you to revive summer memories of Vega and the Ring Nebula in Lyra, the Cygnus Star Cloud, and more.

Meanwhile, Mars is near the meridian and so too are three marvelous spiral galaxies: M31 in Andromeda, M33 in Triangulum, and NGC 253 in Sculptor. Lonely Fomalhaut is low in the south-southwest, while the large Great Square of Pegasus is high overhead. The east blazes with Aldebaran, Capella, Rigel, Betelgeuse, and Pollux (with its pal Castor). Orion, on his side, has fully risen. The Pleiades hang like fruit below one high branch of Perseus, and bright Cassiopeia's W is high in the north.

A few hours later, the dogs Canis Major and Canis Minor rise, marked by spectacular Sirius and Procyon, respectively. But leap ahead to about midnight, and your sky sample includes Orion upright on the meridian, with Taurus and Auriga above him.

Around 3 a.m. Leo and Ursa Major are nudging their noses near the meridian, while the giant Winter Hexagon adorns the southwest. And to the east you can follow the arc from the Big Dipper's handle to Arcturus, and spike on down to Spica.

By 5 a.m., Orion, Sirius, Aldebaran, and the Pleiades begin to set as Vega reappears, this time in the northeast. Finally, as dawn approaches, blazing Venus rises, heralding the night's end.

The Sun is but a morning star. As Thoreau knew, when Venus is the Morning Star it rises in its brilliance and glory ahead of the even brighter and more glorious Sun. He wrote that the Sun itself is "but a morning star." For Thoreau, the rising Sun was also a symbol suggesting the greater brightness and glory awaiting the human race when we finally attain peaceful coexistence with one another and an awareness of our beautiful world and universe.

"Only that day dawns to which we are awake." Time to wake up.

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

WINTER'S HEXAGON This enormous shape spans roughly 50° and includes the stars Sirius, Procyon, Castor, Capella, Aldebaran, and Rigel.

AKIRA FUJII

To find out what's visible in the sky from your location, go to skyandtelescope.org.

A Very Rare Jupiter and Saturn Pairing

The gas giant planets are at their closest since 1623.

On the evening of December 21st, Jupiter and Saturn have their closest conjunction in almost 400 years, and their closest viewable pairing in nearly 800 years. The giant planets are less than 1° apart for most of the month and high enough at dusk for reasonable views.

In addition to a far-south total eclipse of the Sun and favorable Geminid meteor shower, in December Mars is high after nightfall and remains above the 10″-diameter threshold for one final month. Finally, long after Mars sets, brilliant Venus rises in the morning sky.

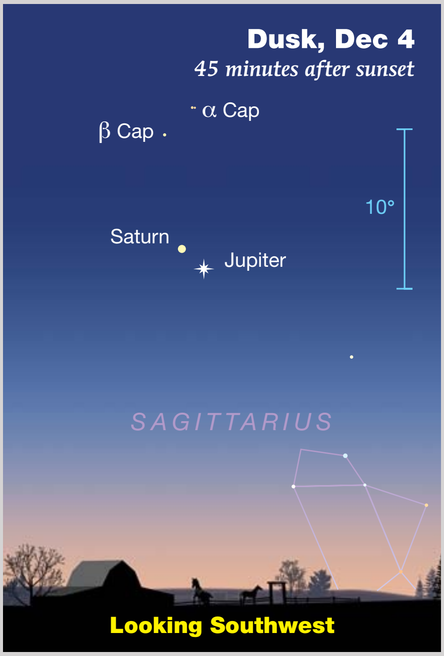
DUSK TO EARLY EVENING

Jupiter and **Saturn** set about 3½ hours after the Sun as December begins, and about 1¾ hours after sunset as the month ends. The two planets cross the border from Sagittarius into Capricornus — first Saturn (on the 15th) followed by Jupiter (on the 18th).

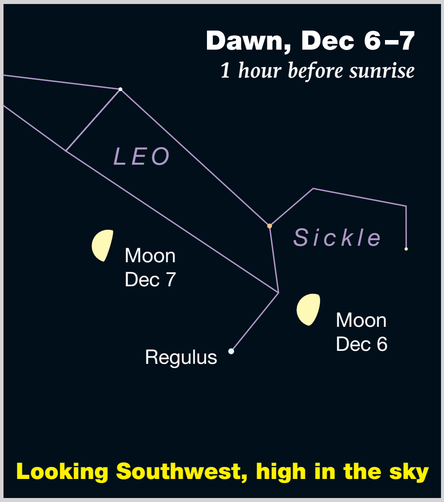
Jupiter and Saturn begin December a little more than 2° apart and are within 1° of each other from the 12th through the 29th. But the big event occurs on the evening of the 21st. That's when Jupiter and Saturn are separated by a mere 6′. For observers at mid-northern latitudes, the two planets will stand roughly 14° above the southwest horizon 45 minutes after sunset on that date. Jupiter is at magnitude –2.0 and 33″ wide, while Saturn shines at magnitude +0.6 and 15″ across, with its rings spanning 35″. At their closest, the two planets appear separated by less than 12 Jupiter widths. Through a telescope at moderate magnification, you can fit both gas giants *and* their brighter satellites all together in a single view.

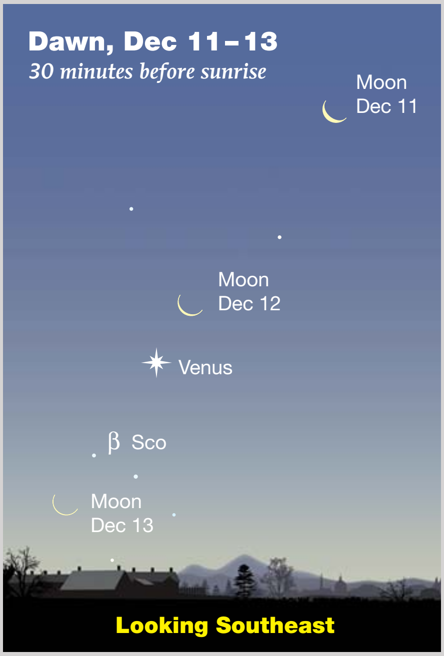
How rare is this month's conjunction? According to calculator extraordinaire Steve Albers, the last Jupiter/Saturn pairing that was closer and readily observable (49° from the Sun) occurred in 1226. The closest of all planetary conjunctions is a *mutual occultation*, in which the disk of one planet passes in front of the other. Albers has turned up a few mutual occultations of Jupiter and Saturn, with the most "recent" one he's found occurring about 8,000 years ago.

Does the 7 BC triple conjunction of Jupiter and Saturn (during which the planets passed near each other three times) account for the Star of Bethlehem? In recent decades, many researchers (including me) have come to favor the triple conjunction of Venus and



◀▼▶ 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.



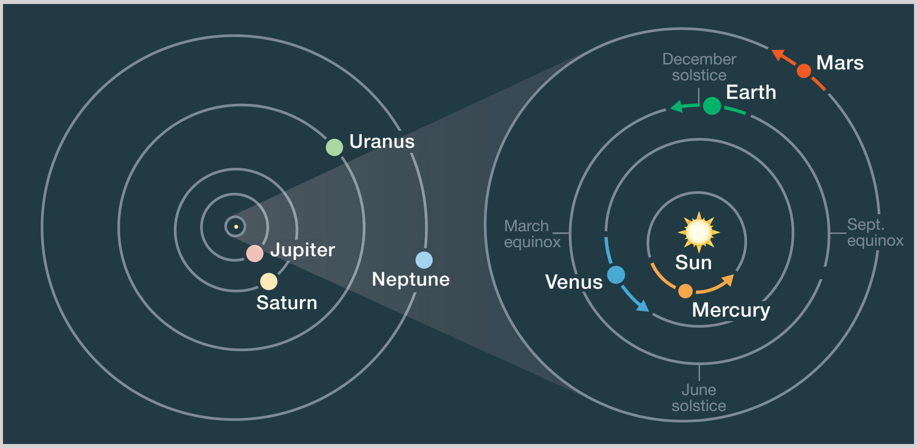


Jupiter that occurred over 3 and 2 BC. That series of encounters included a mutual occultation on June 17, 2 BC!

EVENING

Mars reaches the meridian before 8:30 p.m. on December 1st, and around 7 p.m. on the 31st. As Earth rapidly leaves Mars behind in their orbital race, the Red Planet fades from magnitude –1.1 to –0.3 this month. As a rule of thumb, when Mars is about zero magnitude, its angular diameter is approximately 10″ — often considered the limit for useful observations of the planet in medium-sized telescopes. This month Mars appears distinctly gibbous as its diameter decreases from 14.6″ to 10.5″. The planet passes through its ascending node (is north of the ecliptic) on December 1st, and glides eastward in Pisces all month.

Neptune is a magnitude-7.9 speck in Aquarius, and by mid-December transits the meridian during evening twilight and sets before midnight. Observe it early in the evening when it's still fairly high. **Uranus** glows at magnitude 5.7 in Aries and culminates in the early evening. (A Neptune finder chart appeared in the September issue on page 48; for a Uranus finder chart, turn to page 51 of the October issue.)



ORBITS OF THE PLANETS

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

DAWN

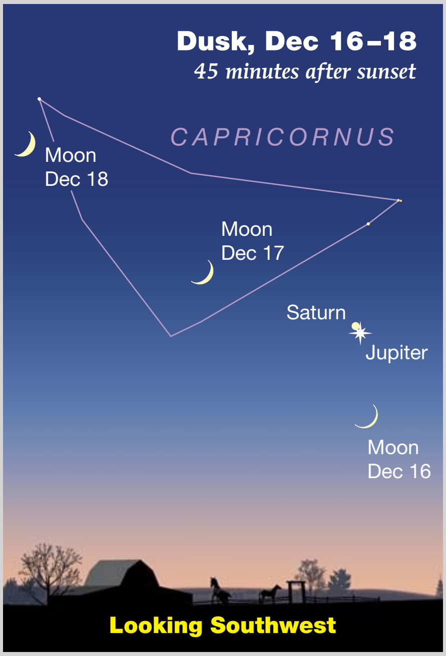
Venus rises in the southeast well over 2 hours before the Sun as December starts, but less than 1½ hours by month's end. The planet shines at magnitude –3.9 throughout December and shrinks a bit, from 11.7″ to 10.7″ as it waxes from 89% lit to 94% lit. Optical aid will help show the fine double star Beta (β) Scorpii only 10′ south of Venus on the morning of the 18th. Venus shines 5.6° north of Antares (and about 100 times brighter) on the morning of the 23rd. For some observers, Venus will be occulted by the Moon on the 12th (see page 50 for details).

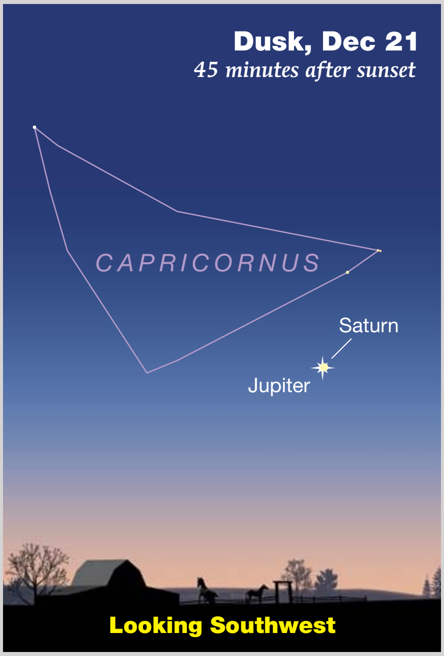
Mercury is visible in binoculars very low in the southeast at dawn for the first few days of December. The planet starts the month at magnitude –0.8 and rises only 45 minutes before the Sun. Mercury passes through superior conjunction on December 20th.

SUN AND MOON

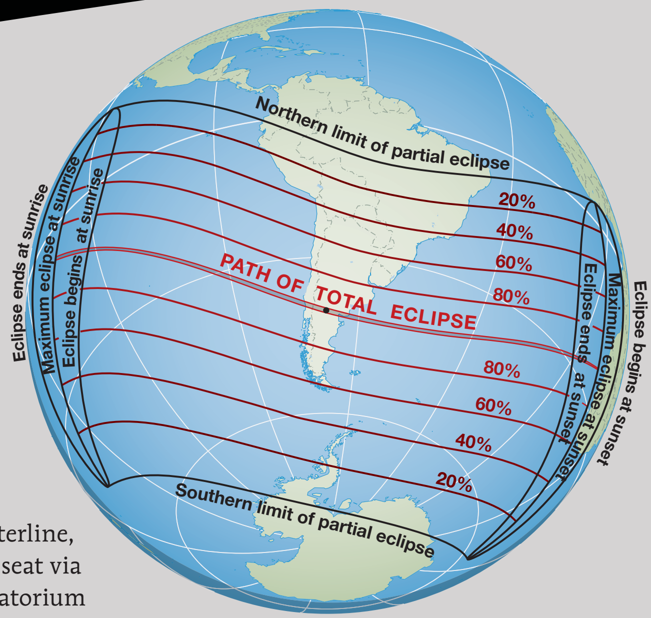
The **Sun** arrives at the December solstice at 5:02 a.m. EST on the 21st, marking the beginning of winter in the Northern Hemisphere and summer in the Southern Hemisphere. The Sun also experiences a total eclipse, observable from parts of Chile and Argentina on the 14th (see page 48 for details).

The **Moon** is a waning gibbous less than 6° to the upper right of Regulus on the morning of December 6th, and a slim lunar crescent floats about 4° to the upper right of Venus at dawn on the 12th. The Moon is essentially absent during the peak of the Geminid meteor shower on the night of December 13-14 (see page 14). Back in the evening sky, a slender lunar crescent shines roughly 5° below the tight Jupiter-Saturn pair on the 16th. On the evening of the 23rd, a waxing gibbous moon is about 5½° below Mars.





■ **FRED SCHAAF** started writing his first book, *Wonders of the Sky: Observing Rainbows, Comets, Eclipses, the Stars and Other Phenomena*, 40 years ago.



A South American Total Eclipse

The Moon's shadow visits Chile and Argentina again.

Concerns about COVID-19 may put a crimp in travel plans for many of us hoping to see the December 14th total solar eclipse, but the show will go on regardless.

I booked a flight to Argentina for the event, but as I write this (at the start of September), international travel remains iffy. Thousands of eager umbraphiles may find themselves in the same situation as we collectively grapple with a pandemic that has upended so many lives. Never fear. Even if you can't make it to the centerline, you're guaranteed a front row seat via livestreaming from the Exploratorium Museum in San Francisco (**exploratorium.edu/eclipse**) and at timeanddate.com (**timeanddate.com/live/eclipse-solar-2020-december-14**).

Much like the 2019 South America eclipse, the track of totality once again crosses Chile and Argentina, but this time about 1,000 kilometers (620 miles) farther south, and during Southern Hemisphere summer. The Moon's shadow touches down at sunrise on the 14th (14:33 UT) in the South Pacific. It rapidly heads east, making landfall 97 minutes later on the Chilean coast, where lucky viewers can catch 2 minutes and 8 seconds of totality. Traveling at 2,400 kilometers per hour, the lunar shadow dashes across the narrow country in 4 minutes, descending from the towering peaks of the Andes down to the deserts and tablelands of Argentina's Patagonia region.


This stunning high-resolution image of the solar corona was made during the July 2, 2019, total solar eclipse near Tres Cruces, Chile.

Weather prospects are generally good along the 700-kilometer-long Argentinian eclipse track. Perhaps the best place to view the event is north of the town of Piedra del Águila, which has a 30% average cloud cover at this time of year. Greatest eclipse occurs 180 kilometers to the east, where observers can experience 2 minutes and 10 seconds of totality, with mid-eclipse occurring at 16:13:30 UT.

Six minutes later, tourists sunning on the beach in the popular coastal resort town of Las Grutas need only peer over the tops of their sunglasses to enjoy 2 minutes and 6 seconds of totality before the Sun reappears and tanning resumes. The shadow then leaves Argentina and travels 7,000 kilometers across the South Atlantic Ocean before departing Earth off the coast of Namibia, at 17:54 UT — 3 hours and 21 minutes after the eclipse started.

Within the umbra's path, observers can watch for Baily's Beads just before

ECLIPSE IMAGE: MILOSLAV DRUCKMÜLLER / PETER ANIOL; ECLIPSE PATH: GREGG DINDERMAN / *S&T* / SOURCE: FRED ESPENAK and after totality, when bits of the solar photosphere briefly shine through gaps along the Moon's rugged limb. As always during a solar eclipse, you must use a safe solar filter or eclipse glasses except during totality, when the solar is completely covered by the Moon.

During totality, have a pair of binoculars at the ready to inspect the bright pinkish-red chromosphere. Chances are you'll see one or more prominences of incandescent hydrogen poking out beyond the dark lunar limb.

Most eclipse watchers would agree that the Sun's corona is the event's most mesmerizing sight. The pearly, unearthly nimbus of light dramatically frames the blackened Moon. Wide-field binoculars reveal the corona's magnetic nature. You can clearly see filaments and whorls of hot gas that recall iron filings around a magnet, as hot coronal gases bend to the will of the solar magnetic field. During solar minimum (currently underway), the corona often appears asymmetric, with long, taffy-like structures on either side of the Sun's equator and vertical field lines streaming from polar coronal holes.

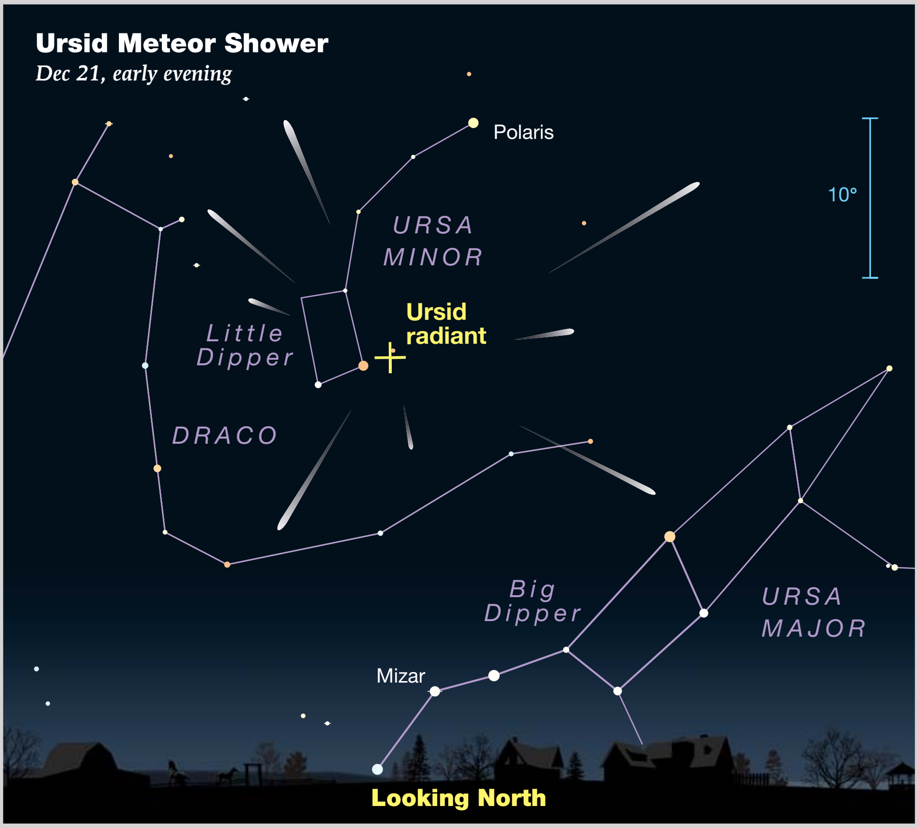
We actually see two coronas during a total eclipse. There's the inner portion called the K corona, comprising free electrons illuminated by sunlight. Beyond that, the F corona or "dust corona" begins. Here, sunlight scatters off particles shed by comets and asteroids along the plane of the solar system. The F corona expands into the zodiacal light, visible at dawn in autumn and dusk in spring.

During totality's brief twilight-darkness, listen for night insects — such as crickets — feel the sudden chill in the air, and relish the fact that you're part of a cosmic alignment along with the Sun and the Moon. Take a few moments to look around the sky, too. Four planets will be visible: Mercury and Venus (found 3° and 24° west of the Sun, respectively), and the close duo of Jupiter and Saturn 35° to the Sun's east.

Before you know it the eclipse will come to an end. Baily's Beads make a final appearance, and the shadow that descended in apocalyptic haste when totality began now hurries away ahead of the returning daylight. Yes, it all goes by too fast.

Two-thirds of South America and a portion of Antarctica will witness a partial eclipse, with 79% of the Sun covered in Santiago, Chile; 74% in Buenos Aires, Argentina; 32% in São Paulo, Brazil; 17% in Lima, Peru; and 1.4% in Guayaquil, Ecuador. For details of the eclipse along the entire path of totality, check out Xavier Jubier's interactive eclipse map at **https://is.gd/2020eclipse**.

December's "Other" Meteor Shower

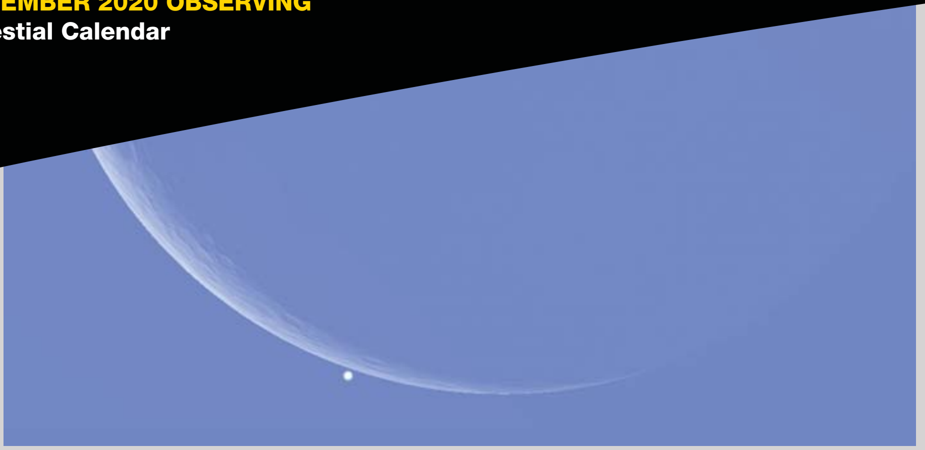


▲ The Ursid radiant is visible all night from most locations north of the equator. You can view the shower beginning in the early evening of December 21st, but the display peaks in the predawn hours of the 22nd.

THE GEMINIDS (see page 14) rightly steal the headlines when it comes to annual meteor showers, but the lesser known Ursids are also worth a look. This shower originates from particles released by Comet 8P/Tuttle in its 13-year orbit around the Sun. Like the Geminids, Ursid meteoroids move relatively slowly, striking the atmosphere at a speed of 33 kilometers per second.

The Ursids are active from December 17–26, and this year they peak in the predawn hours of December 22nd (at around 4 a.m. EST) when 5 to 10 meteors per hour shoot from just near 2nd-magnitude Kochab, the brightest star in the bowl of the Little Dipper. The Moon will be at first-quarter phase and sets around midnight, leaving a dark sky during the shower's peak for observers across North America.

I like to think of the Ursid shower as a little bear briefly emerging from hibernation at the winter solstice and flinging a few meteoroids our way. Playful fella. Follow his lead and leave your warm bed for an hour or so to see what he kicks up.



STELLARIUM

The Moon Eclipses Venus

ON DECEMBER 12TH, two days before the solar eclipse, skywatchers in western North America, Alaska, Hawai'i, and eastern Russia will see a sliver crescent Moon occult the planet Venus. The event takes place during daylight hours, except in Russia where it occurs before sunrise.

Because the Moon will be just 5% illuminated and 25° west of the Sun, you'll likely need binoculars to find the pale lunar crescent. Telescopes will show a tiny, but brilliant, gibbous Venus near the Moon before and after the occultation.

If you live in the Pacific time zone or points west, Venus and the Moon make a beautiful sight at dawn, separated by only 2½°. Observers on the East Coast will see the pair 4° apart. Unfortunately, in the eastern half of North America the pair set before the occultation begins.

We've included occultation times for several cities in the table below. You can determine the details for other locations with most planetarium software packages, including the excellent freeware program Stellarium (**stellarium.org**). Simply dial up the correct date, use the search function for "Venus," and then advance the time until the illuminated lunar limb touches the planet. (It's important to remember to uncheck the "Scale Moon" box in the Sky and viewing options menu so the Moon appears the correct size.) Venus will reappear at the lunar dark limb about an hour after it disappears.

Lunar Occultation of Venus

City	Disappearance / Reappearance	Altitude*
Denver, CO	2:29 p.m. / —	7°
Mazatlán (Mexico)	2:48 p.m. / —	12°
San Francisco, CA	1:11 p.m. / 2:18 p.m.	21°
Vancouver, BC (Canada)	1:02 p.m. / 1:48 p.m.	14°
Anchorage, AK	11:14 a.m. / 12:04 p.m.	11°
Honolulu, HI	10:13 a.m. / 11:36 a.m.	50°

*Altitude of Venus at disappearance. All times local.

Minima of Algol

Nov.	UT	Dec.	UT
1	17:56	3	6:54
4	14:44	6	3:43
7	11:33	9	0:32
10	8:22	11	21:21
13	5:11	14	18:10
16	2:00	17	14:59
18	22:49	20	11:49
21	19:38	23	8:38
24	16:27	26	5:27
27	13:16	29	2:16
30	10:05	31	23:05

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

Action at Jupiter

AT THE START OF DECEMBER, Jupiter is reasonably high in the southwest at dusk and sets around 8:00 p.m. local time. The best time to observe the planet is early in twilight, when it's highest. On December 1st, Jupiter shines brightly at magnitude –2.0 and presents a disk 34″ in diameter.

Any telescope shows the four big Galilean moons, and binoculars usually show at least two or three. The moons orbit Jupiter at different rates, changing positions along an almost straight line from our point of view on Earth. Use the diagram on the facing page to identify them by their relative positions on any given date and time.

All the December interactions between Jupiter and its satellites and their shadows are tabulated on the facing page.

Features on Jupiter appear closer to the central meridian than to the limb for 50 minutes before and after transiting. Here are the times, in Universal Time, when the Great Red Spot should cross Jupiter's central meridian. The dates, also in UT, are in bold. (Eastern Standard Time is UT minus 5 hours.)

November 1: 8:05, 18:45; **2**: 4:42, 14:37; **3**: 0:33, 10:29, 20:25; **4**: 6:21, 16:16; **5**: 2:12, 12:08, 22:04; **6**: 7:59, 17:55; **7**: 3:51, 13:47, 23:43; **8**: 9:39, 19:34; **9**: 5:31, 15:26; **10**: 1:22, 11:18, 21:14; **11**: 7:10, 17:05; **12**: 3:01, 12:57, 22:53; **13**: 8:49, 18:44; **14**: 4:41, 14:36; **15**: 0:32, 10:28, 20:24; **16**: 6:02, 16:15; **17**: 2:11, 12:07, 22:03; **18**: 7:59, 17:55; **19**: 3:51, 13:46, 23:42; **20**: 9:38, 19:34; **21**: 5:30, 15:25; **22**: 1:21, 11:17, 21:13; **23**: 7:09, 17:05; **24**: 3:01, 12:56, 22:52; **25**: 8:48, 18:44; **26**: 4:40, 14:36; **27**: 0:32, 10:27, 20:23; **28**: 6:19, 16:15; **29**: 2:11, 12:06, 22:02; **30**: 7:58, 17:54

December 1: 3:55, 13:51, 23:46; **2**: 9:42, 19:38; **3**: 5:34, 15:30; **4**: 1:26, 11:22, 21:17; **5**: 7:13, 17:09; **6**: 3:05, 13:01, 22:56; **7**: 8:53, 18:48; **8**: 4:44, 14:40; **9**: 0:36, 10:32, 20:27; **10**: 6:23, 16:19; **11**: 2:15, 12:11, 22:07; **12**: 8:03, 17:58; **13**: 3:54, 13:50, 23:46; **14**: 9:42, 19:38; **15**: 5:34, 15:29; **16**: 1:25, 11:21, 21:17; **17**: 7:13, 17:09; **18**: 3:05, 13:00, 22:56; **19**: 8:52, 18:48; **20**: 4:44, 14:40; **21**: 0:36, 10:31, 20:27; **22**: 6:23, 16:19; **23**: 2:15, 12:11, 22:06; **24**: 8:02, 17:58; **25**: 3:54, 13:50, 23:45; **26**: 9:42, 19:37; **27**: 5:33, 15:29; **28**: 1:25, 11:21, 21:16; **29**: 7:13, 17:08; **30**: 3:04, 13:00, 22:56; **31**: 8:52, 18:47.

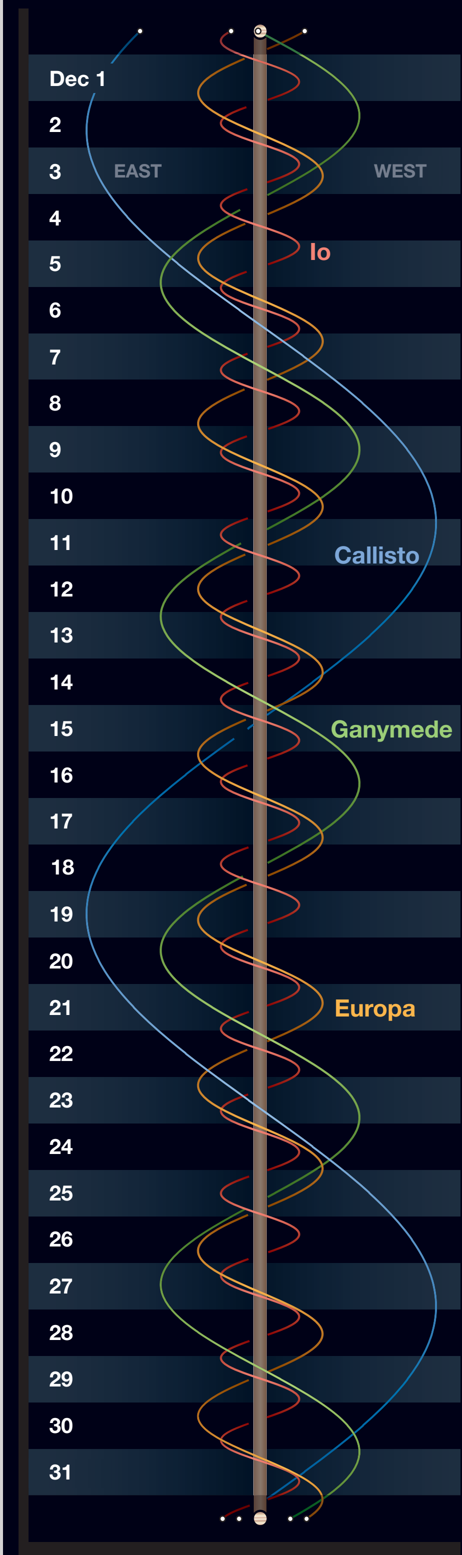
These times assume that the spot will be centered at System II longitude 347° on December 1st. If the Red Spot has moved elsewhere, it will transit 1²/₃ minutes earlier for each degree less than 347° and 1²/₃ minutes later for each degree more than 347°.

Phenomena of Jupiter's Moons, December 2020

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

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

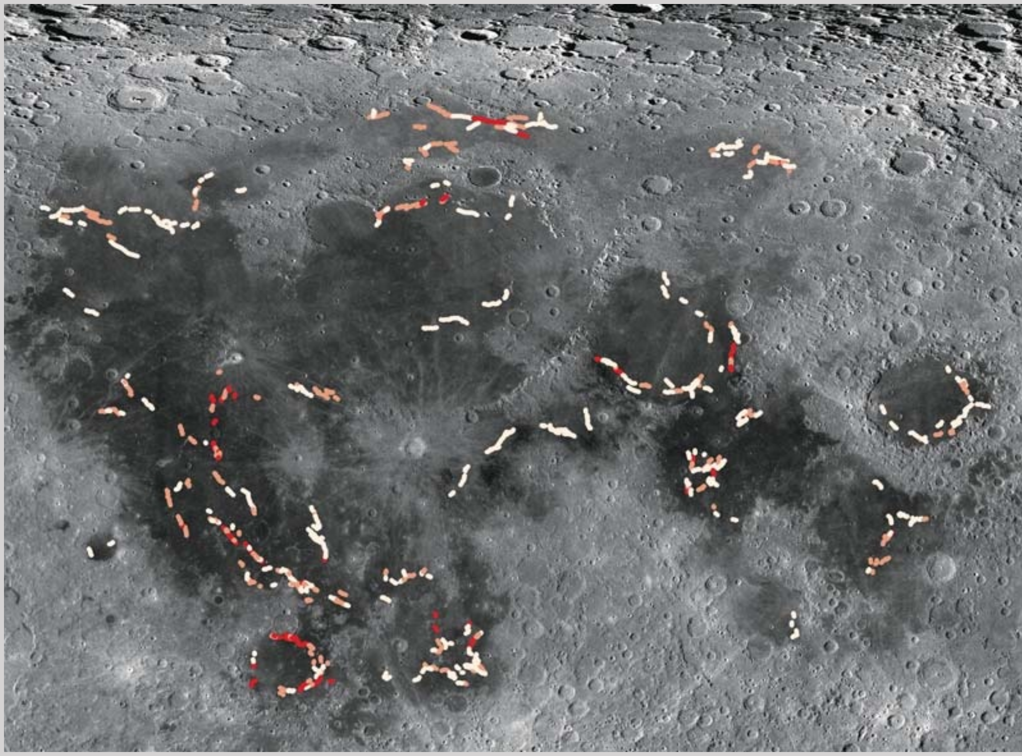
Jupiter's Moons



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

ANTS on the Moon

Warm rocks hint at recent geological activity.



▲ This map shows the distribution of boulder-topped ridges that make up the active nearside tectonic system (ANTS). Areas with higher abundances of boulders are marked in red, with decreasing amounts represented in orange and white.

NASA / GSFC / ARIZONA STATE UNIVERSITY / VALANTINAS & SCHULTZ

Roughly 100 years ago, Harvard College Observatory astronomer William Henry Pickering proposed that vast swarms of insects move across the lunar surface. It was a fantastical attempt to account for the Moon's changing brightness as the Sun's elevation changes throughout the lunar day. He was wrong, but now modern astronomers, using the highest quality orbital data, have detected "ANTS" on the Moon.

ANTS is an acronym for *active nearside tectonic system*, a phrase describing evidence for extensive small-scale movement of areas of the Moon's surface. In a paper published earlier this year, Bern University graduate student Adomas Valantinas and Peter Schultz of Brown University focused on more than 500 locations where clusters of fresh, meter-sized boulders are exposed along the tops of mare wrinkle ridges. While visible in high-resolution Lunar Reconnaissance Orbiter (LRO) images as well as in thermal infrared maps, the boulders are unfortunately far too small to see from Earth.

The detection of the boulders is done two ways. LRO's Narrow Angle Camera resolves objects as small as half a meter across, so fresh boulders show up as sharply defined, tiny bright rocks. The spacecraft's Diviner thermal infrared instrument produces high-resolution temperature maps. When lunar night comes, regolith-covered areas radiate away 14 days of accumulated daytime heat fairly rapidly, but denser rocks cool much slower, so the wrinkle ridge boulders appear as tiny hotspots, like strings of Christmas tree lights.

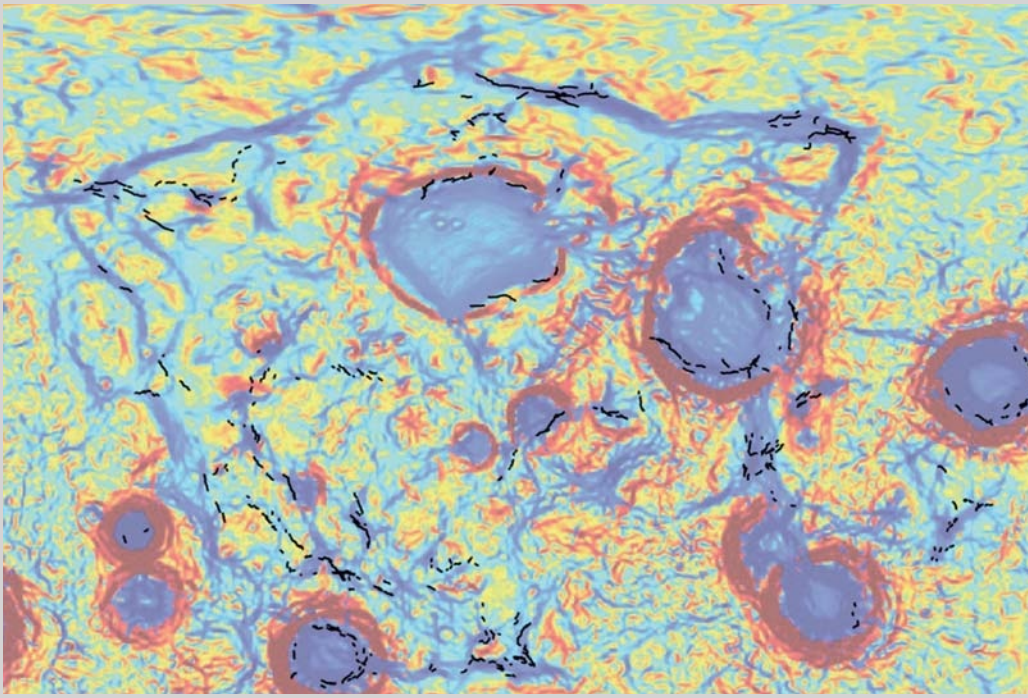
But why do fresh rocks imply recent tectonic activity? Newly exposed rocks and boulders are continuously broken up and reduced to regolith by micrometeorite bombardment. For meter-size rocks the process is estimated to take anywhere from 25 to 300 million years. In geological terms this is very recent, considering that most lunar maria are about 3 billion years old and large, rayed craters like Copernicus are around a third of that age.

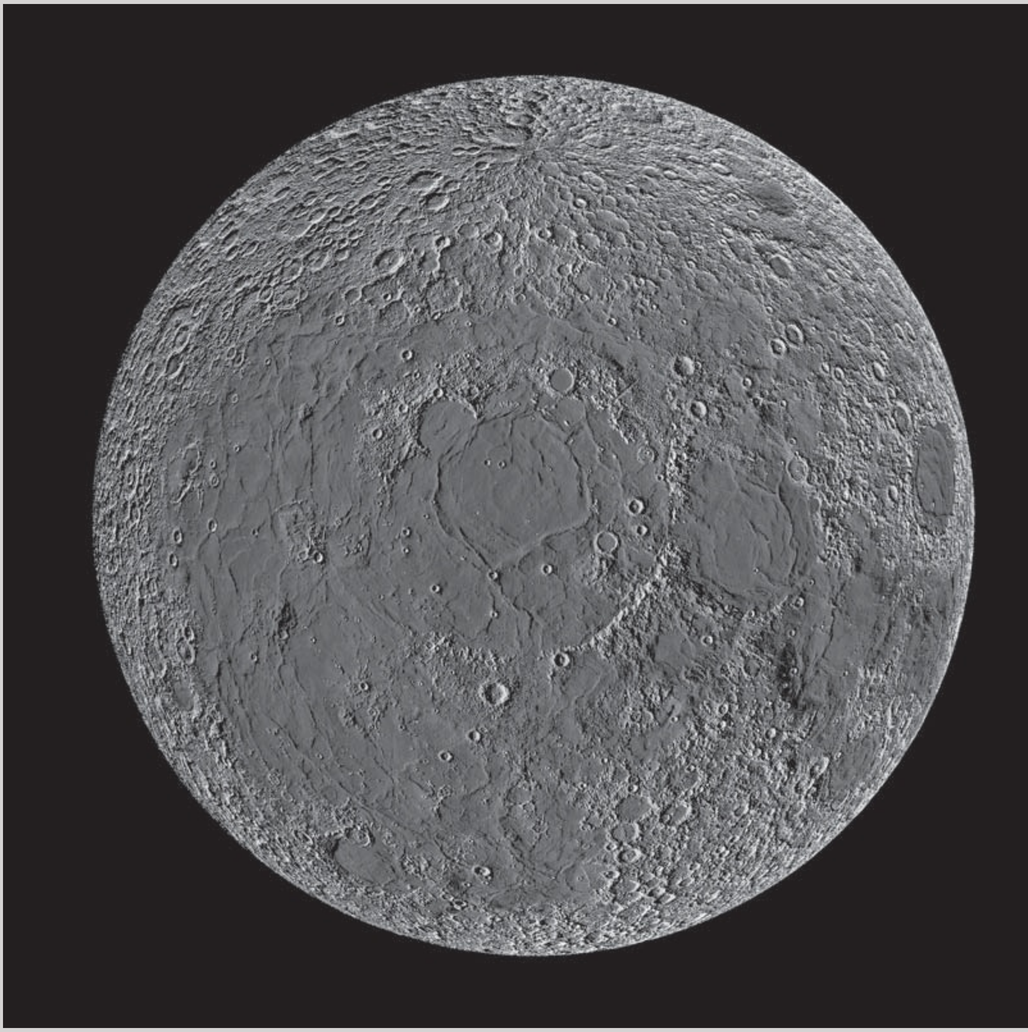
Fresh boulders are widespread on the Moon, but nearly all of them are produced when impacts fracture the lunar crust and excavate crustal blocks. Over time, fresh boulders and rocks erode from interior crater walls and tumble down their steep slopes. The existence of fresh boulders near the tops of near-flat mare ridges can't be explained by the normal mechanisms of impact cratering and micrometeorite erosion, so there must be some other process that is producing them.

Valantinas and Schultz's explanation requires looking back to near the beginning of lunar history. Most of the wrinkle ridges with fresh boulders lie above deep areas interpreted as geologic dikes, discovered on maps created using data from NASA's Gravity Recovery and Interior Laboratory (GRAIL) orbiters (*S&T:* Feb. 2019, p. 52). The dikes were conduits for magma brought from deep in the lunar interior, forming intrusions that were the probable source of mare lavas. The dikes occur under wrinkle ridges that define basin collapse zones, as well as along ridges near the shores of broad mare, such as **Mare Serenitatis** and **Mare Humorum**. Valantinas and Schultz propose that these ancient dikes were reactivated, moving wrinkle ridges slightly upward or sideways, exposing previously buried boulders. They further

▶ (*Top*) The ANTS zones correspond to deep lava dikes in this GRAIL gravity map.

▶ (*Bottom*) ANTS tend to be located along mare ridges. This map highlights all the mare ridges visible on the lunar nearside.





GRAIL MAP: NASA / GSFC / ARIZONA STATE UNIVERSITY / VALANTINAS & SCHULTZ
RIDGE MAP: NASA / GSFC / ARIZONA STATE UNIVERSITY / M. COLLINS

speculate that the reactivation is associated with adjustments from an oblique impact origin for the South Pole–Aitken basin, thought to have formed roughly 4.3 billion years ago.

You can engage in your own examination of ANTS by tracing the ridges that contain them, to see where recent activity is apparently occurring. An easy place to start is **Mare Imbrium**. The Valantinas and Schultz map reveals that most boulder concentrations occur on the wrinkle ridges that define the inner ring of the Imbrium impact basin. The boulder ridges start near **Promontorium Laplace** and pass near **Montes Recti** and **Montes Teneriffe**, and then skip to the ridge west of **Montes Spitzbergen** and to **Dorsum Grabau** west of **Archimedes**. The Serenitatis and Humorum impact basins are rich in ANTS boulders, which occur atop wrinkle wridges near the mare edges. And the radial wrinkle ridges that define **Lamont** in western **Mare Tranquilitatis** are all ANTS sites (though the concentric ridges aren't), renewing questions about the origin of Lamont (*S&T:* Apr. 2019, p. 52) and raising speculations about whether and how Lamont is still tectonically active.

Someday, when there's a network of seismometers on the Moon, it'll be exciting to see if current moonquakes occur along these ANTS ridges. Not mentioned here is the discovery of other small scarps all around the Moon that reinforce the likelihood that the Moon is still seismically and tectonically active. Just as the Moon is not as dry as once thought, we're now learning that it may not be as geologically dead as we thought — it could still be adjusting to events from its earliest history in ways not yet understood.

■ Contributing Editor **CHUCK WOOD** keeps one eye on the latest lunar research to share with *S&T* readers.

To celebrate 20 years of Sue French's stellar contributions to *Sky & Telescope*, we have been sharing the best of her columns throughout 2020. We have updated values to current measurements when appropriate.

The Starry Heavens

Clusters and nebulae abound in compact Cassiopeia.

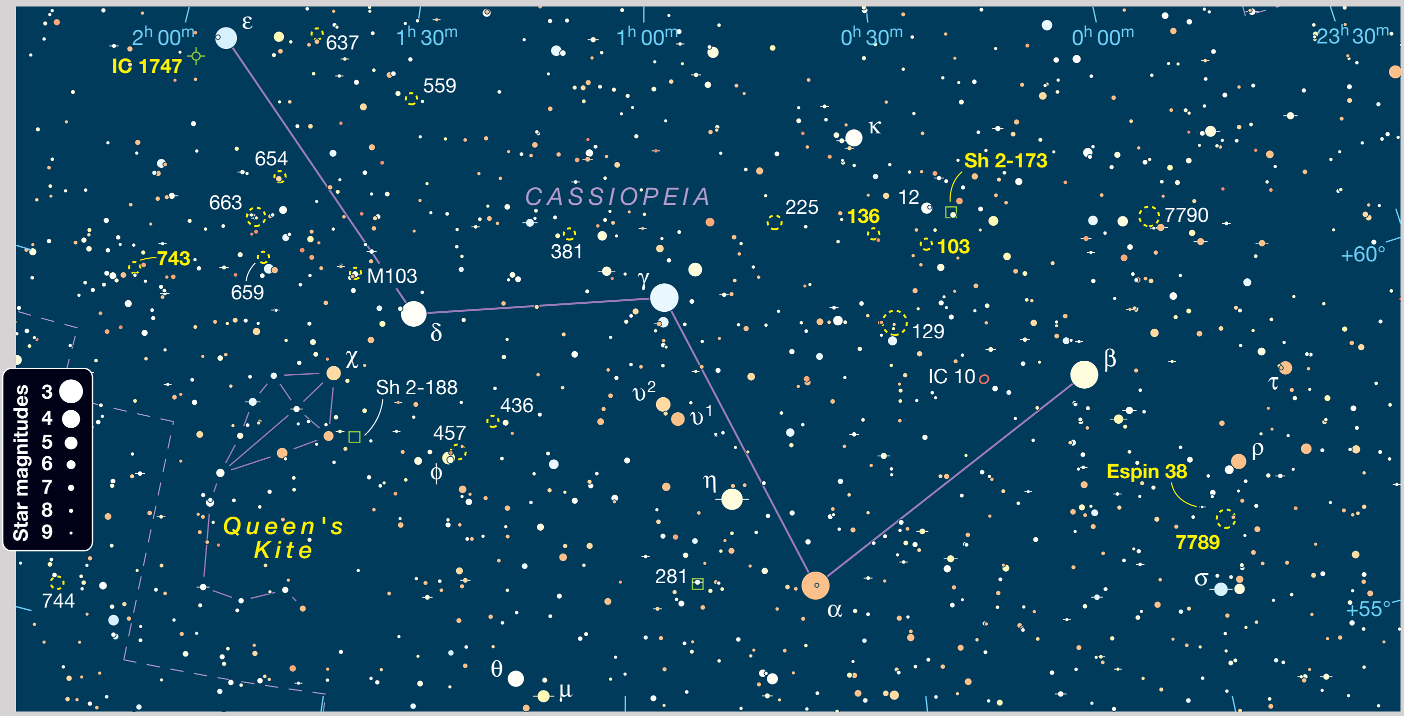
Ye quenchless stars! so eloquently bright,
Untroubled sentries of the shadowy night,
While half the world is lapp'd in /
downy dreams,
And round the lattice creep your /
midnight beams,
How sweet to gaze upon your placid eyes,
In lambent beauty looking from the skies!
— Robert Montgomery,
The Omnipresence of the Deity, 1828

Several bright and shining eyes gaze down at us from Cassiopeia, and a wealth of lesser lights join them from their favored position along the crowded plane of our galaxy, where reigns the Milky Way in soft and misty splendor.

Many of the constellation's twinkling peepers are gathered into star clusters, with **NGC 7789** being one of the most beautiful stellar gatherings in our sky. The cluster shares a low-power field of view with the yellow hypergiant Rho (ρ) Cassiopeiae. A yellow hypergiant is a highly luminous supergiant that suffers prodigious mass loss, as well as occasional eruptions that dim the star with a cloak of ejected material. If Rho replaced our Sun, it would extend out beyond Mars to the inner edge of the asteroid belt.

NGC 7789 is easily visible through my 8×50 finderscope as a sizable, grainy glow. My 130-mm refractor at 23× unveils a beautiful cluster richly populated with pinpoint stars. An orange, 8th-magnitude star on the group's western fringe helps me assign an apparent diameter of 20′ to the cluster. NGC 7789 is stunning at 63× and reveals far too many stars to count, with the brightest weighing in at 10th magnitude. The fainter the stars, the more numerous they become, until they coalesce into a stippled haze in the cluster's teeming, 12′ core.

NGC 7789 is a spectacular sight when viewed through my 10-inch reflector at 70×. Its panoply of stars is enchantingly filigreed with inky black threads that wind through the cluster. Off the group's northeastern side, the double star **Espin 38** displays a yellow-white primary with a ruddy companion to its west-southwest. The companion is a carbon star that varies from magnitude 9.9 to 12.7. Sometimes called Wildt's Red Star, after the German-American astrophysicist Rupert Wildt, this variable is currently



near peak brightness. When I boost the telescope's magnification to 115×, NGC 7789's core stars seem to be arrayed in a strange, spiral pattern that unwinds clockwise from the center for more than 1½ turns.

Beta (β) Cassiopeiae, also known as Caph, lies halfway between NGC 7789 and the large emission nebula **Sharpless 2-173**, and 5th-magnitude 12 Cassiopeiae guards the nebula's east-northeastern edge. The inconspicuous star cluster Mayer 1 rests at the heart of the nebula, with a 7th-magnitude star marking its south-southwestern edge.

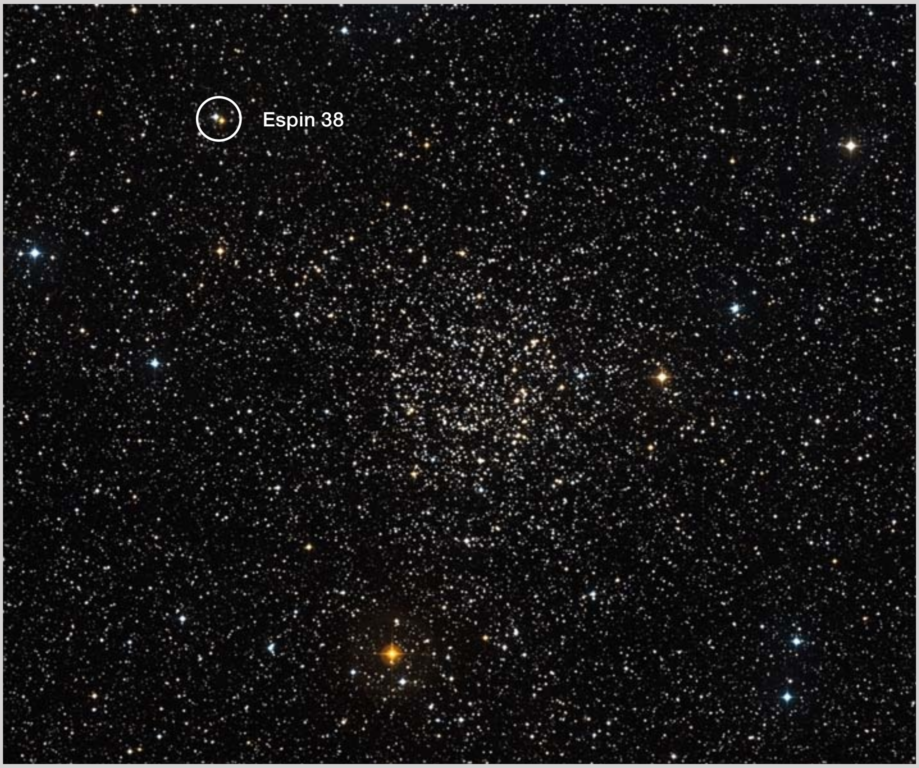
Through my 105-mm refractor at 47×, all I can see of Mayer 1 is a bent band of 10 stars. The brightest one is magnitude 9.5 and defines the cluster's center. These stars are entangled in a feeble glow that spreads southward to a 4′ trapezoid of 9th- and 10th-magnitude stars. The most prominent part of the nebula is a misty arc northwest of Mayer 1. A dark void between it and the cluster nicely delineates the arc's concave inner edge, and a pretty, reddish-orange, 7th-magnitude star adorns the outer edge. Very faint nebulosity weds this arc to the amorphous glow south of the cluster.

Although filters don't help much with the little refractor, a narrowband nebula filter works fairly well with my 10-inch reflector at 68×, expanding Sh 2-173 and emphasizing the dark gap between the arc and Mayer 1. Except for this fairly bright arc, the nebula's outer regions are vague. I'd guesstimate a maximum width of 18′ to 20′.

Mayer 1 was introduced in a 1964 paper by Pavel Mayer entitled "List of Open Star Clusters in Emission Nebulae." It appeared in the Czech journal *Publications of the Astronomical Institute of the Charles University (Acta Universitatis Carolinae. Mathematica et Physica)*. The three clusters designated "Anon." (anonymous) in Mayer's list now bear his name.

Dropping ½° southward from 12 Cassiopeiae with my 130-mm refractor at 37×, I see a small, elongated, granular, fuzzy patch with two stars at its northeastern end. This is the open cluster **NGC 103**. At 102× ten stars emerge from the haze, and a half dozen stars scattered around them fill the group out to a diameter of 3½′. Through my 10-inch reflector at 187×, I count 30 stars within a diameter of 5′. Many are gathered into a bar that tapers southwest, and most of the rest form two drooping arms that sprout from each side of the bar's wide end.

NGC 136 sits just 46′ east-northeast of NGC 103. At 102× the 130-mm refractor readily shows a subtly flecked, diminutive patch of haze, though it does appear rather faint. The cluster spans 1¼′, and a very dim star dots its north-northeastern edge. NGC 136 is lovely through my 10-inch scope at 115×. It brings to mind a little mound of beach sand sparkling with minuscule grains.



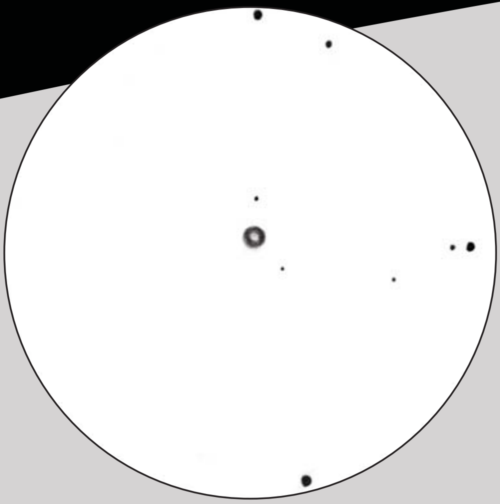
▲ NGC 7789 is extraordinarily rich and old as open clusters go. The wide range of colors among its stars is due to the fact that many have evolved into red giants. Espin 38 is seen at the upper left.

POSS-II / CALTECH / PALOMAR OBSERVATORY

Clusters, Stars, and Nebulae in Cassiopeia

Object	Type	Mag(v)	Size/Sep	RA	Dec.
NGC 7789	Open cluster	6.7	25′	23^h 57.5^m	+56° 43′
Espin 38	Double star	9.8, 10.7	24″	23^h 59.1^m	+56° 58′
Sharpless 2-173	Emission nebula	—	25′	00^h 21.9^m	+61° 44′
NGC 103	Open cluster	9.8	5.0′	00^h 25.3^m	+61° 19′
NGC 136	Open cluster	11.5	1.5′	00^h 31.5^m	+61° 31′
Queen's Kite	Asterism	—	4.0° × 2.3°	01^h 37.8^m	+57° 23′
NGC 743	Open cluster	9.5	8.0′	01^h 58.6^m	+60° 09′
IC 1747	Planetary nebula	12.0	13″	01^h 57.6^m	+63° 19′

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.



◀ Finnish stargazer Jaakko Saloranta sketched IC 1747 as seen through an O III filter on his 8-inch reflector.

The **Queen's Kite** is a nice binocular asterism for those who live under skies compromised by outdoor lighting, and it's straightforward to locate near Delta (δ) Cassiopeiae. Dark skies or large binoculars reveal dim stars that may overwhelm the asterism's pattern.

The Queen's Kite is easily visible through 10×30 binoculars from my moderately light-polluted yard, even with a crescent Moon in the sky. The kite is topped by 4.7-magnitude Chi (χ) Cassiopeiae, and the rest of its stars are 6th and 7th magnitude. From Chi, the 2.2°-tall kite slants southeast, with each corner marked by a star. Additional stars lie along the kite's long sides, two in the east and one in the west, while another star marks the intersection of the kite's crossbars. Below the kite's bottom, a solitary star starts the kite's tail, and farther south, four faint stars in an east-west zigzag complete it. The Queen's Kite is a product of the fertile imagination of Massachusetts amateur John Davis.

With my 105-mm refractor at 17×, sweeping about 4° eastward from Delta Cassiopeiae takes me to a rich starfield 1½° across. The open cluster **NGC 743** is a small knot of stars nestled amid these brighter eyes. At 87× this is a distinctive cluster of 17 stars, 9th magnitude and fainter, in a 7′-wide group. Seven of the brightest stars make a broad, eastward-pointing V, and six stars within the V make a smaller capital D. In the northern arm of the V, the star closest to the point is the John Herschel double h1098 (HJ 1098). The 10th-magnitude primary has a 12th-magnitude companion 18″ to its north.

Our last stop is the petite planetary nebula **IC 1747**, located 30′ southeast of Epsilon (ε) Cassiopeiae. At low magnification, it masquerades as just another star in an eye-catching, sinusoidal curve of 11th- and 12th-magnitude stars that runs east-northeast to west-southwest for 18′. In my 15-inch reflector at 102×, IC 1747 sheds its disguise, appearing fairly bright, small, and round. It's very nice at 216× — quite bright and softly annular with a fainter fringe. The nebula would span half the distance between two field stars that are 26″ apart. I couldn't see the 15.4-magnitude central star nor the brighter patches on the north and south rims of the annulus. Can you?

You don't need a 15-inch scope to enjoy IC 1747. Impressively, Finnish amateur Jaakko Saloranta could clearly see the annulus at 267× with an 8-inch reflector and O III filter.

Williamina Fleming discovered IC 1747 in 1905 while classifying stars by examining photographic, objective-prism spectra. Her description reads, "Assumed to be the following and southern of two faint and difficult objects, which also appears somewhat hazy. The spectrum consists of a bright band having wavelength of about 5000. Therefore, this object has been assumed to be a gaseous nebula."

■ Contributing Editor **SUE FRENCH** wrote this column for the December 2014 issue of *Sky & Telescope*.

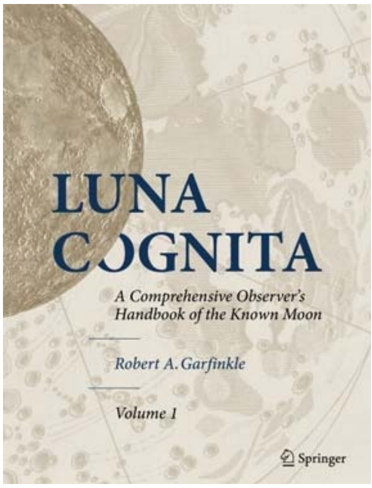
SEAN WALKER / S&T

▶ The large emission nebula Sharpless 2-173 lies west-southwest of the bright, bluish star 12 Cassiopeiae.

All the Right Stuff

LUNA COGNITA: *A Comprehensive Observer's Handbook of the Known Moon (3 vols.)*

Robert A. Garfinkle
Springer, 2020
1,680 pages, ISBN 978-1-4939-1663-4
US $89.99, hardcover.



It is the very error of the moon,
She comes more nearer earth than
she was wont,
And makes men mad.
– William Shakespeare, *Othello*

THE MOOR OF VENICE alludes here to a belief in Shakespeare's day that the Moon could cause actual madness, but you will become a savvy "lunatic" if you read this tour de force by lunar cognoscente Robert Garfinkle. Enhanced with 95 tables and more than 1,300 figures, this three-volume set is more compendium than handbook. Spanning science to photography, it's a must-read for every serious observer of the Moon.

Volume 1 sets the table: mythology and lore; mechanics and formation of the Earth-Moon system; descriptions of lunar features and geological periods; history and operation of the telescope; history and tips regarding lunar photography; and information on reading Moon maps.

The last six chapters of Volume 1 and the first nine of Volume 2 give full descriptions via text and photographs of lunar features observable throughout each night of the lunar cycle, from one New Moon to the next. The information is precise, relevant for observers, and includes interesting supplementary material, such as whom lunar features are named for and depictions of such features on drawings and old maps.

The remaining chapters of Volume 2 discuss a variety of specialized topics: observing special features, from dark halo craters to lunar domes; making measurements, e.g., shadow lengths and photometric assessments of brightness; producing drawings of lunar elements; and observing Moon occultations and lunar and solar eclipses. I especially enjoyed the sections on lunar transient phenomena and the history of solar eclipses.

Volume 3 consists of 17 appendices. These include ephemerides of lunar data and deep-sky objects occulted by the Moon; catalogs of lunar features and spaceflights to the Moon; lists of publishers and observing organizations; and tables for lunar and solar photographers. There's also a section describing different cultural lunar mansion systems — ancient divisions in the sky based on the roughly 28-day lunar cycle. The volume concludes with a complete glossary, bibliography, and indices based on topics, proper names, lunar features, and mythology.

Each chapter opens with a quote involving the Moon (say, from Shakespeare); includes a section on names introduced in the chapter that pertain to relevant lunar constituents; and concludes with an image, such as a picture of Moon-crossed lovers from antique European postcards.

Throughout, many useful figures accompany the text. As an amateur astronomer, I especially liked Figure 4.10, which shows how the Moon is oriented in an eyepiece based on the observing instrument and setup — for example, binoculars, refractor, or Schmidt-Cassegrain telescope with or without a star diagonal.

This wonderful set has something for every observer. It's beautifully published, with quality printing, good photos, and solid binding.

A book of this size is bound to have a few glitches (such as Figure 6.1, which has East and West labels reversed). But overall the figures are coherent and helpful adjuncts to the text. As an antiquarian celestial map enthusiast, I found the descriptions and illustrations of old maps in Section 3.4 ("Selenography and the History of Lunar Nomenclature") and in relevant sections elsewhere to be complete and informative.

This wonderful set has something for every observer. Although one could use the books during an observing session, I would imagine turning to them more while planning for a night's work, or even the day after observing to expand my knowledge of what I had seen. Altogether, the set is beautifully published, with quality printing, good photos, and solid binding. At $90 for the set, it's a real bargain.

■ **NICK KANAS** is a professor emeritus at the University of California, San Francisco, and a Fellow of the Royal Astronomical Society. He's been an amateur astronomer for more than 60 years. We reviewed his book *Star Maps* in the August issue.

 by David Billesbach & Timothy Arkebauer

What Does Your Lawn Think of a Solar Eclipse?

This month, a total solar eclipse will grace the skies of Chile and Argentina. Humans won't be the only lifeforms that take notice.

▲ **GROUND CRESCENTS** Eclipse chasers are familiar with the crescent shadows that foliage can cast during the partial phases of an eclipse. But does the foliage react to the eclipse, too?

MABEL LOOMIS TODD / *TOTAL ECLIPSES OF THE SUN* 1894

People lucky enough to have witnessed a total solar eclipse will tell you what an awesome experience it was and how profoundly affected they were. We humans notice these things and attach a lot of meaning to them. Animals are also acutely aware of solar eclipses. The rapid darkening in the middle of a day can set them on edge. Pets will act confused and sometimes frightened, and livestock will often think that it's evening feeding time in the middle of the day. Birds will start singing their evening songs.

But how do plants perceive an eclipse? What about the elm tree in your yard or the tomatoes in your garden? Do they notice?

During the August 21, 2017, total solar eclipse, we had a unique opportunity to find out. We study how plant communities interact with the atmosphere, the groundwater, and sunlight in a variety of ecosystems. One of our study sites is located in the vast grassland known as the Nebraska Sandhills, very near to where the annual Nebraska Star Party is held. And, luckily for us, this site lay right in the path of totality.

At the site, we have instruments that measure how much CO_2 and water vapor are exchanged between the atmosphere and the vegetation, as well as how much solar energy falls on the surface and heats the air and warms the soil. The amount of CO_2 exchanged between the atmosphere and the soil/plant community is called the *flux* of CO_2. Plants use energy in the visible part of the solar spectrum to "fix" CO_2 from the atmosphere into carbohydrates; that's the basics of photosynthesis. Typically, this process dominates the CO_2 exchange in daytime, and the value for the CO_2 flux is negative — think of it as the plants eating CO_2 from the atmosphere. At night, plant and soil respiration dominates the exchange, and the value is positive. We reasoned that this process should be very sensitive to the eclipse, since it's powered by sunlight.

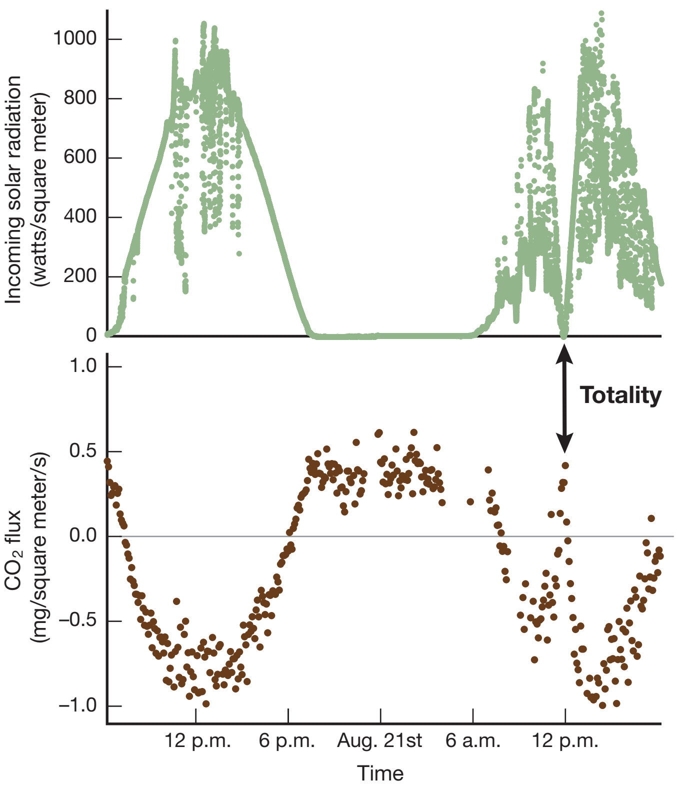
To directly tie the CO_2 flux to the eclipse, however, we needed to also track the change in sunlight. That we did with our radiation sensor, which measures how much solar energy falls on every square meter of surface per second. We decided that together, these two measurements would tell us how plants "see" an eclipse.

The Results

We can measure solar radiation at a fast rate, but to obtain a representative CO_2 flux, we have to average our measurements over several minutes. We chose an averaging time of 5 minutes, which is long compared to the duration of totality at our site (about 90 seconds), but it was the best that we could reasonably do.

On the day of the eclipse, we anxiously watched clouds come and go at our eclipse party in Lincoln. We were rewarded by a break in the clouds just before totality and got to see the spectacle of a lifetime. Afterward, we were eager to see what our instruments had recorded 300 miles away. After recovering the raw data and processing it, we found that we indeed had recorded the response of plants to a total solar eclipse.

In the figure below, our data show the expected drop in sunlight during the eclipse, and the response of the plants via their CO_2 flux. The first thing to notice is that the very noisy radiation plot indicates that there were a lot of small clouds passing across the Sun both before and after totality. The timing of these passing clouds shows that, as in Lincoln, we were lucky to have clearing skies at just the right time. Looking at the CO_2 flux, we see that the plants did indeed respond to the decreasing sunlight by reducing their intake of CO_2 from the atmosphere. The sharp upward flux spike in the afternoon is unmistakable, and it coincides perfectly with the eclipse outlined in the radiation plot.



▲ **HOW PLANTS REACT** These plots record the solar radiation that hit the grass *(top)* and the carbon dioxide the plants "ate" *(bottom)*. Negative CO_2 flux is when plants remove the gas from the air to photosynthesize. During the solar eclipse, vegetation at the test site stopped drawing CO_2 from the air, as though it were nighttime.

THE AUTHORS (2)

▲ **THE EXPERIMENT** The authors' setup in the grass-covered dunes of western Nebraska. The horizontal bar on the left tower supports the radiation sensors; the right tower holds the gas and wind sensors.

To confirm that these results were real, we looked at another of our sites, in central Oklahoma. There, the Sun was about 85% covered, and we saw similar results. In fact, almost every instrument at both sites responded to the eclipse in some way.

So what did we learn from this? First, we can see that the plants responded very quickly and continuously to the decrease, then increase, in sunlight throughout the eclipse. Second, because the CO_2 flux moved to the same positive value as it had the night before, we can tell that the plants completely stopped taking in CO_2 at totality. This is exactly what we expected to happen, and we're very pleased with the outcome.

In the future, we hope to delve more deeply into our data set to learn about other effects that may be present in the plant response. While we aren't able to travel with our instruments to this December's total solar eclipse in Chile and Argentina, we're sure that the people, animals, and plants there will be just as affected as we were.

■ **DAVE BILLESBACH** is a "misplaced" physicist who studies ecosystem-atmosphere interactions at the University of Nebraska. He's been an amateur astronomer and telescope maker since the age of 12. **TIM ARKEBAUER** is a plant physiologist at the University of Nebraska. He's interested in plant-water relations, leaf and canopy gas exchange, and remote sensing.

For more information about the science that the authors do, check out https://ameriflux.lbl.gov.

Measuring the Stars

Here's how you can contribute to the science of astronomy.

Light from the stars reveals their secrets. Gazing at the sky may satisfy our romantic impulses. But when we ask hard questions — What are the stars? How hot? How old? What are they made of? How far away are they? — simply gazing at them is not enough. To learn about them, we need to look at their light analytically.

One way we can answer some of these questions is through the process of *photometry*. This is the art and science of measuring brightness radiated by astronomical objects — a pursuit that a growing number of amateur astronomers is undertaking from backyards, rooftops, balconies, and observatories all over the world. As a science, many amateur astronomers today apply photometry to the study of the most interesting stars: variable ones that change in brightness. Here's how you can get involved and contribute valuable science yourself.

Analyzing Starlight

These days, we can accurately measure the magnitudes of stars by recording them with digital cameras equipped with CCD or CMOS detectors. These detectors consist of an array of millions of tiny photodiodes packed into a convenient chip package. The camera body provides a safe and clean environment for the light-sensitive chip. It also contains electronics to power the chip, scan its array, and return a digital signal representing the image that fell on the chip.

To capture an image, the telescope focuses light on the sensor in the camera. Although CCDs and CMOS work somewhat differently, the process begins the same way. The camera clears stray charge from the photodiode elements. The chip is then ready to receive photons. During the exposure, photons strike the sensor, generating electrons. When the exposure ends, each photodiode in the array holds a number of electrons proportional to the number of photons that fell on it.

The camera then converts these stored electrons into a digital signal and streams it back to the computer. The computer adds information about the image, such as the width and height of the array, the date, time, length of exposure, as well as any other information needed to document the observation. It then saves the data as a FITS file (a standard astronomical file format).

Calibration Is Key

One fundamental problem we face in making accurate measurements of starlight is that every photodiode on a sensor is slightly different from every other photodiode. These differences are small but measurable. Once captured in an image, the signal coming from a photodiode is called a pixel (short for "picture element"). As captured in a raw image, a pixel might be a fraction of a percent more sensitive than its

COUNTING PHOTONS Recording the brightness of stars can be easy, particularly when using modern equipment. Author Richard Berry is seen capturing light from distant stars in his backyard observatory in rural Oregon.

ALL IMAGES COURTESY OF AUTHOR UNLESS OTHERWISE NOTED neighbor, be more affected by noise, or respond to the chip's temperature a bit differently. The key to making scientifically accurate images is to map these small flaws and correct them.

How is this done? First, we need to quantify all the flaws in the detector. This is accomplished by recording and applying images known as calibration frames, commonly referred to as *dark frames* and *flat-field images*.

Dark frames are maps of the small electric current known as *dark current* that accumulates even when no light is striking the photodiode. They also record the fixed-pattern noise signal from the sensor. Dark frames are created by covering the telescope or closing the camera's shutter and recording an image with the same duration and at the same temperature as the light images you make of your target stars.

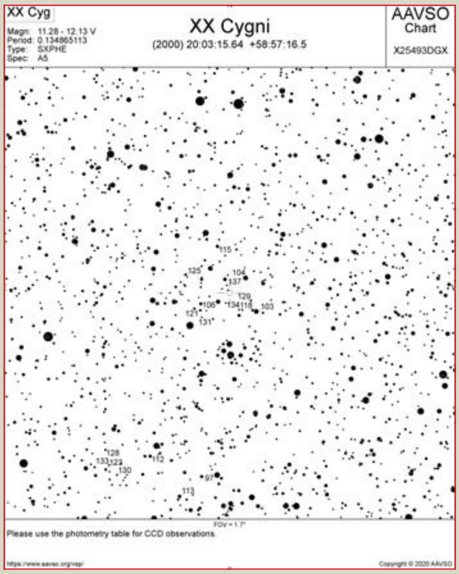
Because dark current varies randomly, we need to take many dark frames and average them together. If I were planning to record 5-minute exposures of my target, I'd also take a few dozen 5-minute dark frames.

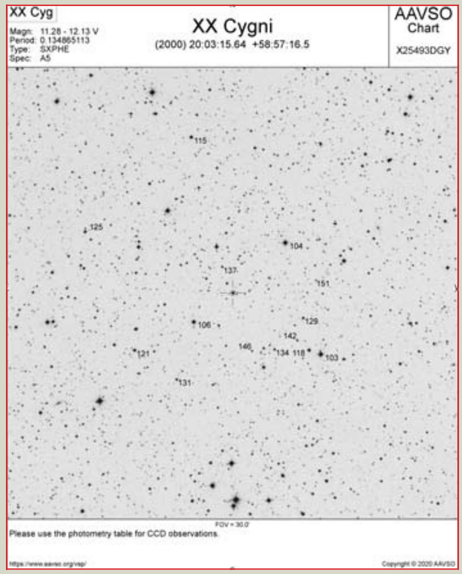
The other calibration frame is a flat-field image. This records each photodiode's sensitivity to light, as well as any variations in the optical train of your telescope, including vignetting or dust motes on any optical element in the light path that can slightly skew the measured result. Typically, these are images of the twilight sky or a uniform light source, such as an electroluminescent panel. Flat-field images also require their own dark frame calibration, which you take using the same exposure you used for the flat frame. These are called dark-flat frames, or sometimes flat darks.

To beat down random variations in these images, an observer typically records multiple dark, flat, and flat-dark frames and then averages each of the results to produce low-noise "master" dark and flat frames.

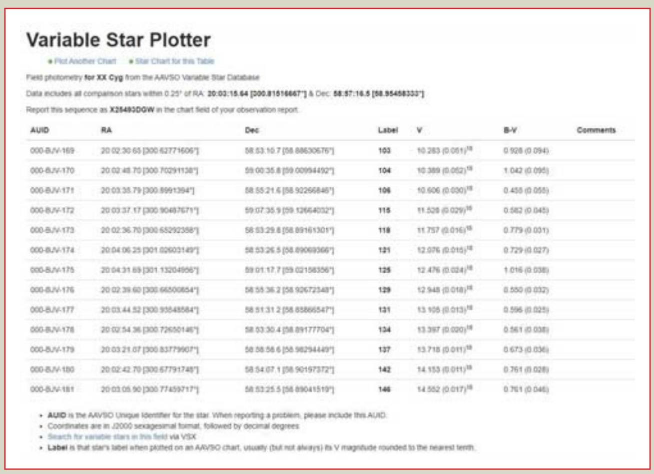
After a night of imaging, you typically open the images of your target stars in your preferred astronomical imaging program. Depending on your camera, the images may look a bit noisy and mottled with "donut"-shaped dark areas. You then apply your master calibration frames — subtracting the master dark frame to remove dark current, then dividing it by the master flat-frame to

▲ **SIMPLE SETUP** Most any telescope and camera combination on an accurate tracking mount will produce excellent photometric data.





▲▶ **QUICK CHART** *Above:* The Variable Star Plotter on the AAVSO website (**aavso.org/apps/vsp**) produces finder charts for known variable stars to help you pinpoint your target. *Above right:* Using the advanced options, you can also create a chart with DSS (Palomar Sky Survey) images, as well as produce a table of suitable comparison stars in a specified field seen at right.



Variable Star Plotter

• Plot Another Chart • Star Chart for this Table

Field photometry **for XX Cyg** from the AAVSO Variable Star Database

Data includes all comparison stars within 0.25° of RA: **20:03:15.64 [300.81516667°]** & Dec: **58:57:16.5 [58.95458333°]**

Report this sequence as **X25493DGW** in the chart field of your observation report.

AUID	RA	Dec	Label	V	B-V	Comments
000-BJV-169	20:02:30.65 [300.62771606°]	58:53:10.7 [58.88630676°]	**103**	10.283 (0.051)[15]	0.928 (0.094)	
000-BJV-170	20:02:48.70 [300.70291138°]	59:00:35.8 [59.00994492°]	**104**	10.389 (0.052)[15]	1.042 (0.095)	
000-BJV-171	20:03:35.79 [300.8991394°]	58:55:21.6 [58.92266846°]	**106**	10.606 (0.030)[15]	0.455 (0.055)	
000-BJV-172	20:03:37.17 [300.90487671°]	59:07:35.9 [59.12664032°]	**115**	11.526 (0.029)[15]	0.582 (0.045)	
000-BJV-173	20:02:36.70 [300.65292358°]	58:53:29.8 [58.89161301°]	**118**	11.757 (0.016)[15]	0.779 (0.031)	
000-BJV-174	20:04:06.25 [301.02603149°]	58:53:26.5 [58.89069366°]	**121**	12.076 (0.015)[15]	0.729 (0.027)	
000-BJV-175	20:04:31.69 [301.13204956°]	59:01:17.7 [59.02158356°]	**125**	12.476 (0.024)[15]	1.016 (0.038)	
000-BJV-176	20:02:39.60 [300.66500854°]	58:55:36.2 [58.92672348°]	**129**	12.948 (0.018)[15]	0.550 (0.032)	
000-BJV-177	20:03:44.52 [300.93548584°]	58:51:31.2 [58.85866547°]	**131**	13.105 (0.013)[15]	0.596 (0.025)	
000-BJV-178	20:02:54.36 [300.72650146°]	58:53:30.4 [58.89177704°]	**134**	13.397 (0.020)[15]	0.561 (0.038)	
000-BJV-179	20:03:21.07 [300.83779907°]	58:58:58.6 [58.98294449°]	**137**	13.718 (0.011)[15]	0.673 (0.036)	
000-BJV-180	20:02:42.70 [300.67791748°]	58:54:07.1 [58.90197372°]	**142**	14.153 (0.011)[15]	0.761 (0.028)	
000-BJV-181	20:03:05.90 [300.77459717°]	58:53:25.5 [58.89041519°]	**146**	14.552 (0.017)[15]	0.761 (0.046)	

- **AUID** is the AAVSO Unique Identifier for the star. When reporting a problem, please include this AUID.
- Coordinates are in J2000 sexagesimal format, followed by decimal degrees.
- Search for variable stars in this field via VSX
- **Label** is that star's label when plotted on an AAVSO chart, usually (but not always) its V magnitude rounded to the nearest tenth.

correct non-uniformities in the chip and the telescope optics. The resulting calibrated image consists of millions of pixels corrected for the sensor's quirks and foibles. Each pixel in the image becomes a reasonably faithful record of the light that fell on the corresponding photodiode at the focus of your telescope. Photometrists refer to properly calibrated images as "science frames."

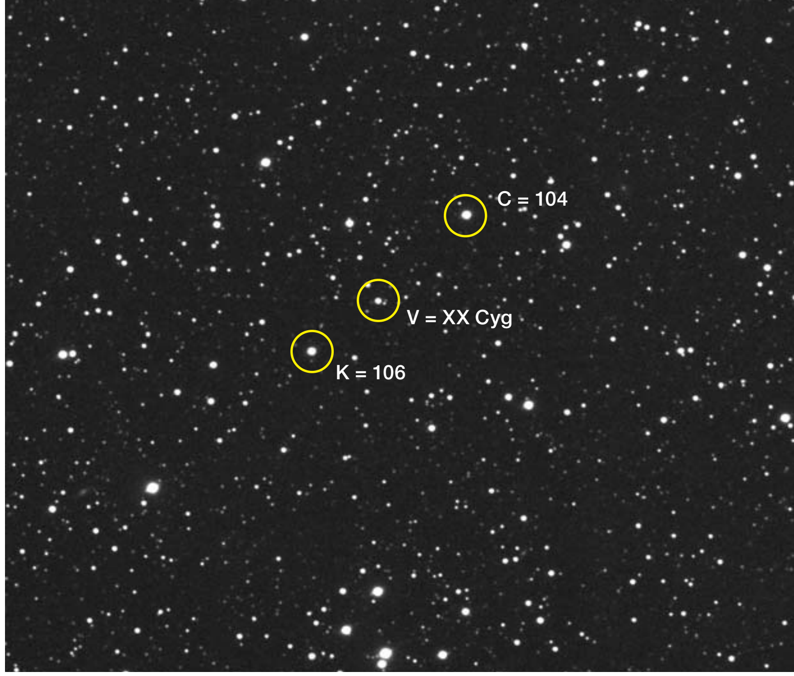
Astronomers Use Filters

Color is integral to astronomy. The eye sees a narrow range of wavelengths centered at 555 nanometers, in the yellow/green, but stars radiate over a wide range of wavelengths depending on their energy output, temperature, and chemistry. To limit what wavelengths the camera sees, we place carefully defined color filters ahead of the image sensor.

Color filter photometry gave birth to one of the most powerful tools astronomers use: the *Hertzsprung-Russell* diagram. The diagram shows the absolute magnitude, measured through a V-filter, against the color, measured via the difference between V-filter and B-filter magnitudes, for a range of stars. By plotting an individual star on this diagram, you can glean its relative redness or blueness, clues to its temperature and spectral class. Color photometry reveals which stars are main sequence, blue giants, red giants, red dwarfs, and white dwarfs, and where our Sun fits among them.

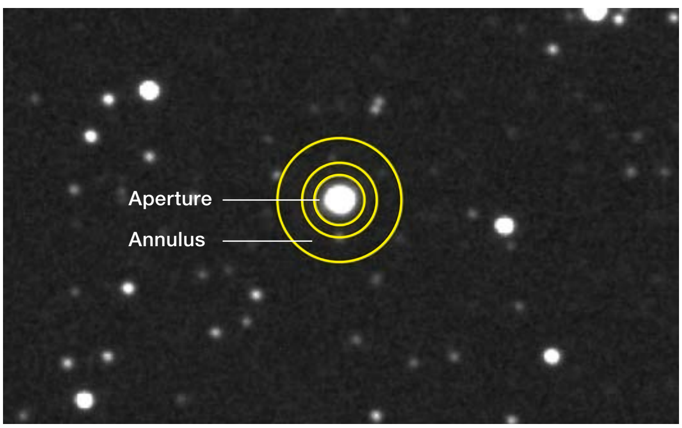
Measuring Magnitudes

So you have a science image filled with stars. How do you extract the magnitude of a star from an image? Fortunately, most good astronomical image-processing software includes tools to measure the magnitudes of stars. After loading your image into your preferred program, the first task is setting the radii of the measurement tool that you will use to extract magnitude measurements. You can use any star for this. The tool typically has three radius settings. The innermost is the *aperture*. This should be set to fit tightly around the star you are studying but without cutting off its edges, ideally containing at least 90% of the target stars light. The aperture contains the combined light of the star and its sky background. The second and third radii define an *annulus* (or "donut") of sky surrounding the star image. The inner radius of the annulus must be larger than the aperture radius, leaving a gap. The outer annulus radius should be big enough to include a good amount of sky, but small enough to exclude any nearby bright stars. The annulus is used to measure the sky brightness.

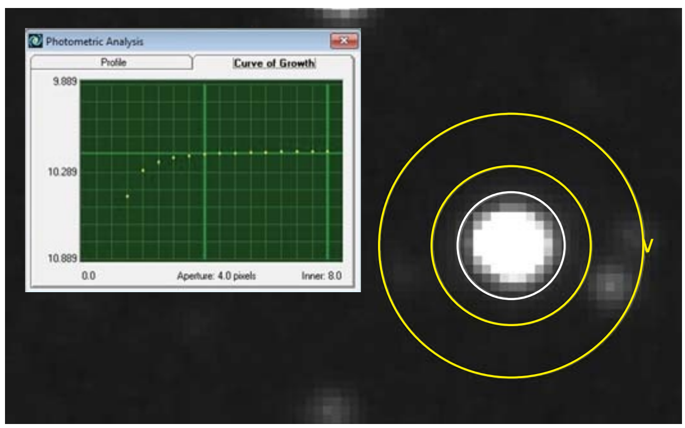


▲ **DIFFERENTIAL PHOTOMETRY** XX Cygni (center) is a variable with a 3.23-hour period that you can easily monitor throughout an entire cycle in a single evening. The two circled stars at upper right and lower left are the comparison star and "check" star (see page 64). If the photometry has been done correctly, the variable will change while the others do not.

▼ **APERTURE IS KEY** To measure a star's brightness, we measure a star as well as the surrounding sky. The area inside the inner ring or *aperture* measures the combined sky plus star brightness, while the middle and outer rings define a "donut" or *annulus* of the sky by itself. Software then subtracts the annulus measurements from the aperture to produce the total pixel sum and the instrumental magnitude of the target star.



▼ **APERTURE ADJUSTMENTS** Users of *AIP4WIN* can use the Curve of Growth tab in the Photometric Analysis tool to fine-tune the aperture radius setting. This graph displays the instrumental magnitude of the star image versus the radius of the aperture. If the aperture is set too small, it doesn't measure all of the star's light. If the aperture is set too large, it includes unnecessary sky. In this example, the instrumental magnitude becomes asymptotic at 4.0 pixels, meaning a 4-pixel aperture radius is the proper radius setting for this star.



Photometric Filters

From the cool red (*M*) stars to hot blue (*B*) stars, the intensity of starlight varies with wavelength. The job of photometry is to measure light in defined wavelength ranges. Astronomers use filters to control what wavelengths they measure. Photometry began using the eye as a light sensor; now, a visual magnitude estimate reflects the star's brightness at approximately 555 nm (yellow/green), with little input from the blue and red ends of the spectrum.

Unfiltered Photometry

Filters are not always necessary when performing photometric observations. Astronomers carry out some types of observations with a clear filter or no filter at all. A filter is not crucial when we observe eclipsing binary stars and pulsating stars to find the time of minimum or maximum light, or to characterize timing and periodicities in the light of cataclysmic variables.

Single-Filter Photometry

CCD and CMOS sensors respond to a wide range of wavelengths. To approximate the response of the eye, the Johnson-Cousins V filter is the single filter of choice. This filter's transmission peaks at 545 nm (yellow/green), nearly the same as the peak sensitivity of the eye.

Johnson-Cousins UBVRI Filters

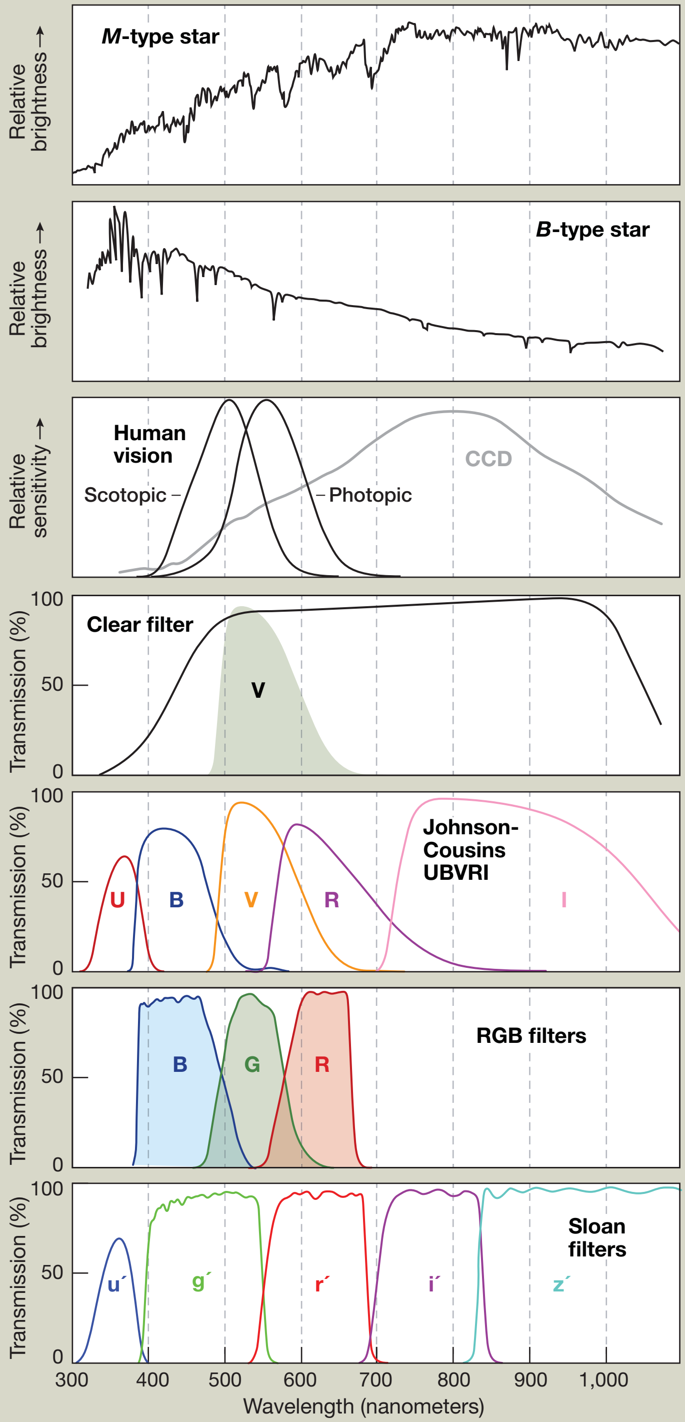
The classic UBV filters have a long history in astronomy. For amateur astronomers today, a Johnson-Cousins UBVRI filter set is a good choice. Since a full set can be expensive, many amateurs start with two: V and B. You can add I and R filters later and skip the U filter entirely. Magnitudes transformed to the UBV system enable astronomers to model the physical properties of the star or object observed.

Tricolor RGB Filters

Although photometrists prefer V filters, you *can* use a tricolor green filter instead of a V filter if you must. Just be sure to use the tricolor green (TG) filter designation when you report the magnitude.

Sloan Filters

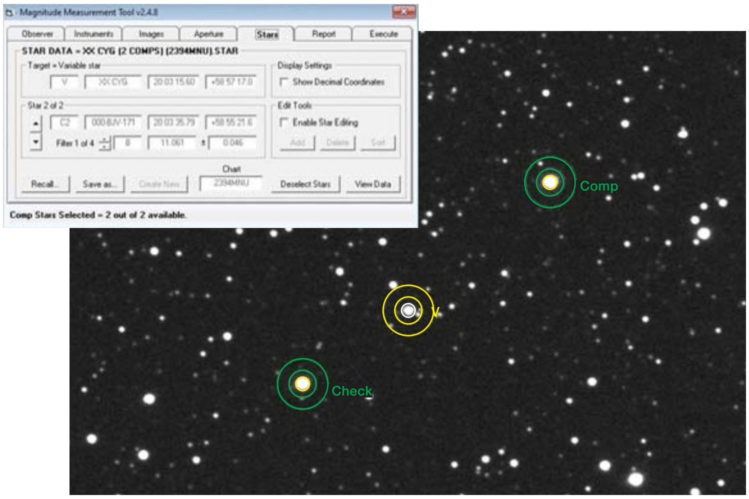
The latest additions to the photometrist's wish list are Sloan filters. The system comprises five color bands – u′, g′, r′, i′, and z′. They divide the wavelength range from the atmospheric ultraviolet cutoff at 300 nm to the sensitivity limit of silicon sensors at 1,100 nm into five non-overlapping passbands.



LEAH TISCIONE / S&T

With the radii set, click on a star you wish to measure. The computer surveys the pixels near your click point, finds the brightest ones, and computes a preliminary center for the star image. From that location, an algorithm decides which pixels contain starlight and which do not. It finds the weighted "center of gravity" of the star pixels and finds the exact center of the star image: its centroid.

The aperture you chose appears as a circle with its center aligned at the centroid, surrounded by the inner and outer annulus radii. The software then gets to work counting the



▲ **BATCH PROCESSING** Every serious photometry program includes batch processing to measure many images with just a few clicks. This window shows the Stars tab of the Magnitude Measurement Tool in *AIP-4WIN*. Here you mark the star you intend to perform photometric measurements on (V), the comparison star, (C1), and the check star (C2). This tool computes the exact time of mid-exposure in each image, converts it into Heliocentric Julian Date (the standard time format for photometric data), adds the air mass, saves the instrumental magnitudes of the stars, and writes it in formats favored by the AAVSO and other institutions.

number of pixels inside the aperture radius and finds the sum of those pixels. Next, it surveys all the pixels in the annulus. The average value of the annulus pixels is close to the sky brightness, though not exactly because the annulus often includes a few faint stars. The program may take the median value of the annulus pixels, or it may apply a more complex algorithm to find an accurate sky brightness.

The computer's final step in the process is to subtract the light from the background sky. The trick is this: The computer found the total pixel value in the aperture (star plus sky) and also counted the number of pixels in the aperture. It multiplies the sky background value by the number of aperture pixels, then subtracts the sky total from the star *plus sky* total. The result is the total pixel value of the star image with no sky light.

Our end goal isn't a brightness in pixel values, but rather a brightness in the logarithmic scale of stellar magnitudes. The magnitude equation $m = -2.5 \log_{10}(S)+Z$, converts the linear pixel value sum to an instrumental magnitude, m. In the equation, S is the signal, the sum of star pixels, and Z is the zero-point constant. The zero-point constant is determined by observing standard stars to produce a reasonable apparent magnitude value.

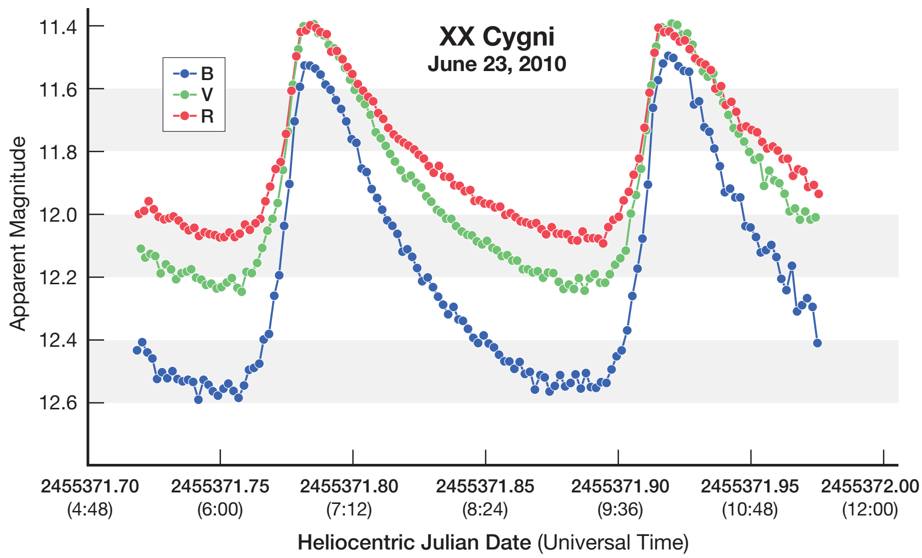
Photometry Made Easy

Differential photometry is the "sweet spot" for amateur astronomers, and my preferred method for as long as I have been doing photometry. This technique measures a star's brightness relative to a nearby comparison star of known magnitude. For many observing programs, you can ignore atmospheric extinction and transforming instrumental magnitudes into standard magnitudes. Best of all, differential photometry is a great way to get started doing photometry.

Visiting the American Association of Variable Star Observers (AAVSO) observer page (**aavso.org/observers**), you'll find extensive advice about choosing variable star observing programs. Fair warning: It can be overwhelming! But as an example, let's focus on just one star, one of my favorites: **XX Cygni**. It's a pulsating SX Phe star, with a 3.23-hour period and an amplitude of 0.85 magnitude, and it varies enough to see visually in a telescope. You can observe an entire cycle or more in just one night, and for northern observers, it's high in the sky in summer through late autumn. (A fast variable during the winter months is BL Camelopardis.)

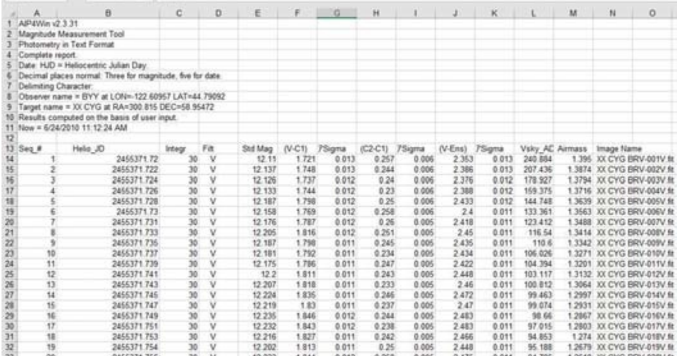
Making a series of variable star observations is just like making sub-exposures for a stacked deep-sky image. For this work, you can use a CCD or CMOS camera (including DSLR and mirrorless models). Be sure to take matching dark and flat frames, or use library master darks and flats to calibrate the images. On each image, extract the instrumental magnitudes of the variable (V), the comparison star (C1), and the "check" star that serves as a second comparison (C2). (The XX Cygni figure on page 61 shows the AAVSO star chart and an image from a time series.)

Enter the time each image was made, along with the V, C1, and C2 magnitudes into a spreadsheet program. To find differential magnitude, place the difference between the variable and comparison star in one column and the difference between the check star and the comp star in the other. When you plot them on a graph, the XX Cygni plot rises and



▶ **FINAL CURVE** The repeating cycle of the star's brightness variability becomes clear after graphing the value for XX Cygni in a series of B, V, and R images. This observing campaign spanned roughly 6 hours, resulting in 135 magnitude measurements with each filter.

XX CYGNI GRAPH: LEAH TISCIONE / S&T


AIP4Win v2.3.31
Magnitude Measurement Tool
Photometry in Text Format
Complete report.
Date: HJD = Heliocentric Julian Day
Decimal places normal: Three for magnitude, five for date.
Delimiting Character:
Observer name = BYY at LON=-122.60957 LAT=44.79092
Target name = XX CYG at RA=300.815 DEC=58.95472
Results computed on the basis of user input.
Now = 6/24/2010 11:12:24 AM

Seq_#	Helio_JD	Integr	Filt	Std Mag	(V-C1)	?Sigma	(C2-C1)	?Sigma	(V-Ens)	?Sigma	Vsky_AC	Airmass	Image Name
1	2455371.72	30	V	12.11	1.721	0.013	0.257	0.006	2.353	0.013	240.884	1.395	XX CYG BRV-001V.fit
2	2455371.722	30	V	12.137	1.748	0.013	0.244	0.006	2.386	0.013	207.436	1.3874	XX CYG BRV-002V.fit
3	2455371.724	30	V	12.126	1.737	0.012	0.24	0.006	2.376	0.012	178.927	1.3794	XX CYG BRV-003V.fit
4	2455371.726	30	V	12.133	1.744	0.012	0.23	0.006	2.388	0.012	159.375	1.3716	XX CYG BRV-004V.fit
5	2455371.728	30	V	12.187	1.798	0.012	0.25	0.006	2.433	0.012	144.748	1.3639	XX CYG BRV-005V.fit
6	2455371.73	30	V	12.158	1.769	0.012	0.258	0.006	2.4	0.011	133.361	1.3563	XX CYG BRV-006V.fit
7	2455371.731	30	V	12.176	1.787	0.012	0.26	0.005	2.418	0.011	123.412	1.3488	XX CYG BRV-007V.fit
8	2455371.733	30	V	12.205	1.816	0.012	0.251	0.005	2.45	0.011	116.54	1.3414	XX CYG BRV-008V.fit
9	2455371.735	30	V	12.187	1.798	0.011	0.245	0.005	2.435	0.011	110.6	1.3342	XX CYG BRV-009V.fit
10	2455371.737	30	V	12.181	1.792	0.011	0.234	0.005	2.434	0.011	106.026	1.3271	XX CYG BRV-010V.fit
11	2455371.739	30	V	12.175	1.786	0.011	0.247	0.005	2.422	0.011	104.394	1.3201	XX CYG BRV-011V.fit
12	2455371.741	30	V	12.2	1.811	0.011	0.243	0.005	2.448	0.011	103.117	1.3132	XX CYG BRV-012V.fit
13	2455371.743	30	V	12.207	1.818	0.011	0.233	0.005	2.46	0.011	100.812	1.3064	XX CYG BRV-013V.fit
14	2455371.745	30	V	12.224	1.835	0.011	0.246	0.005	2.472	0.011	99.463	1.2997	XX CYG BRV-014V.fit
15	2455371.747	30	V	12.219	1.83	0.011	0.237	0.005	2.47	0.011	99.074	1.2931	XX CYG BRV-015V.fit
16	2455371.749	30	V	12.235	1.846	0.012	0.244	0.005	2.483	0.011	98.66	1.2867	XX CYG BRV-016V.fit
17	2455371.751	30	V	12.232	1.843	0.012	0.238	0.005	2.483	0.011	97.015	1.2803	XX CYG BRV-017V.fit
18	2455371.753	30	V	12.216	1.827	0.011	0.242	0.005	2.466	0.011	94.853	1.274	XX CYG BRV-018V.fit
19	2455371.754	30	V	12.202	1.813	0.011	0.25	0.005	2.448	0.011	95.188	1.2679	XX CYG BRV-019V.fit

▲ **ASSEMBLED DATA** Magnitude data from variable star measurements are submitted to organizations such as the AAVSO and other institutions that collect, curate, and serve variable star data to astronomers both amateur and professional. The data in this form was used to produce the light curve on the facing page.

falls while the check star plot remains flat. The beauty of this method is that atmospheric extinction is nearly the same for all three stars and cancels out.

For some historical context, search online for "astronomy XX Cygni" to learn how the Harvard astronomer Harlow Shapley made light curves for this star in 1914 and 1915, and see how many other astronomers have studied its slowly changing period of variation.

Correcting Atmospheric Extinction

We Earth-bound observers view stars through our planet's atmosphere: It acts as a filter, blocking fractions of the star's light at different wavelengths. The loss is called extinction. In differential photometry, the V star, C1, and C2 suffer nearly equal extinction, so it largely cancels out. However, if your goal is to obtain an accurate magnitude for a star, you must measure the extinction every night and compensate for it.

Astronomers call the depth of atmosphere between the target and the telescope *air mass*. Straight overhead, the air mass equals 1, or one atmospheric thickness. At 45° from the zenith, starlight passes through 1.4 air masses, and at 60° the air mass reaches 2. Photometrists prefer to avoid working through an air mass greater than 2.5. Many camera-control programs embed the computed air mass in each image's FITS header.

The observing procedure to measure extinction is simple: As the evening progresses, you measure the instrumental magnitudes of two stars, one rising and the other setting. As the eastern star rises, it brightens; stars in the west dim as they set. Performing this measurement once an hour is often enough. At the end of the night, plot a graph of instrumental magnitude versus the air mass. On a clear night, the plot should be a straight line. The slope of a best-fitting line through the points tells you how much extinction occurs for each air mass — the extinction coefficient — which is typically around 0.2 magnitudes per air mass for a V filter. Corrections get a bit more complicated for very red and very blue stars, where you may encounter non-linear effects.

To correct for extinction, you subtract the air mass of the star times the extinction coefficient from the instrumental magnitude. That gives the star's magnitude at zero air mass – outside Earth's atmosphere. Extinction coefficients at high altitude observatories are smaller than those in humid, hazy, and low-altitude continental observing sites, which also often change from night to night.

Transformation to Standard Magnitude

Quite often the goal in photometry is to produce a standard magnitude that can then be compared directly to the magnitudes measured at any other observatory with any other telescope and camera. Just as correcting for atmospheric extinction removes the effects of a star's location in your sky, transformation to the standard magnitude system corrects the instrumental signature of your telescope and camera. But even though you may be using a set of Johnson-Cousins UBVRI or Sloan filters, minor variations in the filters you use, or the wavelength sensitivity of your camera's sensor, will introduce small mismatches.

The solution is similar to that for atmospheric extinction: Observe a set of diverse standard stars that have carefully determined U, V, B, R, and I (or Sloan) magnitudes, then determine linear equations that transform your extinction-corrected instrumental magnitudes to the standard system. You first determine the transform coefficients and zero-point for each filter you are using. To do this, image one of several open clusters (such as M67 or M11) or standard fields, then extract the instrumental magnitudes. The AAVSO provides complete instructions and software for recording standard fields, as well as generating coefficient values and applying transforms.

Get Involved

You'll want to get your feet wet with an observing program of differential photometry as you gain confidence in your newfound knowledge of this rewarding branch of astronomy. Photometry is an excellent pursuit on bright moonlit nights. As you get deeper into it, every night offers an opportunity to find something quite unexpected, as well as the satisfaction of knowing that you're making a real contribution to astronomy.

■ **RICHARD BERRY** is a long-time telescope maker, astrophotographer, and member of the AAVSO.

FURTHER READING:

The Handbook of Astronomical Image Processing by Richard Berry and James Burnell (**willbell.com/aip/index.htm**). Written for amateur astronomers and includes a copy of *AIP4WIN* PC software.

The Sky Is Your Laboratory: Advanced Astronomy Projects for Amateurs by Robert Buchheim (**https://is.gd/skylab**). Advice and projects on observing and performing photometry.

To Measure the Sky: An Introduction to Observational Astronomy by Frederick R. Chromey (**https://is.gd/measurethesky**). An undergraduate college astronomy laboratory textbook.

The AAVSO Guide to CCD Photometry (**aavso.org/ccd-camera-photometry-guide**). A practical guide to getting started.

The Unistellar eVscope

Does this little reflector live up to the claim "100× more powerful than a regular telescope"?

▲ Unistellar's eVscope is no ordinary Newtonian reflector. It offers "enhanced vision" views of deep-sky objects by taking long-exposure digital images and displaying them both in the eyepiece and on the screen of a smartphone or tablet connected via Wi-Fi.

Unistellar eVscope

U.S. Price: $2,999 plus shipping.
unistellaroptics.com

What We Like

Ease of setup and use

Excellent image quality

Extensive manual control

Citizen-science features

What We Don't Like

Glow in eyepiece barrel

Tiny camera sensor

Narrow field of view

LET'S BE HONEST: To the untrained eye, most celestial objects look unimpressive in a typical backyard telescope. Sure, there are exceptions, such as the Moon, bright planets, the (safely filtered) Sun; the most colorful double stars; and about as many showpiece star clusters, nebulae, and galaxies as you can count on your fingers and, if you're generous, your toes. But most of the deep-sky objects in celestial atlases and catalogs are not worth showing to our nonastronomer friends and neighbors, because the dim gray views in the eyepiece just can't compare with the bright colorful Hubble images the public has gotten used to seeing.

Unistellar, a crowd-funded startup with offices in Marseille, France, and San Francisco, California, has come up with a solution: the eVscope, or "enhanced vision" telescope. Advertised as "100× more powerful than a regular telescope," the eVscope — a mere 114-mm (4.5-inch) f/4 reflector — plainly shows the spiral arms of the Whirlpool Galaxy and the red glow of hydrogen gas and the dusty "pillars of creation" in the Eagle Nebula, even from a city.

The eVscope doesn't violate any laws of physics. But when you look into its eyepiece in "eV" mode, you're not looking at the photons collected by the optics, as you would in an ordinary instrument. Those have been intercepted by a sensitive digital camera and converted to a display on a small color screen — so you're looking at a long-exposure image. I was skeptical that this would feel anything like looking through a "normal" telescope. But when I pointed the unit that Unistellar loaned us at my first deep-sky target, turned on eV mode, and peered into the eyepiece, I surprised myself by jumping up and down and shouting like a little kid.

The eVscope also makes deep-sky astrophotography effortless and enables users — even those just getting started in astronomy — to make scientifically valuable observations. The more I used it, the more I came to appreciate what a game-changer it could be.

eVscope Inside & Out

You can tell at a glance that the eVscope is no ordinary reflector because the eyepiece is at the "wrong" end, near the altitude axis and primary mirror. That's a good thing, though, because it means the eyepiece position doesn't change a lot as the telescope points around the sky. Instead of holding a

▲ The eVscope's eyepiece is really a tiny OLED monitor.

ALL PHOTOS BY AUTHOR EXCEPT WHERE OTHERWISE NOTED diagonal mirror, the telescope's secondary obstruction houses the camera, which provides a true field of about 37 × 27 arcminutes with a pixel size of 1.7 arcseconds. The eyepiece view is circular as in regular telescopes, so it's almost — but not quite — wide enough to fit the entire full Moon.

Unistellar says the effective magnification of the eyepiece is 50×. That translates into an apparent field of about 25 degrees, comparable to an old Huygens ocular. It's a bit like looking down a tunnel, but the light you see at the end of that tunnel can be spectacular!

The telescope is attached to a single-arm alt-azimuth fork mount that incorporates drive motors, an onboard computer, and other electronics. There's no hand control, though — you communicate with the eVscope wirelessly using a smartphone or tablet running the *Unistellar* app, available for both iOS and Android devices. (I tested version 1.0.5, but by the time you read this, a major update to version 1.1 should be available.) What you see in the eyepiece is also displayed on your handheld device. I used both an iPhone 8s and a 4th-generation iPad.

The aluminum tripod is a premium model with a wide range of adjustment to accommodate observing while sitting or standing. The combined weight of the system is about 9 kg (20 lb).

Unistellar says the built-in rechargeable battery should last up to 10 hours. My summer nights were too short to test that in one go, but it seems about right since I could observe for several hours for several nights before needing to recharge the battery.

The removable plastic dust cap incorporates a detachable Bahtinov mask to aid in focusing the telescope, accomplished by rotating a ring behind the primary mirror. There are also collimating screws for use with a supplied wrench to make sure the mirror is properly squared with the camera. Instructions for collimating and focusing the telescope are included in a 12-page technical guide that comes in the box along with a handy quick-start guide. Additional instructions and answers to frequently asked questions are on Unistellar's website, which I found quite informative and where new tips are added regularly.

Getting Started

When you press a button on the fork arm to turn on the eVscope, a thin ring of faint red LED light comes on around the button's rim — a thoughtful touch to ensure no interference with dark adaption. Within a minute, the eVscope emits a Wi-Fi signal that you connect to as you would any other network via your smart device settings.

Next, launch the Unistellar app. It will indicate that you're connected to the eVscope with "Status: Operator." The app starts on the "eVscope" tab; you'll see an image display labeled "Live-View Mode & Sky Tracking Off." The word "On" should follow "Mode," because the camera is on, just not integrating — the displayed image is refreshing 20 to 30 times per second. Unistellar tells me this will be fixed in app version 1.1. As long as it's dark enough, you may already notice some stars on your device screen.

You'll also see a digital joystick with a yellow dot and four directional arrows. You drag the dot up or down and left or right to slew the telescope (the farther you drag it, the faster the motors turn), and you tap the arrows to nudge the scope a few arcminutes in any direction to center a target or, say, pan around the Moon. At startup, slew the telescope so it's pointing toward open sky about one-third of the way down from the zenith to the horizon. It doesn't matter which direction it's facing, though in twilight it helps to aim where it's darkest.

If the stars displayed on your handheld device aren't sharp, turn the focusing ring until they're as tiny as you can make them, or follow the instructions for using the Bahtinov mask. Then look into the eyepiece and turn its diopter adjustment ring until the stars look like points there too.

Next, tap the auto-alignment button next to the joystick — it looks like a reticle or gunsight. This launches one of the eVscope's most advanced features: autonomous field detection. The camera records an image and compares the star pattern against a celestial database to figure out exactly where it's pointed. This goes quickly because the software already knows your location and the current date and time thanks to the Global Positioning System (GPS) receiver in your smart device. Once

▶ The eVscope comes with a high-quality, lightweight, adjustable tripod. For an extra $349.00, you can get a foam-padded backpack made of the same material as computer bags. The backpack is too big for an airliner's overhead bin but easily fits in your car's back seat or trunk and makes light work of carrying the eVscope and tripod to your observing site. Other accessories include a dust cap, slotted Bahtinov focusing mask, eyepiece cover, charging cable and wall plug, quick-start guide and technical guide, and a set of tools in case anything needs adjustment or tightening.

synced to the sky, the app reports “Sky Tracking On.”


▲ *Left*: The eVscope’s tripod has a built-in bubble level. A disk on the bottom of the mount fits into the tripod ring and is secured with two large threaded knobs. *Right*: The back end of the eVscope tube includes a large, knurled ring that you turn by hand to focus the optics. Note the larger bump that serves as a reference point at the top of the ring. You can adjust the two collimating screws (left and top) if necessary with an included Torx wrench to square the primary mirror with the built-in digital camera.

Observing and Imaging the Deep Sky

The app’s “Explore” tab features a catalog of celestial targets from which to choose, based on your location and the current date. If you go to the settings within that tab, you can specify whether you’re observing from a city, a suburb, or the countryside; the target list then shortens or lengthens accordingly. It begins with recommended highlights such as Messier objects, then offers more choices grouped by category, including galaxies, nebulae, and clusters — which, for beginners’ sake, should be labeled “Star Clusters.” Unistellar says the full catalog contains many thousands of objects and is revised and updated regularly. Tapping on an object brings up some basic data about it and a few paragraphs of description. If you want to observe and photograph something that’s not listed, you can enter its coordinates manually.

Once you’ve picked a target, tap the “Go to” button. Quickly and quietly, the eVscope slews to the vicinity, takes a picture, and reports “Field detection in progress.” Once the software figures out how close it got, it commands the drive motors to make whatever adjustments are needed to center the target. Every deep-sky object I asked the eVscope to show me landed at or very near the center of the field.

Observations begin in live-view mode. What you see on your handheld device’s screen and in the eyepiece is not much to speak of: galaxies are indistinct smudges, and nebulae barely show up at all. But tap the “enhanced vision” icon — an eye with a star above it — wait a minute, and then look again. Now every galaxy is different: face-on spirals sport graceful spiral arms, and edge-on spirals are bisected by razor-thin dust lanes. Nebulae glow with distinctive reds, greens, and blues that you can see not only on your handheld screen, but also in the eyepiece. And you see not just the bright central parts that show up in a larger telescope (such as the 14-inch Schmidt-Cassegrain I used alongside the eVscope), but the faint outer reaches too. As long as you remain on a particular target, the image keeps improving as the eVscope and app “track and stack” successive exposures, automatically accounting for field rotation in the process. It takes only a few minutes to acquire a color astrophoto that anyone would be proud of.

As long as you’re in eV mode, you can save images on your device and/or send them to friends and family via text or email. There are two save options: the full image, or a circular crop with an overlay of the object’s name or coordinates, the exposure time, your location, and the date. I would have liked to have the exposure time, at least, saved with the full-frame images; unless you’re taking notes, the only way to keep track of it otherwise is to save a labeled circular image and then quickly change the setting and save an unlabeled rectangular version — something made more difficult than it should be with the app’s

▲ The eVscope is attached to a single-arm alt-azimuth fork mount with motors on both axes. The oval button near the bottom is the power switch, which glows dim red when the instrument is operating and flashes blue while the battery is charging.

▲ The base of the eVscope’s mount includes a small USB-C port for charging the built-in battery with a supplied cable and wall plug as well as a larger USB-A port to charge your smartphone or tablet using your own cable. The round disk fits into a flange on the tripod.

"Save image" button in a different tab and several taps away from the overlay's on/off toggle. In addition to the operator, up to 9 others can connect with "Status: Watcher" and save images on their own devices.

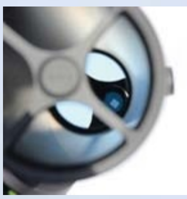
Both live-view mode and enhanced vision default to auto-exposure, but you can turn that off and make manual adjustments to gain (equivalent to ISO speed), exposure time, brightness, and contrast. This gives you wide latitude in fine-tuning the image quality, which advanced users will appreciate. I found it particularly helpful in adjusting the eyepiece image, which if left too bright illuminates the inside of the barrel, which Unistellar should consider roughening or flocking with felt or some other absorber/diffuser.

Citizen Science Made Easy

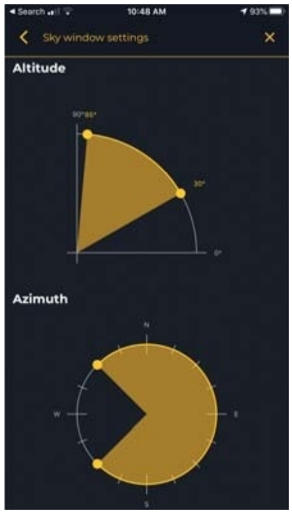
One of the features that distinguishes the eVscope is a close partnership between Unistellar and the SETI Institute. Franck Marchis, Senior Astronomer at the latter and Chief Scientific Officer at the former, has worked to ensure that eVscope users interested in contributing to astronomical research can do so as easily as they can take astrophotos. The partners envision having widely distributed observers capturing asteroid occultations and exoplanet transits, monitoring cometary activity, and recording supernovae and other transients. The Unistellar app includes a "Science" tab, but much of what's there is grayed out while development and beta-testing continue.

I asked Marchis if I could test the eVscope's citizen-science functionality. He responded by having a colleague send me step-by-step instructions for recording stellar light curves along with predictions for some upcoming exoplanet transits. The recipe was simple and clear, and on two successive nights I managed to record — via hours-long series of 3.95-second exposures — the passage of two different exoplanets in front of their host stars. One blocked 2.8% of its star's light, the other just 1.3% — the shallowest transit detected with an eVscope to date. And this with a 4½-inch telescope!

I had to download my eVscope image sequences from the onboard memory to my iPhone, then upload them to Unistellar. SETI Institute scientists did

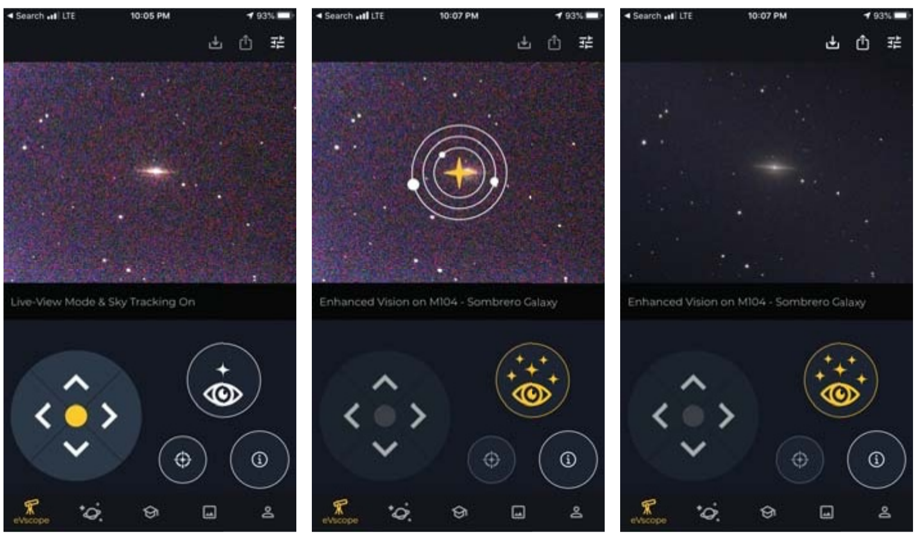



The 114-mm (4½-inch) f/4 primary mirror reflects incoming starlight not to a secondary mirror, but to a sensitive Sony IMX224 CMOS imaging sensor with 1,280 by 960 pixels, each 3.75 microns square (inset).



◄ In the app's Explore tab, you can specify which parts of the sky are accessible from your observing site and/or where you'd prefer not to observe to avoid looking through too much atmosphere. In this example, the eVscope is set to ignore targets below 30° altitude and in a range of western azimuths where, say, the view is blocked by tall trees or buildings. The app won't let you point within 5° of the zenith because alt-az Go To mounts have trouble adjusting their aim in this part of the sky.

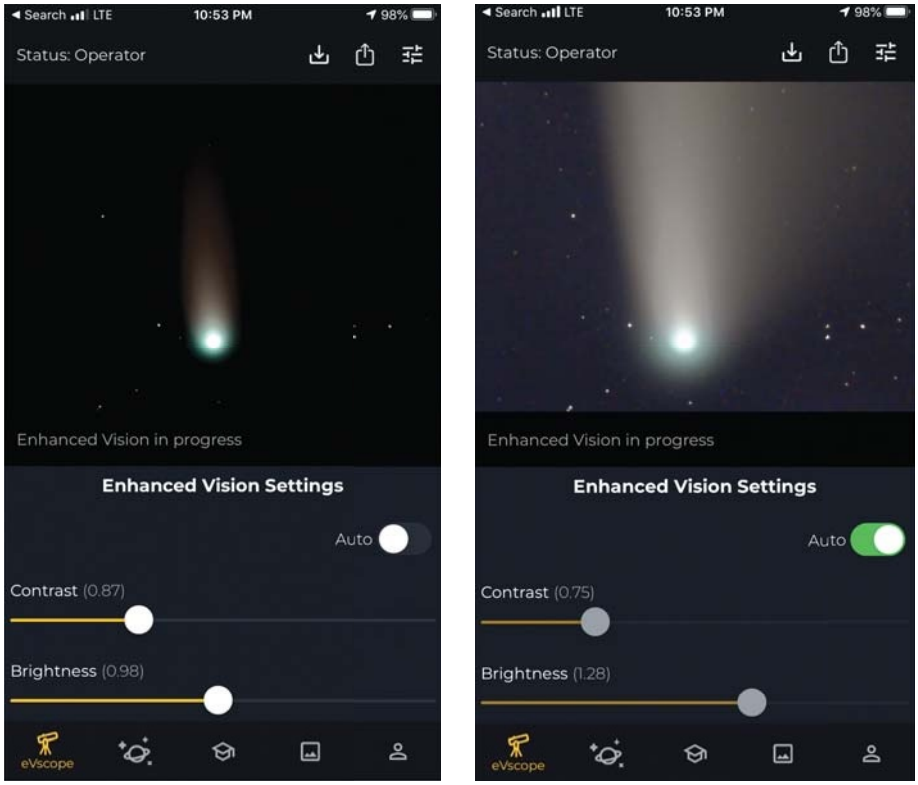
▼ *Left:* When you ask the eVscope to show you a celestial object — in this case M104, the Sombrero Galaxy in Virgo — it starts out in live-view mode, displaying a nonstop series of fraction-of-a-second exposures. The galaxy is much more obvious than it would be in an ordinary 4½-inch reflector, but it's not particularly attractive. *Middle:* Tap the eye-and-stars icon to launch enhanced-vision (eV) mode; you'll now see an animated display of planets orbiting a star while you wait for a several-second exposure to accumulate. *Right:* Once eV mode kicks in, you'll see a much better image that gets more spectacular as it coadds additional exposures. The image on your device screen can also be viewed in the eVscope's eyepiece.



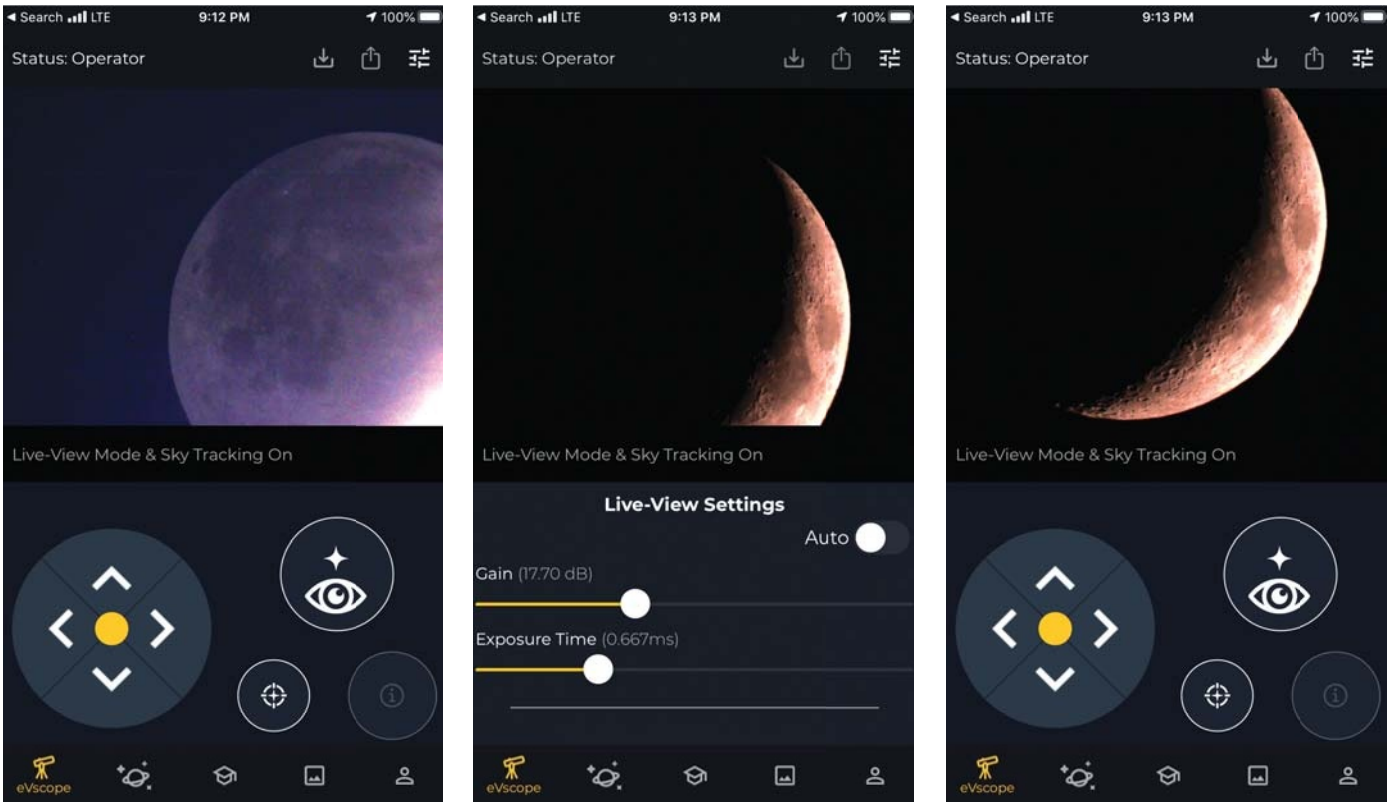
the processing and analysis and emailed me the results. In the works, I'm told, is an update that will give users two options: upload your image data to a server where all the processing will be done automatically, and/or transfer it to your own computer and process it yourself. I think most advanced amateurs, professionals, and science educators will prefer that second approach.

Concluding Thoughts

So, is the eVscope truly "100× more powerful than a regular telescope"? Yes, just as any regular telescope with a camera will produce images that show vastly more than you can see in the eyepiece. I've looked through 1-meter reflectors,



▶ Thanks to the ability to direct the eVscope to any celestial coordinates, the author zeroed in on Comet NEOWISE on July 20th. These screen grabs compare an auto-exposure image (far right) with another where the brightness and contrast were tweaked manually (near right).



▲ *Left:* The eVscope's auto-exposure software is optimized for faint deep-sky objects, so when you observe the Moon, the illuminated portion is severely overexposed. That's fine if Earthshine is your target, but if you want to see lunar craters and mountains, you need to tap the slider icon at the top right, then disable automatic exposure and manually reduce the gain and exposure time (middle). With a few taps on the arrow buttons you can then center the Moon and enjoy a reasonably detailed live view (right).

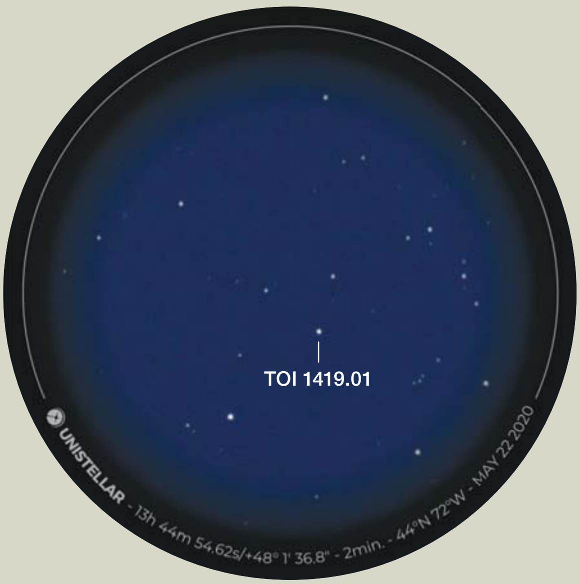
which have nearly 100 times the collecting area of an eVscope, and I don't recall ever seeing a galaxy's spiral arms so easily and a nebula's glowing gases so colorfully as in the eVscope. I know: It's an image, not "the real thing." But as my non-astronomer wife exclaimed when she first peered into the eVscope's eyepiece at the Whirlpool Galaxy (which she has struggled to discern in my 14-inch SCT), "I thought I'd be cynical, but it's absolutely beautiful and doesn't look fake at all!" Faint fuzzies no more!

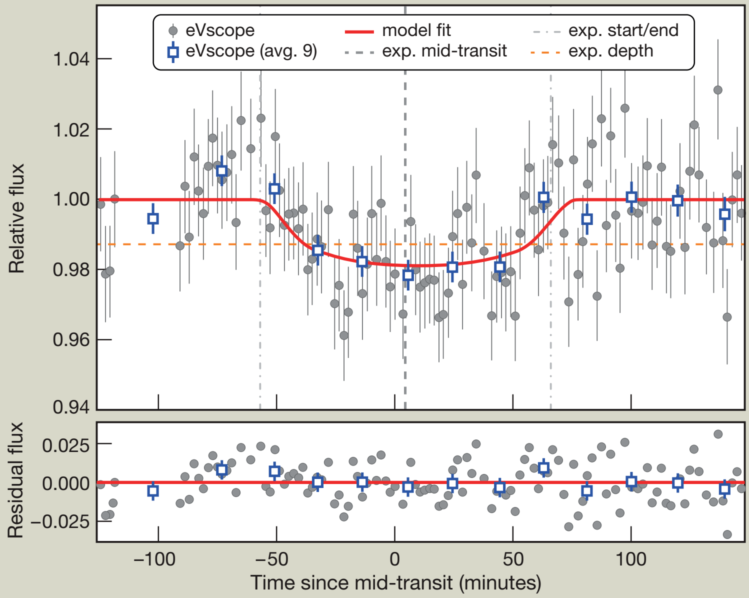
Of course, there's a downside: The eVscope's 450-mm focal length and 50× magnification are insufficient to provide knock-your-socks-off views of the planets. I look forward to a time after the COVID-19 pandemic when public star parties can resume, and I can give newbies a chance to look through an eVscope and a conventional telescope side by side. I think that would be an ideal pairing: a regular scope for the Moon and planets, and an eVscope for deep-sky objects.

At $3,000 the eVscope isn't for everyone. But advanced technologies usually work their way down from expensive top-of-the-line equipment to lower-priced basic models. Even if that doesn't happen in this case, plenty of newcomers to astronomy spend thousands on their first telescope. Too often they find the instrument too heavy to carry and/or too complicated to use and end up regretting their purchase. I doubt that anyone who starts out with an eVscope will be disappointed as long as they understand that it's not going to provide great views of the planets. I suspect that as more people have a chance to compare the view in an eVscope to the view in larger traditional telescopes, Unistellar will find a sizable market for their product. Every astronomy club that holds public star parties should get one.

▲ When saving images in the eVscope's app, you have two choices: a round, cropped, labeled version or a rectangular, full-frame, unlabeled version. The former resembles the view in the eyepiece when eV mode is enabled (minus the labels, of course). This pair shows Messier 16, the Eagle Nebula in Serpens.

■ Senior Contributing Editor **RICK FIENBERG** worked at *Sky & Telescope* from 1986 to 2008 and is now Press Officer of the American Astronomical Society, the magazine's new publisher.





Despite its diminutive size, the eVscope puts remarkable scientific capabilities in the hands of backyard observers. The author collected data for this light curve on the night of May 21-22. It shows a 1.3% dip in brightness as a planet about two-thirds the mass of Jupiter crossed in front of its magnitude-11.3 host star in Ursa Major; the star itself is a little cooler and less massive than the Sun. "TOI" in its name means it's a "target of interest" identified by NASA's Transiting Exoplanet Survey Satellite (TESS). Transits occur once each orbit every 2.9 days. The data points are ratios of the brightness of the target star to that of a reference star. Gray dots represent the median of 25 individual 3.95-second exposures, and blue squares are averages of 9 gray dots. In the lower panel, residual flux is the difference between the data and the model. The red curve is a model fit to the data and is consistent with expectations based on TESS observations of earlier transits. Courtesy the SETI Institute.

◀ BARGAIN TRIPLET

Orion Telescopes & Binoculars expands its EON line of affordable extra-low dispersion (ED) apochromatic refractors. The new Orion EON 130mm ED Triplet Apochromatic Refractor telescope ($2,499.99) features an air-spaced objective lens with one element of FK-61 ED glass to produce color-free images at the eyepiece. This moderately fast 5.1-inch f/7 refractor is ideal for both visual observing and astrophotography, with enough aperture to yield detailed views of the Moon and planets, as well as many deep-sky objects beyond the Messier list. The scope includes a 2½-inch, dual-speed, rack-and-pinion focuser with both 2-inch and 1¼-inch eyepiece adapters. A pair of mounting rings, a Vixen-style dovetail mounting bar, and a protective hard case are included with each purchase.

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89 Hangar Way, Watsonville, CA 95076
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◀ SOLAR SYSTEM IMAGER

Orion Telescopes & Binoculars adds two new models to its line of planetary imaging cameras. The Orion StarShoot Mini 6.3mp Color Imaging Camera ($399.99) and Orion StarShoot Mini 6.3mp Monochrome Imaging Camera ($429.99) both feature the sensitive Sony IMX178 CMOS detector with 2.4-micron-square pixels in a 3,040 x 2,048 array. Each unit is capable of recording 59 full-resolution, 14-bit frames per second through its USB 3.0 interface and is ASCOM compatible to work with most popular planetary and deep-sky camera-control software. Additionally, both cameras incorporate an ST-4-standard guiding port to permit use as an autoguider. Each camera's nosepiece includes a C-thread to 1¼-inch nosepiece adapter threaded to accept standard 1¼-inch filters. A 2-meter USB 3.0 cable and 6-pin autoguiding cable comes with each purchase.

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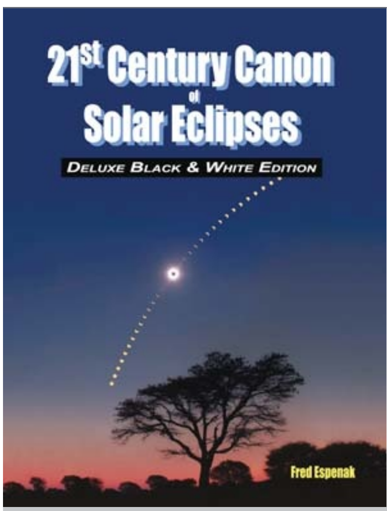

◀ ECLIPSE COMPENDIUM

Astrophysicist and *Sky & Telescope* contributor Fred Espenak releases *21st Century Canon of Solar Eclipses: Deluxe Black & White Edition* ($29.99). The book contains comprehensive information on the essential characteristics of every one of the 224 solar eclipses occurring during the 100-year period extending from 2001 to 2100. It also includes a catalog listing the parameters for each eclipse. Of particular note is the series of 224 maps plotting the paths of every solar eclipse (total, annular, and hybrid), which helps readers identify countries and major cities within each eclipse path. 296 pages, 8½-by-11 inches, paperback.

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Ceramic Mirrors

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ANYONE WHO'S GROUND MORE than a couple of primary mirrors begins to look at pretty much anything round and hard as potential mirror material. I've seen mirrors made out of glass tabletops, chunks of storefront door, and even a granite paving stone.

And now, thanks to Oregon ATM Mark Yonker, I've seen one made out of ceramic. Not the glass-like Black Vitrified Ceramic that's been popular for several years, nor Zerodur, which is a "fully densified ceramic," but plain old pottery-style fired clay.

Mark got the idea from Pat Cannon, his high school physics instructor, but the idea goes back at least as far as the 1970s (*S&T:* Oct. 1975, p. 259 and March 1976, p. 202). Mark freely admits he's not the inventor of ceramic mirrors but is instead a pursuer of them.

The idea is fairly simple: Pour liquid ceramic (called slip) into a mold, fire it in a kiln, glaze it, and finish out the mirror's parabola on the thin glaze layer.

As with many simple concepts, the devil is in the details.

First, you have to choose which kind of ceramic to use. Earthenware? Stoneware? Porcelain? Each has its advantages and disadvantages, although porcelain comes out the clear winner due to the fineness of its grain. When fired hot enough, porcelain becomes almost glass-like in its smoothness and lack of internal voids. Plain white pottery slip works, though, as Mark's mirror demonstrates.

Then comes the mold. You could just pour a flat, round slab and hog it out like a normal mirror blank, or you could honeycomb the back to reduce weight and improve cool-down time. Mark chose the latter, placing hexagonal blocks of plaster of Paris inside the mold before he poured the slip over it, then removing them once the slip had stiffened, but not hardened.

A sufficiently gadget-happy person could spin-cast a perfect parabola into the surface while it's a liquid, but hogging out "greenware," as the dried-but-not-fired ceramic is called, is so simple that spin-casting is hardly worth the effort. Just use another greenware disk as the tool and you'll have your curve within minutes, no grit required.

▲ The back of the ceramic mirror is honeycombed to reduce both its weight and cool-down time.

▼ An aluminized ceramic mirror looks pretty much like any other from its reflective side.

Ceramic shrinks when it dries, and it shrinks some more when it's fired. That can distort its figure, so you have to expect some fine-tuning of the curve in the "bisque" (fired) stage. So, Mark fired the greenware tool, too.

After he'd fine-ground the mirror to the right sagitta (he went with a 10-inch f/4.8), Mark glazed the surface and fired it again to melt the glaze. That provided a smooth, glassy surface that he could then fine-grind, polish, and parabolize like a normal mirror.

A point worth making: At this stage, Mark had put about $5 into the project. The cost of the blank is insignificant! You can make half a dozen of them and choose the best one to finish out.

The mirror wasn't beautiful. The glaze cracked, as large spans often do, and those cracks affected the figure. Mark continued to polish and parabolize it, and he got it to maybe half-wave precision before he decided that was good enough for a proof of concept and sent it off to be coated.

He built a basic Dobsonian scope to house the mirror and tried it out. It wasn't the sharpest mirror ever made, but it served pretty well, splitting doubles down to maybe four arcseconds and providing pleasing views of galaxies and

JERRY OLTION (3)

▲ Mark Yonker pours the slip over the hexagonal honeycomb backing for a 24-inch mirror.

nebulae. Mark is a deep-sky observer, so he kept using the mirror for several years, partly for the novelty of it and partly because it was perfectly adequate for his purposes.

The coating deteriorated over time — bubbles in the glaze made it look like it was slightly under-polished — so Mark recently had it recoated. Unfortunately, the ferric chloride used to strip off the old coating also attacked the glaze, which affected the mirror's figure. Now its limit is about six arcseconds.

So the mirror wasn't a complete success, but it certainly wasn't a failure, either. Given that this was the first one Mark did, there's clearly plenty of room for refinement of the process.

That's where you come in. Health issues and other projects have prevented Mark from taking this concept further, but he and I agree that it's a concept worth pursuing. There are plenty of naysayers out there who will tell you that ceramic mirrors won't work, but I've looked through Mark's scope and beg to differ. This scope performs a lot better than Isaac Newton's ever did — and just look where that path led. Someone needs to pick up this loose ball and run with it.

Interested parties may contact Mark via me at **j.oltion@gmail.com**.

■ Contributing Editor **JERRY OLTION** would try this himself, but his project queue is already years long (the hazard of writing this column every month).

▷ SIGNS OF ACTIVITY

Bryan Goff

A massive prominence towers over the Sun's south-western limb in this image taken on July 4th.

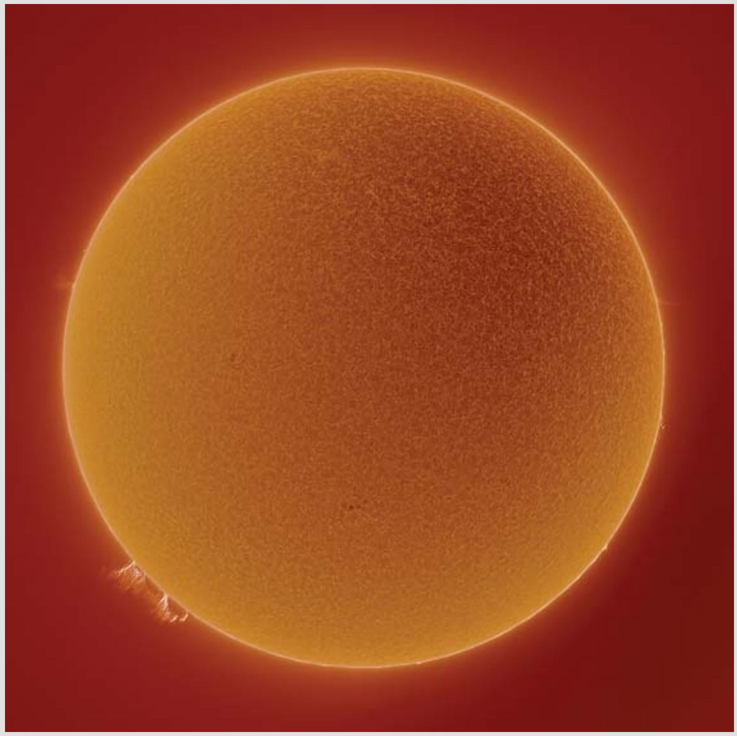
DETAILS: *Coronado Solarmax III 70mm Solar Telescope with ZWO ASI174MM high-speed video camera. Stack of 125 frames.*

▽ PERSEID HILLS

Jeff Dai

Several bright Perseid meteors appear to converge towards the antipodal point of the shower radiant behind the colorful sandstone hills in the Zhangye Danxia Geopark in the Chinese province of Gansu. Jupiter appears near the center of the image, with fainter Saturn to its upper left.

DETAILS: *Canon EOS 6D Mark II DSLR camera with 16-to-35-mm lens at 16-mm. Composite of 5 exposures, each totaling 15 seconds at ISO 3200.*



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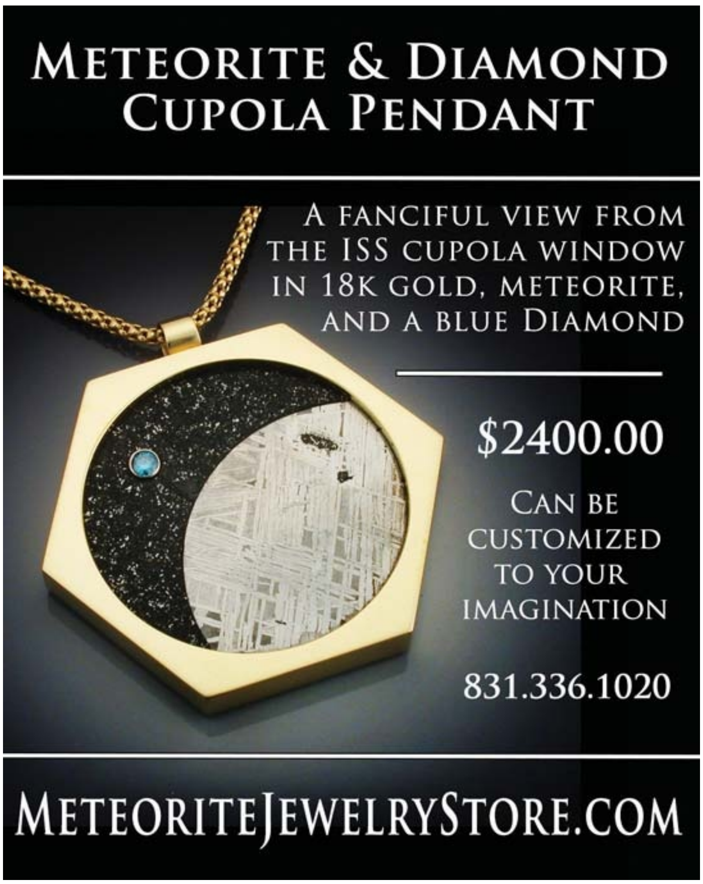
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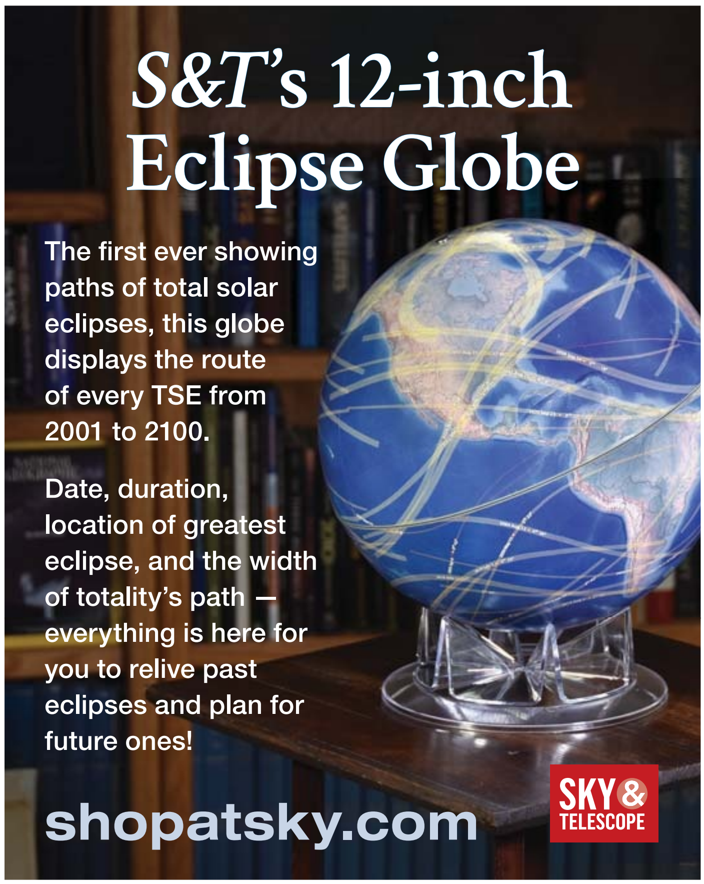
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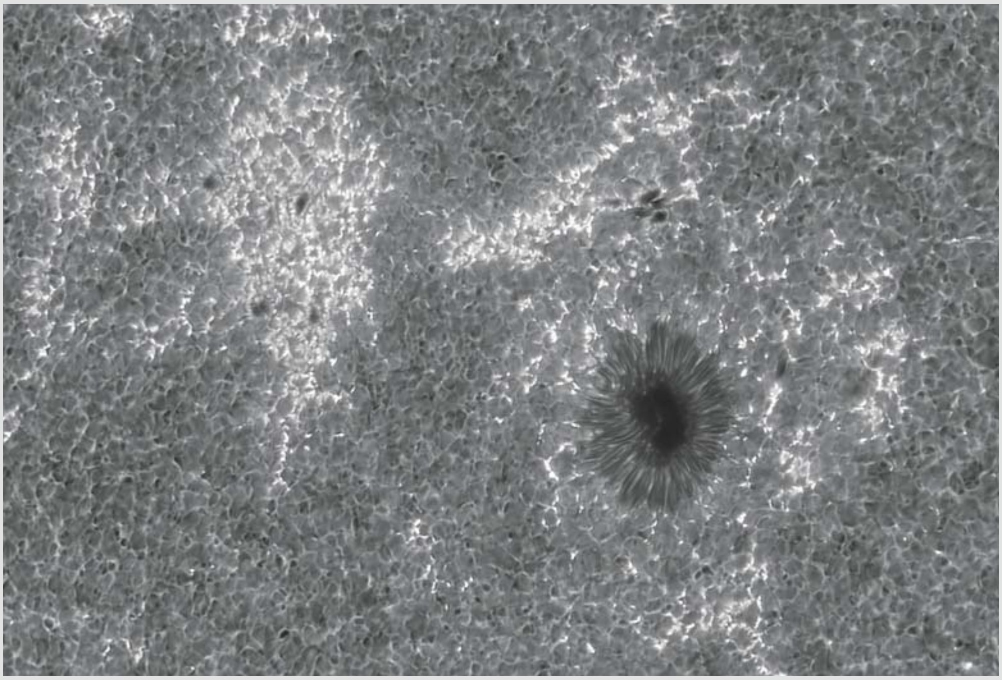
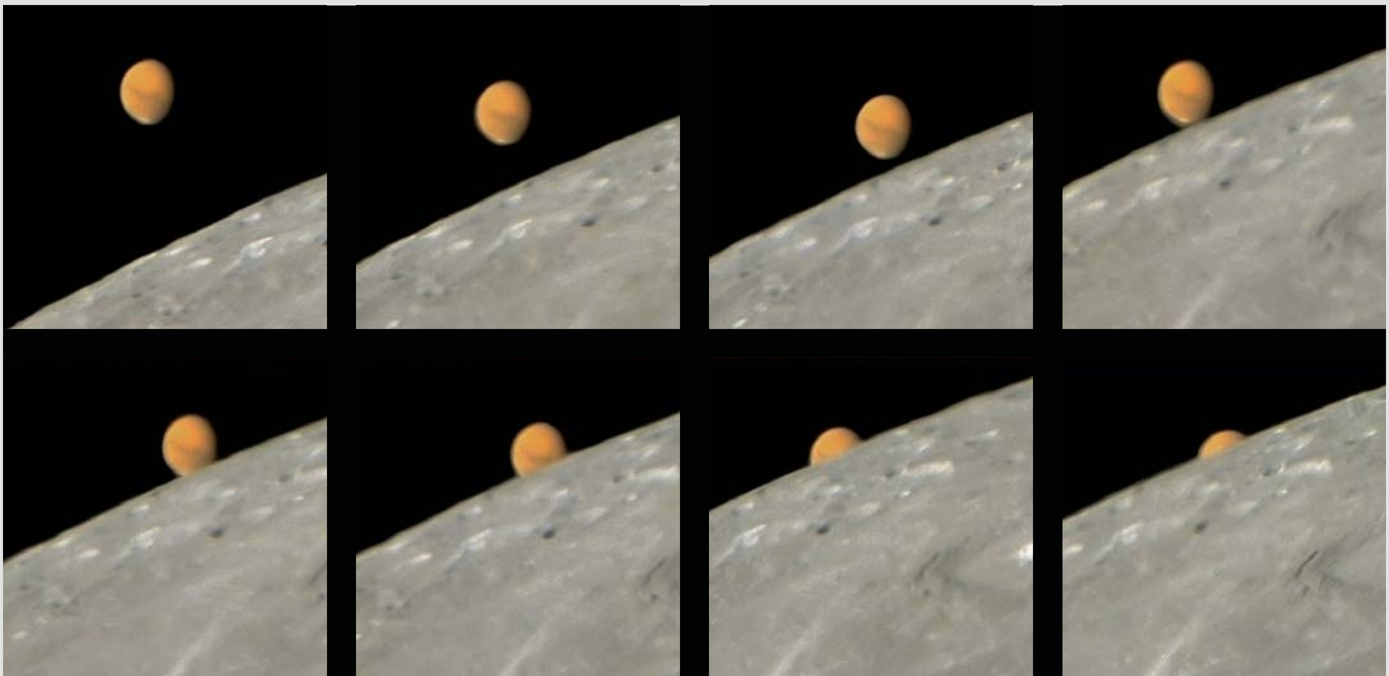


◁ CRACKLING SOLAR CALCIUM

Christian Viladrich

In another sign of increasing solar activity, sunspot AR 2770 appears in exquisite detail surrounded by lighter plage on the morning of August 7th.

DETAILS: *300-mm Newtonian reflector with ZWO ASI290 video camera. Stack of 150 six-millisecond exposures recorded through Alluxa CaK and Edmund Optics 394 filters.*



DISAPPEARING ACT

Ricardo José Vaz Tolentino

The Moon passes in front of Mars on the morning of August 9th, as seen from Belo Horizonte, Brazil, during the first of three occultation events between the Red Planet and our satellite in the latter half of 2020.

DETAILS: *Sky-Watcher Flextube 400P SynScan Newtonian reflector with Orion StarShoot Solar System Color Imaging Camera IV. Total exposure: 1/250 second per frame.*

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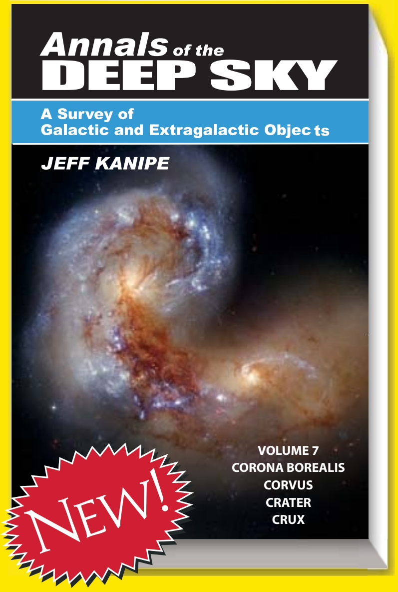

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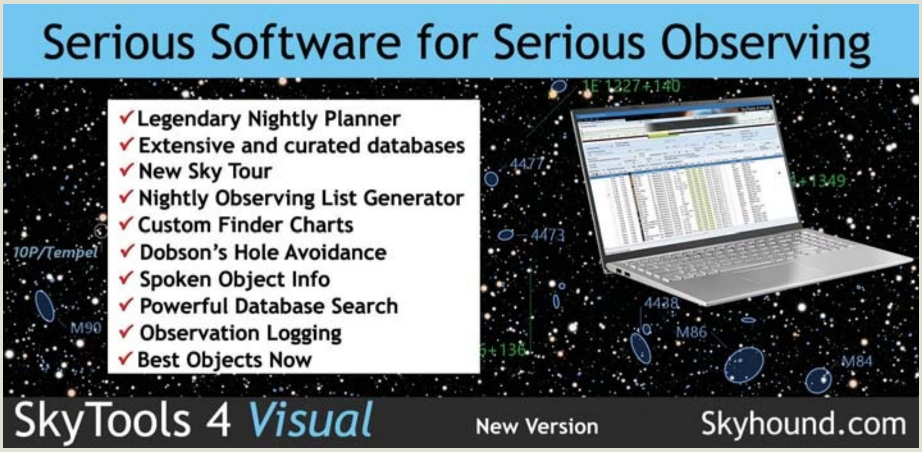

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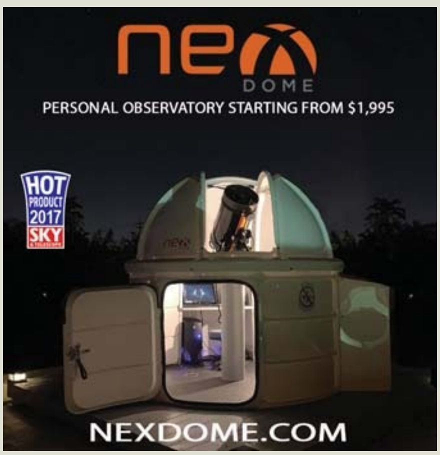

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Time to Get Serious

To truly bolster diversity and inclusion in astronomy, leaders need to require and incentivize the removal of barriers.

WHEN I WAS ASKED TO WRITE an update to my 2010 Focal Point, “Expanding Diversity in Professional Astronomy” (*S&T:* Feb. 2010, p. 86), I was curious to remind myself where my thinking was back then. Ten years allows for quite a bit of growth (and cynicism) in a person’s life.

At the time, my opinion piece induced some to claim it was preposterous to think that a lack of diversity, due to an absence of minority perspectives, could have any effect on the quantity or quality of science that teams could accomplish. But studies have since demonstrated how more diverse teams outperform homogeneous groups at various endeavors (see, e.g., **https://is.gd/diversityparadox**).

Unfortunately, the hope that the field would embrace the logical and ethical reasons for improving racial and ethnic diversity in astronomy in the years following the publication of the National Research Council’s Astro2010 decadal survey appears to have been no match for institutional impotence and structural inertia. Thus, what is valued as part of scientific merit in our culture has not significantly evolved. Further, the lack of meaningful guidance in the Astro2010 report on issues of workforce diversity and inclusion left interested astronomers without fundable mandates to address these challenges.

Some progress *has* been made. Individual scientists and departments have taken up grassroots efforts to tackle a few broad issues in the field’s scientific culture. Spurred on by the 2015 Inclusive Astronomy meeting (see, e.g., **https://is.gd/inclusiveastronomy**), some initiatives have begun to gain traction, including those focused on removing barriers to access, creating inclusive climates and practices, and improving access to policy, power, and leadership.

These actions have led to results: the widening of diversity conversations beyond a narrow exchange that favored mostly white women; reconsideration of the heavy use of the GRE test in graduate admissions — demonstrative of excluding underrepresented minorities — toward a more holistic view of graduate admissions candidates; broader discussion of diversity and inclusion topics within research collaborations and at scientific conferences and workshops, including as invited talks and presentations; and calls for wider access to astronomical resources and data.

But while these are all worthy accomplishments, especially in the absence of high-level leadership, they have done little to expand diversity in our professional ranks. According to the American Institute of Physics, while the total number of physics and astronomy professors increased from 2008 to 2016 (the last year for which numbers are available), the number of Black and Hispanic professors remained at the same tiny percentage of the academic work-

force: about 0.2% and 0.4%, respectively. Even in 2020, I am often the only Black scientist at a conference, on an advisory panel, and in my workplace.

Without policies that incentivize and require prioritization of these concerns, the work needed to change them across the culture won’t get done. The efforts described above will continue to progress only in rare, enlightened realms and will not become part of how we do science, or how we include and retain an ethnically and racially diverse set of talent in our workforce.

My 2010 piece focused on pipeline concerns of bringing minority students into the field, but in the years since I recognize that, as with the larger society, the structural and institutional barriers to increasing the numbers of minority professionals in the field cannot be dealt with by simply recruiting more students. We can only remove such barriers by demanding their demise and rewarding actions that bring our field to a place that has better values, traditions, and norms.

As we look to the Decadal Survey on Astronomy and Astrophysics 2020 report, due next year, let’s commit to doing better — now.

■ **DARA NORMAN** is an astronomer and deputy director of the Community Science and Data Center at the National Optical-Infrared Astronomy Research Laboratory (NOIRLab) in Tucson, AZ.

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