IMAGING: In Pursuit of Perfect Points
PAGE 64

ELUSIVE PREY: Face-on Spirals
PAGE 30

WORKBENCH: 3D-Printing a Binoscope
PAGE 74

SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

Cosmic CONTROVERSY

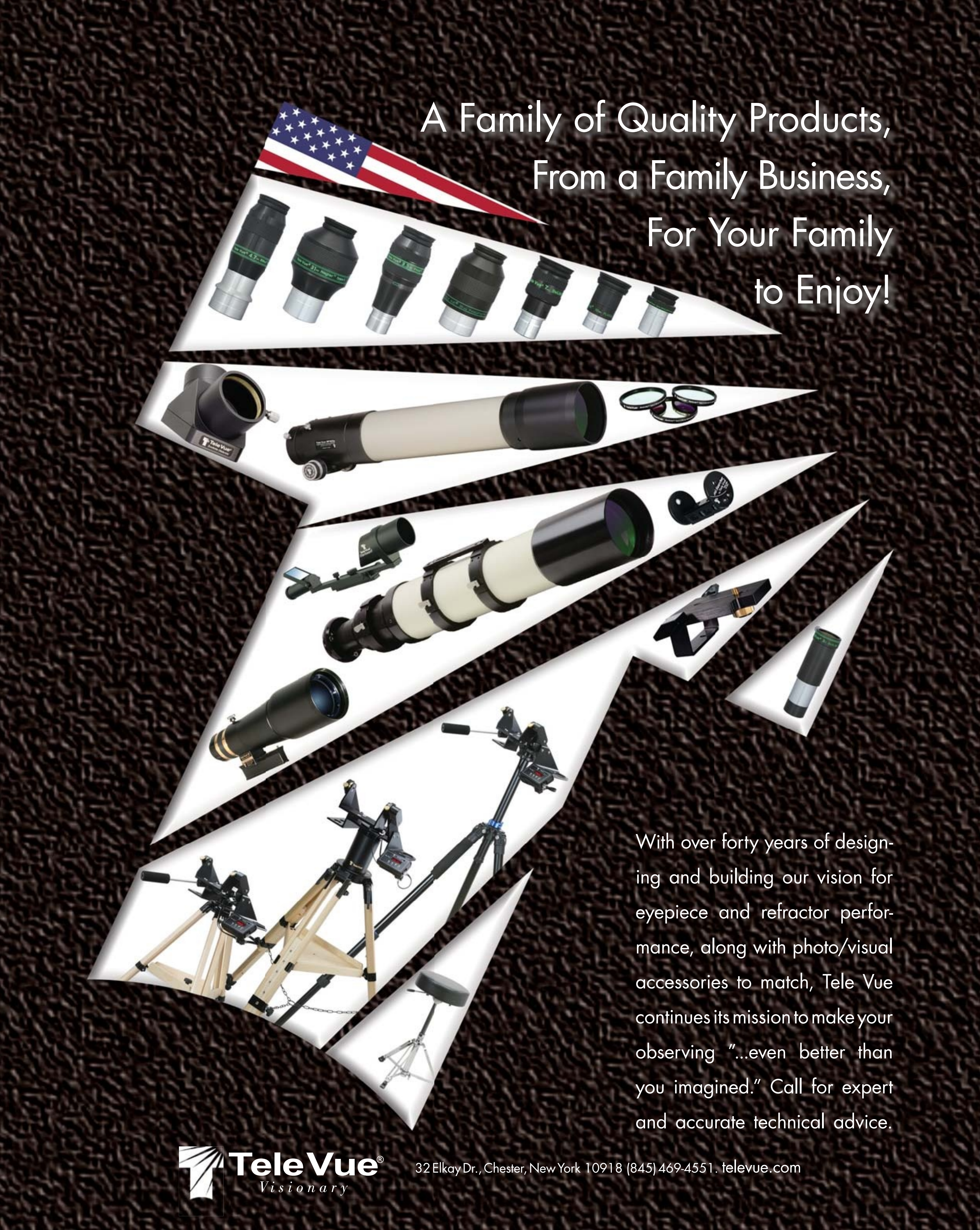
Scientists Debate the Universe's Expansion Rate
PAGE 22

JUNE 2019
skyandtelescope.com

World-Class Observing at Glacier National Park
PAGE 58

LIGHTING THE FUSE: Why Do White Dwarfs Explode?
PAGE 14

Beyond the New General Catalogue
PAGE 54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CONTENTS

SKY&TELESCOPE
THE ESSENTIAL GUIDE TO ASTRONOMY

June 2019 VOL. 137, NO. 6

JOHN ASHLEY

ON THE COVER

Artist's concept evoking the expanding universe we inhabit.
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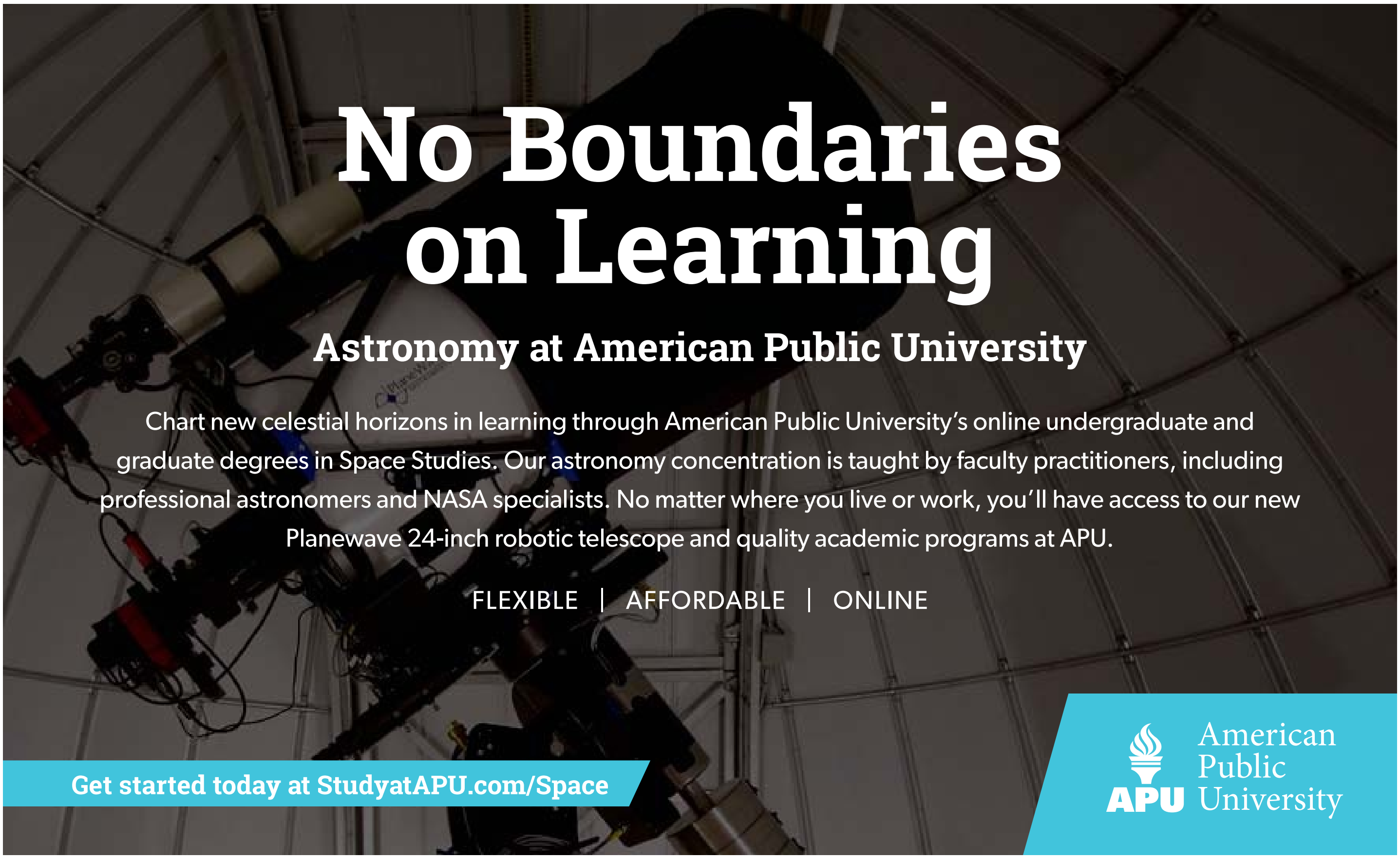

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Coming to Terms

IN COSMOLOGY, A CURIOUS RELATION is at play in the naming of things: The simplicity of terms used as shorthand for cosmic phenomena tends to be inversely proportional to how puzzling those phenomena are. Take the lingo that crops up in our pair of cosmology features in this issue, which concern Type Ia supernovae and the universe's expansion rate, respectively.

In her article on page 14, Shannon Hall discusses the *single-degenerate scenario* and the *double-degenerate scenario*. Sounds like one bully in a schoolyard versus two. We put such terms in italics as red flags: Warning, jargon! But those two concepts simply refer to whether white dwarfs explode because of interaction with a companion star (single scenario) or with a second white dwarf (double scenario).

In his feature on page 22, Govert Schilling mentions the *period-luminosity relationship*. This mouthful just means that the more luminous a Cepheid pulsating star is, the more slowly it pulsates.

G299 is the colorful remnant of a Type Ia supernova, one kind of *standard candle*.

NASA / CXC / U. TEXAS

Metaphor can help us grasp the complex — and coin more user-friendly terms. In these articles, you'll read about the *tip of the red giant branch*. *Gravitational lenses*. *Standard candles*, which serve as rungs on the *distance ladder*.

It's when you get to the most baffling cosmic stuff of all that our sobriquets become the most basic. A child might as well have suggested them. Dark energy. Dark matter. Big Bang. We don't italicize those three because everyone is familiar with them — even many a child — yet cosmologists have more questions about them than just about anything else.

As scientists strive to crack such bedrock mysteries, they grapple with others along the way. These include the two compelling conundrums investigated in these features. Hall wonders: How many ways can you skin a Type Ia supernova? That is, how many types of detonators can trigger such catastrophic blasts? We don't know, but it's more than we'd thought.

Schilling, for his part, asks: Why do the world's leading cosmologists come up with two entirely different numbers for the Hubble constant, the current expansion rate of the universe? It's as if they watched the same Super Bowl yet insist on two different final scores, with each side having every reason to believe its conclusion is the correct one.

There are no answers, or only partial answers, to these questions. And that's what fires up scientists intent on unraveling such enigmas — call them what you will.

Peter

Editor in Chief

SKY & TELESCOPE
The Essential Guide to Astronomy

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Solar Seeing

Johnny Horne, in his review of Daystar's Solar Scout (*S&T:* Mar. 2019, p. 58), mentioned that "I experienced slightly better seeing when I used the SS60C outside on my lawn," and in the early morning hours. Long ago, I had to do my PhD observations of the solar chromosphere at the Sacramento Peak Observatory in the hour or so after sunrise, before the atmosphere heated up. And lore has it that seeing was better longer there when the lawn was being watered. That led Hal Zirin at Caltech to build the Big Bear Solar Observatory in a lake on an artificial island, which led to much longer periods of good seeing during the day. Great solar movies resulted.

I'm looking forward to using Big Bear's 1.6-meter Goode Solar Telescope again this November 11 for the transit of Mercury.

Jay M. Pasachoff • Pasadena, California

▲ Located in Big Bear Lake in Southern California, Big Bear Solar Observatory is operated by the New Jersey Institute of Technology.

NEW JERSEY INSTITUTE OF TECHNOLOGY

Expectation Bias

I enjoyed Tom Dobbins's discussion of expectation bias (*S&T:* Mar. 2019, p. 52). His mention of the Heinkel He-113 reminded me of Johann von Goethe's famous quote, which sums things up: "*Man sieht nur, was man weiß*" or "You only see what you know."

Mark L. Mitchell
Hockessin, Delaware

According to Scale

Dave Nakamoto's letter (*S&T:* Mar. 2019, p. 7) gave a nice analog for comprehending the vast emptiness around and within the Local Group. Even more locally, if the Sun were the size of a poppy seed, the Alpha Centauri system (our closest stellar neighbors) would be about 9 miles away. Except for our star's own planetary, Kuiper, and Oort debris, there's a lot of space out there.

Mike Douglass
Poolesville, Maryland

Catching the Waves

Thank you for Robert Naeye's excellent article "Pulsar Timing Arrays" (*S&T:* Jan. 2019, p. 22). The illustration on page 24 shows a diagram of gravitational waves squeezing space in one direction and stretching in the perpendicular direction, then vice versa in the next half-cycle. But one question comes to mind: Does that mean that gravitational waves are polarized?

Vad Falcone
Leeds, United Kingdom

Camille Carlisle replies: *You have an astute eye! I ran your question by LIGO's spokesperson, and he said that yes, all gravitational waves are in some polarization or another. The general theory of relativity permits two polarization states, called plus (+) and cross (x) states. The two polarizations are 45 degrees apart, rather than the 90 degrees for polarized light. In general, waves will be a superposition of plus and cross states. Alternative gravity theories predict additional polarization patterns to the two that GR permits.*

To detect the polarization of gravitational waves, scientists need detectors at different angles — but the two LIGO sites are essentially aligned. It's only now with the addition of Europe's Virgo detector that scientists can start to look at the polarization of gravitational-wave signals, but they will need at least four sites to analyze the polarization comprehensively. Fortunately, the Japanese are building the KAGRA detector, which is scheduled to begin observing in late 2019. Check out **https://is.gd/WZRapG** *and* **https://is.gd/Bov6fz** *for more info.*

More Bang

I enjoyed reading Faye Flam's "What Came Before the Big Bang?" (*S&T:* Feb. 2019, p. 16) and found the various speculations relating to the Big Bang and the multiverse theory very interesting. However, after finishing the article I wondered whether the physicists whose views were presented had perhaps stepped outside the bounds of physics and into the realm of philosophy.

One problem with the multiverse theory is that it implies we can stop using science to understand why our particular universe exists, because our universe had to come about in an infinite number of universes. It also implies that there must be an infinite number of universes exactly like ours. To me, that is no more satisfying than justifying our universe by simply saying that God made it this way. Both scenarios are equally not falsifiable and therefore not science by definition.

Angelo DiDonato
Macomb, Michigan

Dated Material

In her feature "Secrets of Polaris" (*S&T:* Mar. 2019, p. 14), Camille Carlisle notes, "In 1912 Henrietta Swan Leavitt discovered that the brighter a Cepheid is intrinsically, the longer it takes to cycle through a pulsation period." Actually, Leavitt discovered the Cepheid period-luminosity relation in 1907, not the frequently cited 1908 or 1912. In a

1907 paper she writes, "It is worthy of notice that . . . the brighter variables have the longer periods." In the library at the Harvard-Smithsonian Center for Astrophysics, that 1907 paper is bound into a volume dated 1906–1908, making it impossible to know the exact year the paper appeared and explaining why the year 1908 often appears instead. Imagine, then, my joy when I saw the same paper here in the Berkeley library, with each individual paper stamped with the date on which the library had received it!

Ken Croswell
Berkeley, California

Camille Carlisle replies: *I cited 1912 because Leavitt's 1907 paper seemed less definitive to me. In the 1912 work she writes that "In [the previous work], attention was called to the fact that the brighter variables have the longer periods, but at that time it was felt that the number was too small to warrant the drawing of general conclusions." Thus, I considered 1912 to be the year that it all came together. But she certainly saw a trend earlier, so using the earlier date for the discovery makes sense.*

Kept in the Dark

I had an optical mishap similar to Pat Plunkett's (*S&T:* Jan. 2019, p. 84).

At a public star party a few years ago, I was trying to find M27, the Dumbbell Nebula in Vulpecula, using my C8. It wasn't a Go To, but I had nailed the object many times before by star-hopping. But for the life of me I couldn't find it that night. When the crowd left, I tried again and again just out of stubbornness. No luck. I eventually hurt my back trying to find the object, which was nearly at the zenith.

The next day, as I put away my equipment, I noticed the eyepiece had an orange filter still screwed into it. I use that filter for Saturn. At the star party, I had been on Saturn before deciding to move on to M27, and I forgot to remove the orange filter. While I know better than to use a planetary filter on a nebula, I had no idea an orange filter would make the thing completely disappear. I could have spent all night looking for that nebula and never found it!

Bill Dellinges
Apache Junction, Arizona

FOR THE RECORD

- John Goodricke identified Delta Cephei's periodic pulsations in 1784, not 1794 as printed (*S&T:* Mar. 2019, p. 16). Incidentally, although Delta Cep is often reported as the first Cepheid discovered, Eta Aquilae technically beat it by a few weeks (*S&T:* Oct. 1997, p. 90).

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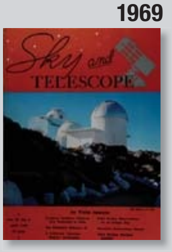
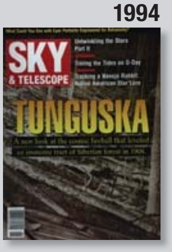
75, 50 & 25 YEARS AGO by Roger W. Sinnott

1944

1969



1994



June 1944

Cometary Aurora? "[Sylvain] Arend, at Uccle, Belgium, noticed a nebulous object of 13th magnitude with a nucleus, close to Comet Whipple (1942g) on March 29, 1943. . . . [Not long after,] Dr. Brunner-Hagger, at Zurich, Switzerland, [recalled] that a fine aurora had been seen on March 27.8. Terrestrial aurorae are caused by corpuscular radiation from the sun. Suppose the diffuse object in the comet's tail had the same origin? From the time elapsed . . . he deduced that the solar corpuscles travel at the rate of about one astronomical unit in 30 hours."

A clever suggestion! In fact, coronal mass ejections from the Sun put a kink in the tail of Comet Ikeya-Zhang in 2002 and blew off most of Comet Encke's tail in 2007.

June 1969

Phantom Planets "Distant only 5.9 light-years from us, Barnard's star is traveling across the sky at the enormous rate of one degree in 350 years. This proper motion shows a very slight waviness, from which in 1963 Peter van de Kamp of Sproul Observatory deduced the presence of an unseen companion. . . .

"Now Dr. van de Kamp points out an alternative interpretation of the observations. The measured deviations of Barnard's star may result from perturbations by *two* unseen companions, revolving in approximately coplanar circular orbits with periods of 26 and 12 years. . . . The deduced masses are 1.1 and 0.8 that of Jupiter, respectively. These objects may therefore be thought of as planets."

Probably van de Kamp was misled by astrometric errors. As far as we know today, no exoplanets circle Barnard's Star, but about 4,000 of them belong to other host stars. Most were identified by subtle variations in the star's radial velocity, or else by weak dips in its light during transits by the planet.

June 1994

Ida's Moon "Two instruments on the Galileo spacecraft have found a small satellite within 100 kilometers of the asteroid 243 Ida. A mere 1½ km across, the tiny moonlet appears in images taken . . . during a flyby of Ida last August 28th. . . .

"Most probably the two objects ended in the same vicinity after the collision long ago that created the Koronis family of asteroids. . . . In that case the moon could have been captured into a stable orbit. . . . Project scientists hope to resolve such questions about Ida and its companion once the remaining Galileo images and spectra are in hand."

Earlier there had been a few reports of two dimmings as an asteroid occulted a star, suggesting a satellite. But Ida's moon, later to be named Dactyl, was the first proven case (not counting Pluto's Charon, spotted in 1978 when Pluto was still considered a major planet). Almost 400 asteroidal moons are now known to exist.

SOLAR SYSTEM

Hayabusa 2 Touches Asteroid, Collects Sample

ON FEBRUARY 21ST, the Japanese spacecraft Hayabusa 2 grabbed its first sample from the asteroid 162173 Ryugu, the asteroid it has been orbiting since last summer (*S&T:* Oct. 2018, p. 11). Immediately after the craft touched down, it fired a tantalum bullet at the asteroid's surface and knocked away material that flew up into a sampling horn. Then the spacecraft took off again. Hayabusa 2 has now sealed the sample collection compartment, saving the sample for return to Earth.

Finding the right spot to sample Ryugu was more challenging than anticipated. When Hayabusa 2 arrived at Ryugu on June 27, 2018, it found a uniformly rocky asteroid with no smooth areas on which it could alight. The team had to develop new sampling-site selection criteria, identifying two extremely narrow locations where they'd have to navigate the spacecraft between boulders. The team tried out descending toward those sites twice. Back on Earth, they also tested whether the bullet-firing mechanism would liberate enough material from a rocky surface. Testing went well, so the team proceeded.

The spacecraft has no way of measuring just how much material made it into the collection chamber, so we won't know for sure what Hayabusa 2 has collected until it returns to Earth. However, all the spacecraft telemetry are consistent with success. The mission allows for two additional attempts at sample collection, though the mission team still has to decide whether obtaining another one would be worth the added risk.

Hayabusa 2 also has one more experiment to perform: its Small Carry-on Impactor (SCI), a probe that will carry explosives to accelerate a 2-kg copper lump at Ryugu's surface in an attempt to create an artificial crater. Hayabusa 2 will shelter from the impact behind the asteroid's bulk, but before it hides, it will deploy a camera to watch in its place. The spacecraft will then emerge to pick up surface debris. Being able to directly compare material from the asteroid's weathered surface to its relatively pristine interior would be a boon to scientists, who must often determine bulk composition from remote observations of asteroids' surfaces.

▲ Hayabusa 2 took this picture of Ryugu as the spacecraft began ascending after its brief touchdown. Hayabusa 2's shadow can be seen, along with a dark splotch where the spacecraft's thrusters blew away lighter materials on Ryugu's surface.

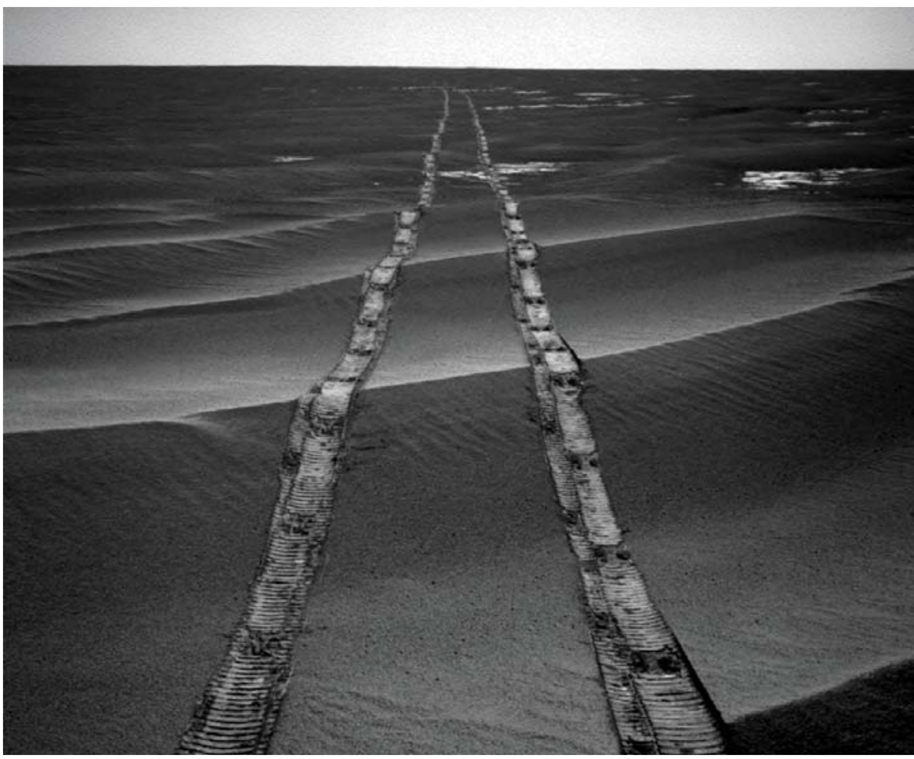
Hayabusa 2 will remain in proximity to Ryugu until November or December. Its return will take about a year. After dropping its sample in the Australian desert in December 2020, the spacecraft could potentially extend its mission to fly past another asteroid.

■ EMILY LAKDAWALLA

MARS

Opportunity Reaches the End of the Road

NASA FORMALLY ANNOUNCED the end of the Opportunity mission on February 13th. The team last contacted the rover on June 10, 2018, days before a dust storm enveloped the planet and likely coated the rover's solar panels, cutting off its power supply. The storm was both darker and longer than one that Opportunity had weathered in 2007. The team attempted to make contact over the following eight months,



◀ NASA's Opportunity rover looked back over its own tracks on August 4, 2010.

HAYABUSA 2: JAXA / TOKYO UNIV. / KOCHI UNIV. / RIKKYO UNIV. / NAGOYA UNIV. / CHIBA INSTITUTE OF TECHNOLOGY / MEIJI UNIV. / AIZU UNIV. / AIST; OPPORTUNITY: NASA / JPL-CALTECH

SPACE MISSIONS

Israeli Lander Launches for the Moon

A SPACEX FALCON 9 ROCKET carried the lunar lander Beresheet ("in the beginning" in Hebrew) to space on February 21st. It's headed for a soft landing on the Moon in mid-April.

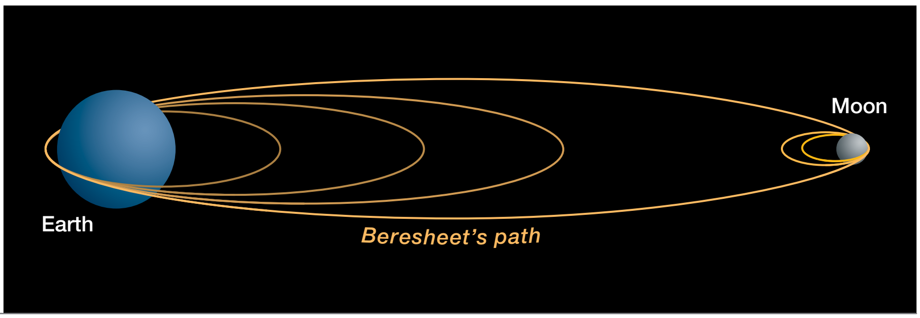
The privately funded lander, built by Israeli company SpaceIL, was a secondary payload accompanying an Indonesian communications satellite and a U.S. Air Force satellite. All three were placed in geostationary orbit, but that only takes Beresheet about a tenth of the way to the Moon. The lander must propel itself the rest of the way by slingshotting around Earth in increasingly elongated orbits. After a seven-week journey, the mission will target a landing in the northern part of Mare Serenitatis ("Sea of Serenity").

SpaceIL and its Beresheet lander were born from the Google Lunar XPRIZE, which challenged teams to land on and explore the Moon. The competition's March 31, 2018, deadline for $30 million has passed, so SpaceIL won't win any money. Still, the team did well for itself, raising $100 million to fund the lander from the Israeli Space Agency and private donors.

The solar-powered lander is expected to last 2 to 3 days on the lunar surface. Although it's primarily a technology demonstrator, Beresheet carries a small science package equipped with an instrument to measure magnetism in Moon rocks, as well as a laser retroreflector contributed by NASA and several cameras. Beresheet also bears a small time capsule, including a 30 million-page archive of human history and civilization encoded on nickel discs.

If the mission is successful, Israel will become the fourth nation — behind the United States, Russia, and China — to make a soft landing on the Moon.

■ DAVID DICKINSON



SPACEIL

sending more than a thousand recovery commands, but to no avail.

About 14½ years ago, Opportunity bounced to a landing inside Eagle Crater on January 25, 2004, ultimately traversing 45.16 km (28.06 miles). Its record-breaking journey broke new ground in both exploration and planetary geology.

The rover was the first mission to identify and characterize a sedimentary rock record on a world other than Earth. The layers of sulfate-rich sandstone it discovered pointed to a wet past for the Red Planet. But as Steve Squyres (Cornell University) noted, "It wasn't 'water on Mars, water on Mars!' It was really 'sulfuric acid on Mars.'"

In 2008, Opportunity embarked on what was essentially a second mission. Driving 21 kilometers over three years to Endeavour Crater, the rover arrived to find older rocks along the crater's rim that were laden with clay minerals. This evidence suggested Mars went through an earlier era when the water coursing through its rocks had been fit to drink.

The end of the Opportunity mission leaves Curiosity as the sole rover on Mars, but it should soon have company: NASA's Mars 2020 rover and the European Space Agency's Rosalind Franklin rover are due to head to the Red Planet during next year's launch window.

■ DAVID DICKINSON

IN BRIEF

A First Wave of Transient Discoveries

The Zwicky Transient Facility (ZTF) is now fully operational, scanning the entire northern sky every three days. After first light in November 2017, the ZTF began science operations in March 2018. Its first order, though, was to build an archive of "reference images" for comparison against new images; now that step is complete. The ZTF has already identified nearly 1,200 supernovae and 50 small near-Earth asteroids, including two that zipped past Earth at roughly a third of the distance to the Moon. Another asteroid, 2019 AQ_3, was discovered on January 4th with the shortest known orbital period: It whips around the Sun every 165 days, keeping it within Venus's orbit. The ZTF has also observed more than a billion stars, spotted new binary star systems, and caught two star-shredding black holes in the act. Many of these observations are detailed in papers to appear in a special issue of the *Publications of the Astronomical Society of the Pacific*, but this wave of discoveries is only a hint of what's to come.

■ SHANNON HALL

Gravitational-Wave Alerts from LIGO

Now that the Laser Interferometer Gravitational-wave Observatory (LIGO) has 11 detections under its metaphorical belt, the team is prioritizing follow-up observations. To that end, LIGO is making all gravitational-wave detections public knowledge right away during its third observing run (April 2019 – April 2020). As improvements have been made to both the LIGO and Virgo detectors in between observing runs, this observing run should herald a period of enhanced discovery. Scientists expect at least a few black hole mergers every month, as well as at least one neutron star merger per year. The team will be distributing all gravitational-wave signals via the Gamma-ray Coordinates Network (GCN). Coordinates of new events will be distributed via GCN Notices, while announcements of follow-up observations will come in GCN Circulars. You can visit the GCN website (**https://gcn.gsfc.nasa.gov**) to subscribe to Notices, Circulars, or both via your email. Or, if you prefer to have an app for that, citizen scientist Peter Kramer has created *Gravitational Wave Events* for iOS.

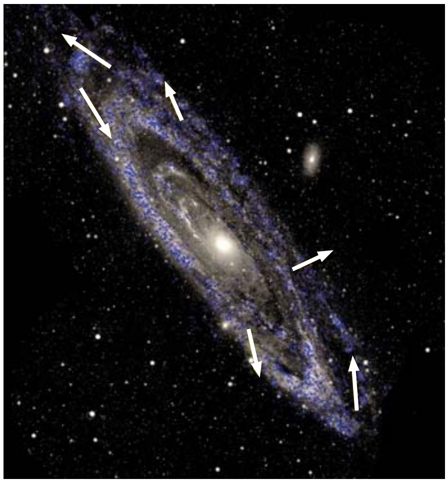
■ MONICA YOUNG

GALAXIES

Gaia Peeks at Local Group's Past and Future

ASTRONOMERS HAVE USED the European Space Agency's Gaia satellite to measure stellar motions in Andromeda (M31) and its satellite Triangulum (M33) — the largest galaxies in the Local Group outside of the Milky Way. The results answer some key questions about the galaxies' interactions.

Roeland van der Marel (Space Telescope Science Institute) and colleagues averaged the motions of 1,084 and 1,518 stars in the Andromeda and Triangulum galaxies, respectively. After measuring the galaxies' rotation and their motion across the sky, the team then simulated their past and future movement, looking billions of years backward and forward in time.



▲ The European Space Agency's Gaia satellite monitored stars (blue dots) in the Andromeda Galaxy, shown here at ultraviolet wavelengths. Astronomers averaged the stellar motions (arrows) to understand the galaxy's rotation and its movement on the sky.

The projections enabled the astronomers to investigate the relationship between the two galaxies. Hubble Space Telescope images and radio data from the Very Long Baseline Array had previously suggested that they might have passed close by each other 6 billion years ago and are swinging by each other again. But the new Gaia-based simulations reveal that Triangulum is only now making its first approach to Andromeda. This result suggests that the galaxies in the Local Group have come together relatively recently.

The team's analysis also recalculated the Milky Way's meet-up with Andromeda. While astronomers have long known that Andromeda is barreling toward us at about 110 km/s, it has been hard to gauge how fast our sister galaxy is moving sideways. Hubble data had indicated a small sideways motion of about 17 km/s, indicating a head-on collision. But now, after averaging the Hubble results with the new Gaia measurements, van der Marel's team finds that Andromeda is sliding sideways more quickly, at around 60 km/s.

The two galaxies are still due for a merger, but their first encounter will be more of a glancing blow than a head-on collision, says van der Marel. The revised velocity also means the expected encounter will occur 600 million years later than originally thought, in 4.5 billion years' time.

■ BEN SKUSE

MILKY WAY

What Has Our Galaxy in a Twist?

▲ Like the Milky Way, the spiral galaxy ESO 510-G13 has a pronounced warp in its gaseous disk, as well as a less pronounced warp in its disk of stars.

ASTRONOMERS MAPPING out luminous stars across the Milky Way are exploring what bent our galaxy's disk.

We've known since 1957 that the Milky Way is warped like thrown pottery gone wrong. It's not alone — at least half of all galaxies are warped. But the cause remains unclear: Are we seeing the collective motions of billions of stars that pull on each other, or is the cause external, such as gravitational interactions with satellite galaxies?

Using 1,339 Cepheid variable stars from the Wide-field Infrared Survey Explorer catalog and a number of visible-light surveys, Xiaodian Chen (Chinese Academy of Sciences) and his colleagues have mapped out two-thirds of our galaxy's stellar disk to better understand its shape.

The Cepheids' pulsations relate directly to their luminosity, making them reliable markers of distance. The scientists thus use the stars to trace the warped disk out 65,000 light-years from our galaxy's center. Chen and his colleagues replicated the disk's shape with a mathematical model, which they then used to probe the source of the warping. Their results appear February 4th in *Nature Astronomy*.

The team found that the warp within the central Milky Way arises naturally, as the inner stellar disk pulls on and distorts the outer part of the disk. But in the outer reaches of the galaxy, more than 50,000 light-years from the center, the warp's shape changes. The researchers speculate that infalling dwarf galaxies might have sculpted the outer Milky Way, or the warp might reflect a misalignment between the galactic disk and the larger halo of dark matter around it.

As infrared surveys continue to find more Cepheids on the farside of the Milky Way, astronomers will eventually be able to map out the whole disk for better insight into its structure.

■ MONICA YOUNG

ANDROMEDA: STAR MOTIONS: ESA / GAIA; BACKGROUND IMAGE: NASA / GALEX; R. VAN DER MAREL / M. FARDAL / J. SAHLMANN (STSCI); WARPED GALAXY: NASA / STSCI

GALAXIES

Radio Survey Finds Hundreds of Thousands of Galaxies

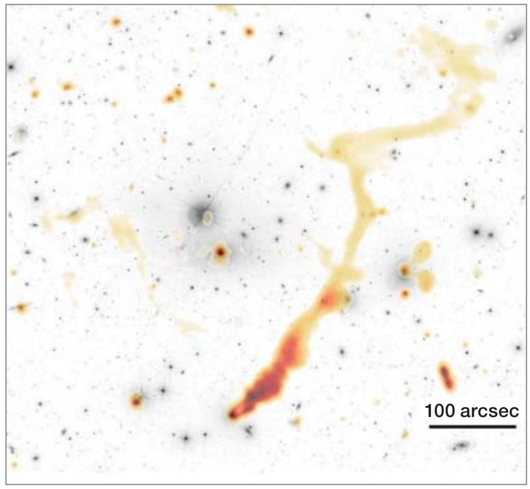
THE LOW FREQUENCY ARRAY (LOFAR), which is exploring the sky at low radio frequencies, has found 325,694 new radio sources, most of them faraway galaxies.

These results represent the first phase of LOFAR's ambitious Two-metre Sky Survey and appeared February in a special issue of *Astronomy & Astrophysics*. The accompanying high-resolution mosaic images, which include radio emission at frequencies between 120 and 168 MHz, show details as fine as 6 arcseconds across. Under ideal circumstances, LOFAR may return images with a resolution of 0.5 arcsecond.

About 70% of the new radio sources have visible-light counterparts in the Sloan and Pan-STARRS surveys, providing astronomers with rough distance estimates. Most of the sources are distant galaxies whose central black holes power jets.

LOFAR sees jet activity on much longer time scales than existing, higher-frequency radio surveys. The radio waves from the galaxies that LOFAR has found are primarily generated when electrons spiral along magnetic field lines that thread the jets. After these electrons have been spiraling for a while, they slow down and emit lower-frequency radio waves.

One intriguing result is that all the most massive galaxies appear to exhibit long-lasting jet activity close to their cores, which suggests that their central black holes are feeding more or less continuously. The new observations will shed light on the evolution of supermassive black holes over cosmic time. Eventually, astronomers' goal is to find the very first supermassive black holes in the universe.



▲ LOFAR captured radio emission (orange) in galaxy cluster Abell 1314, superimposed on an inverted visible-light image (grayscale). The extended radio emission in this image comes from past collisions with other clusters.

There's much more to come. The first phase of the survey covers 424 square degrees, centered on the handle of the Big Dipper. But that's only about 2% of the eventual survey area, which will cover the whole northern sky.

■ GOVERT SCHILLING

SOLAR SYSTEM

Pluto & Charon Missing Small Craters

SCIENTISTS STUDYING New Horizons images of craters on Pluto and its moon Charon have concluded that the outer solar system contains fewer small objects than expected.

In the March 1st *Science*, Kelsi Singer (Southwest Research Institute) and colleagues tallied up the craters on old, smooth surfaces on Pluto and its largest moon. If the Kuiper Belt is — or was — crowded enough for frequent collisions, astronomers ought to have seen many more craters formed by small objects than by big ones.

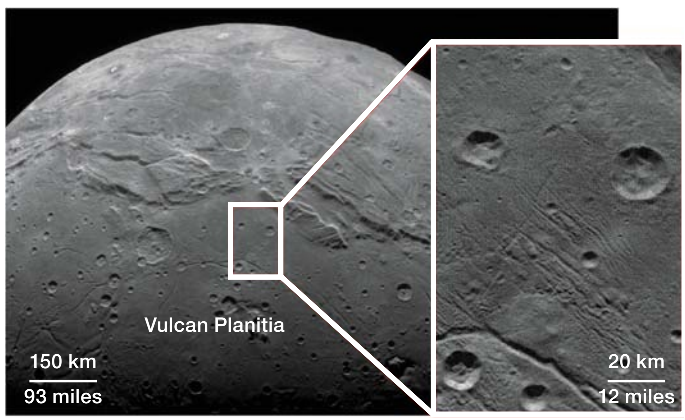
But what Singer's team found was that craters less than 13 km (8 miles) across were surprisingly scarce on Pluto and Charon. Geological processes such as cryovolcanism and glacial activity would have erased the bigger craters along with the small ones, the scientists say. Moreover, there are no known processes that would preferentially erase smaller craters. The dearth of small craters translates to a lack of Kuiper Belt objects spanning less than 1 to 2 kilometers.

The findings appear to contradict results from a recent star-monitoring survey conducted by Ko Arimatsu (National Astronomical Observatory of Japan) and colleagues, who spotted a single stellar occultation and interpreted it as a kilometer-size Kuiper Belt object passing in front of a background star (*S&T:* May 2019, p. 9). Since even a single find was unexpected, the scientists argued that the discovery points to an *excess* of kilometer-size objects in the outer solar system. However, Arimatsu acknowledges that extrapolation from a single event is difficult; one kilometer-size object could still be consistent with the New Horizons results.

If small objects — and thus collisions — are truly scarce in the Kuiper Belt, then its population contains isolated and pristine remains of the early solar system. Further study of the population's size distribution could help scientists distinguish between different theories of planet formation.

■ MONICA YOUNG

● Read more about both studies at **https://is.gd/smallKBO**.



▶ Singer and colleagues counted craters on the smooth, geologically stable Vulcan Planitia on Charon, shown here.

SURVEY FIELDS: RAFAËL MOSTERT / LOFAR SURVEYS TEAM / SLOAN DIGITAL SKY SURVEY; PLUTO: NASA / JHUAPL / SWRI / K. SINGER by Shannon Hall

Lighting a Cosmic Fuse

Type Ia supernovae — the cosmic mileposts that helped prove the universe is accelerating — are not as uniform as astronomers once thought they were.

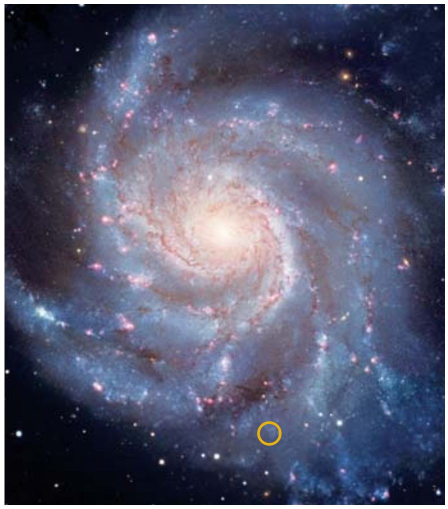
Peter Nugent knew he had to act fast. It was a little past noon on August 24, 2011, and he was sifting through images of the previous night's sky when he discovered a new point of light: a young supernova explosion. While the explosion was only 12½ hours old, it was already so bright that it outshone the nearby stars in its galaxy and so large that its ballooning debris cloud would easily fill the orbit of Saturn.

Nugent checked the time of the image and saw that another 16 hours had already passed. He dashed to the phone.

Some 20 minutes later, a colleague swung a telescope in the Canary Islands toward the blast and shot a spectrum. The speedy observations told Nugent (University of California, Berkeley) that the supernova had surged in brightness: It was now five times more luminous than it was in the discovery images. It had also doubled in size, the debris cloud now large enough to fill the orbit of Uranus.

But perhaps the most exciting characteristic of the "new star" was that it sat within the spiral arms of the Pinwheel Galaxy, a mere 21 million light-years away. Catching a supernova so soon after the explosion was rare, but catching an early supernova so close was the chance of a lifetime.

Nugent spent the next 36 hours awake, convincing those running space- and ground-based telescopes to observe the supernova. As night's shadow swept from the Atlantic across North America, Lick Observatory and the CARMA radio array peered at the new star. Then, as darkness continued farther west and hit the Pacific Ocean, the Gemini North Observatory and the Keck Observatory in Hawai'i swung their mirrors in its direction. In all, seven observatories imaged the supernova that first night. In the days and weeks that followed, SN 2011fe became the most studied supernova yet.



PINWHEEL LIGHTS UP In August 2011 a white dwarf exploded in M101 as a Type Ia supernova.

And it wasn't just any supernova: SN 2011fe was a special kind of supernova, called Type Ia. These outbursts each explode with a near-identical luminosity, brightening and fading in a predictable pattern that allows astronomers to calculate their cosmic distance — making them a crucial tool in cosmology. In an advance that secured the 2011 Nobel Prize in Physics, for example, they helped prove that the universe is expanding at an ever-increasing rate.

But just what causes these identical flares? Astronomers have long thought that Type Ia supernovae are like fireworks built in a cosmic assembly line, each set off by the cataclysmic death of a white dwarf (the stellar remnants that cram the mass of the Sun into the volume of Earth). Indeed, the immense amount of data enabled Nugent's team to confirm that the star that went bang was the size of a white dwarf.

But there's one problem: White dwarfs can't explode on their own. They are remarkably stable, so something else has to trigger their eruptions — and astronomers don't agree on what that something is.

"It's crazy that these are some of our fundamental cosmological probes and we don't know what causes them," says Ryan Foley (University of California, Santa Cruz).

But thanks to that fateful observation in 2011 and others since, many astronomers have come to accept what they have long denied: that there might be more than one way to create a Type Ia supernova. That means that the standard candles cosmologists depend on are anything but standard.

B. J. FULTON (2); EXPLOSION GRAPHIC: TATIANAZAETS / ISTOCK / GETTY IMAGES PLUS


SN 2011fe

A Tale of Two Supernovae

A Type Ia supernova is easy to pick out from the crowd. It increases in brightness in a matter of hours, before fading over the course of hundreds of days. Its spectrum contains silicon, calcium, and iron, but no hydrogen or helium. Because Type Ia explosions look radically similar to one another, astronomers long assumed that they originated from an identical physical process, one in which white dwarfs play a starring role.

The problem is, something has to push them over the edge. "You have a mysterious agent — some kind of hidden assassin — who came along and caused this white dwarf to explode but did so in such a way that it left very little evidence that it was ever there," says Stuart Sim (Queen's University Belfast, UK). That assassin is likely a companion star, but astronomers are unsure if it's another white dwarf, a star like the Sun, or a giant bloated star that ran out of hydrogen fuel in its core long ago.

It's a crucial question because the nature of the companion determines the exact cause of death. If the companion is a white dwarf, then the two stars will spiral in toward each other and collide in a violent explosion. But if the companion is a larger star, either like the Sun or a red giant, then the white dwarf will siphon matter from it until it ignites a runaway thermonuclear reaction in the core and blows itself to smithereens.

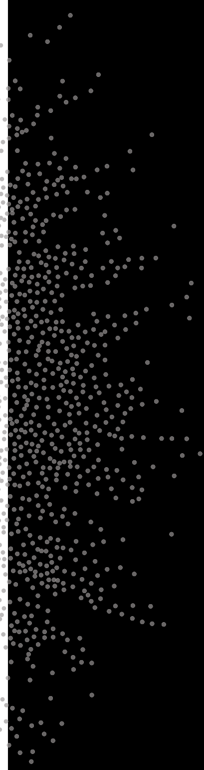
Researchers have long argued over which scenario is true. The thinking throughout most of the 20th century was that the "hidden assassin" is a comparatively larger star, which could feed the dwarf until it reaches a critical limit. The dwarf actually scrunches down in size as it siphons material from its companion star, which causes its density and temperature to skyrocket. Eventually, conditions become so extreme that there is no longer space for the atoms' electrons, which are forced into the nuclei, igniting a runaway thermonuclear reaction that forces the star to explode. Because that reaction always occurs when the star hits the same density and temperature, it explodes with an identical brightness — explaining why all Type Ia supernovae look alike.

Or so we thought. Then in 1991, two supernovae were discovered that did not explode at their expected luminosities — one was fainter and one was brighter. "That meant they were not standard candles and you really had to worry about this," says Alexei Filippenko (University of California, Berkeley). Luckily, astronomers soon discovered that the brightest supernovae fade more slowly than their dimmer

EXPLOSION GRAPHIC: TATIANAZAETS / ISTOCK / GETTY IMAGES PLUS

THE MASS LIMIT

Astronomers often speak of Type Ia supernovae as the explosions of white dwarfs that hit a specific mass limit of 1.4 Suns, called the Chandrasekhar mass. But in fact the dwarf never reaches that limit: If it did, gravity would force it to collapse, not explode. Instead, as the dwarf approaches the Chandrasekhar mass, it contracts, causing the internal temperature and density to spike. At a certain point — which is incredibly close to the Chandrasekhar mass — carbon fusion ignites and blows the white dwarf apart.



▶ SCENARIO #1: SINGLE DEGENERATE
A white dwarf paired with a much larger star — such as an aged red giant — can siphon gas from the companion star and skirt itself in a disk *(A)*. As the disk gas falls onto the white dwarf, the temperature and density build until carbon fusion ignites and the white dwarf explodes with a standard luminosity *(B)*.

▶ SCENARIO #2: DOUBLE DEGENERATE
Over billions of years, two white dwarfs will inspiral toward each other by emitting gravitational waves *(A)*. Eventually they will collide and be destroyed *(B)*. Because the white dwarfs don't have to reach a critical density and temperature in order to explode, the resulting flash could have a range of luminosities depending on the white dwarfs' masses.

> **"You have a mysterious agent — some kind of hidden assassin — who came along and caused this white dwarf to explode but did so in such a way that it left very little evidence that it was ever there."**
> **—Stuart Sim**

kin, meaning that astronomers could correct for the difference and continue to use the objects in cosmology. As many scientists say, they're not standard candles, but they're *standardizable* candles.

Still, scientists did not know why some Type Ia supernovae reached different brightnesses, causing many to reconsider an alternate possibility: White dwarfs were instead dancing a deadly waltz with their own kind.

Because the dwarfs collide in this scenario, the final system won't necessarily hit the same critical conditions every time. White dwarfs in a binary can vary in weight from 0.3 to 1.4 times the mass of the Sun, so the final system could theoretically vary from 0.6 to 2.8 Suns (although having two massive white dwarfs paired up is highly unlikely). Convert that to energy and you have a wide range of luminosities, thus explaining the oddities discovered in 1991.

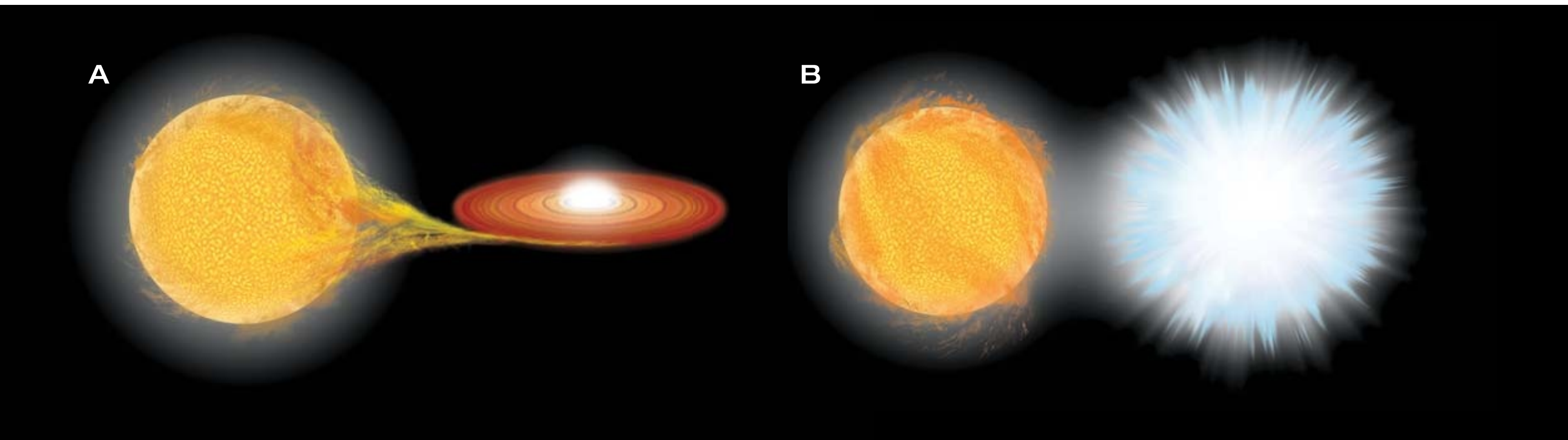
By 2011, the pendulum had swung toward this so-called *double-degenerate scenario*, where "degenerate star" refers here to a white dwarf (as opposed to the *single-degenerate scenario*, where there is only one dwarf and a large star). Not only can low-mass companions explain the range of brightnesses, but they also explain why astronomers had failed to spot bereaved companion stars within the debris of ancient supernova remnants.

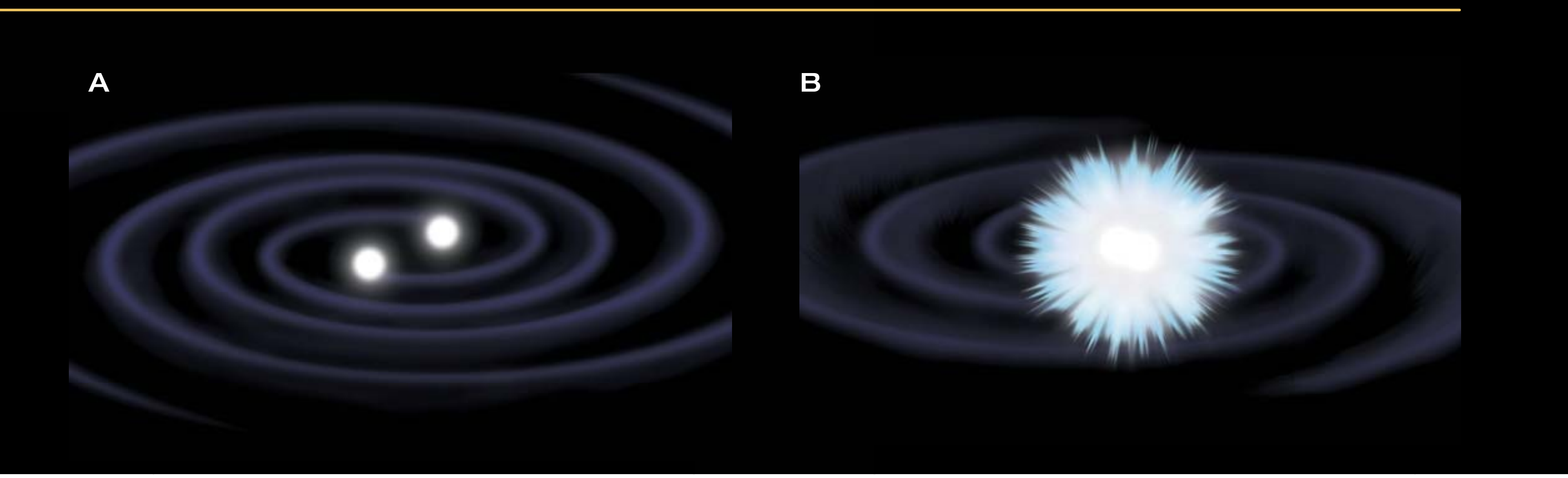
Indeed, when Nugent discovered the nearby supernova, he was able to scour previous images to search for signs of a companion. But Hubble images of the Pinwheel Galaxy taken before the blast revealed no trace of a star at SN 2011fe's location, leaving him to argue that the culprit could be no larger than a second white dwarf.

More Than One Pair Can Tango

The case, however, was far from closed. Consider another stellar blast also detected by Nugent and his colleagues in 2011. At first, the supernova, known as PTF 11kx, looked like

GREGG DINDERMAN / S&T (2)





a typical Type Ia. But then, roughly 60 days after it exploded, its spectrum started to shapeshift, revealing bright hydrogen emission lines. The ballooning cloud of debris had slammed into shells of circumstellar gas that had almost certainly been expelled from a companion red giant star.

It was quite the surprise: Astronomers had generally favored one scenario or the other. Instead, they had copycat killers on their hands. "I think this is a case where Occam's razor has failed us," says Andrew Howell (University of California, Santa Barbara).

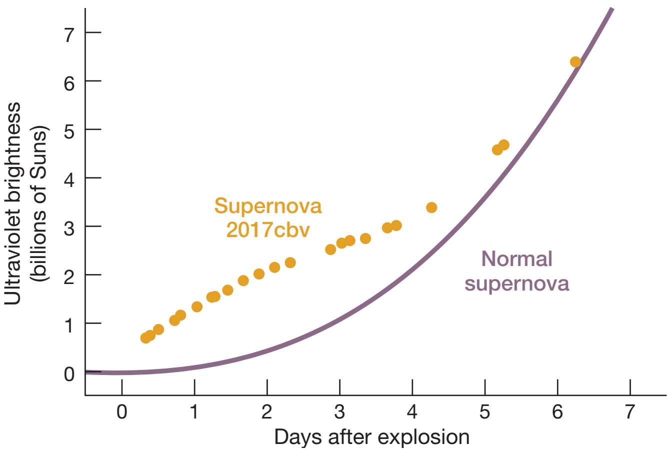
Still, scientists only had one clear example of a Type Ia supernova sparked by a large star. In 2010, Daniel Kasen (University of California, Berkeley) suggested a way to find more. He predicted that when the white dwarf explodes, the fireball of expanding ejecta will slam into the surviving companion star — a run-in that heats up the ejecta and causes it to brighten. That event should produce an abnormal blue bump in the supernova's early light curve.

Astronomers searched for this signal in existing data sets but found no definite examples — until 2017. On March 10th, David Sand (University of Arizona) discovered a Type Ia supernova on the outskirts of the spiral galaxy NGC 5643. With help from the Las Cumbres Observatory, a network of (then) 18 telescopes around the world that monitors objects continuously, he and his colleagues observed the supernova every 6 hours for 5 days. The resulting chart of its changing luminosity revealed a temporary jump in brightness that matched the prediction for what would happen as the supernova blast struck a companion star. It was further evidence that Type Ia supernovae can form with the help of a large star.

And it was not the only one. Last year, astronomers also spotted evidence for this elusive blue bump within a Type Ia supernova's light curve that had been closely monitored by NASA's planet-hunting Kepler space telescope. Unlike previous observations, which often miss the supernova's earliest moments, Kepler imaged the star before it exploded and every 30 minutes thereafter — providing the best evidence yet that a star can explode with the help of a large companion.

With a growing number of observations supporting each scenario, many astronomers now suspect that doomed white dwarfs tango with a variety of companions, large and small. That has caused researchers to move on to the next game: determining how often single-degenerate and double-degenerate scenarios each produce Type Ia supernovae. Ryan Foley's studies of sodium in supernova remnants, for example, indicate that roughly 25% have the telltale outflows of gas they'd expect from the winds blowing off red giants or other nondegenerate stars. As such, he argues that roughly a quarter of Type Ia supernovae are triggered by larger companions.

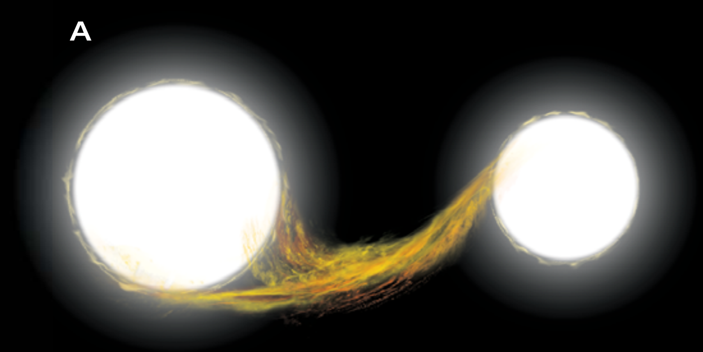
Melissa Graham (University of Washington) thinks the number is much lower, however. She recently conducted a



▲ **THE BLUE BUMP** Type Ia supernovae brighten and fade in a predictable pattern. Usually, their ultraviolet brightness follows the purple curve. But SN 2017cbv was abnormally bright its first two days, a boost astronomers think comes from the explosion's debris slamming into a companion star.

GREGG DINDERMAN / *S&T* (2)

▶ **SCENARIO #2½: DOUBLE DETONATION**
In a twist on the double-degenerate scenario, one white dwarf may steal from the thin layer of helium enveloping a second, less massive (but wider) dwarf *(A)*. Eventually enough gas piles up on the more massive dwarf to trigger an explosion *(B)*. This surface explosion sends a shock wave deep into the dwarf that kicks off a detonation in the carbon core, producing a supernova *(C)*.



survey with the Hubble Space Telescope that took a second look at the locations where Type Ia supernovae had once exploded. Because SN 2011kx only displayed hydrogen — and hence proof of a gaseous companion — roughly 60 days after its explosion, she worried that astronomers might have missed that signature in other supernovae that weren't observed for so long. But after observing 70 different supernovae that exploded one to three years ago, she found only one that contained those telltale hydrogen emission lines. Assuming that such lines come from a large star that triggered the Type Ia supernovae, such scenarios occur less than 5% of the time.

Moreover, Graham notes that the finding only proves a large star is nearby, not that it pushed the star to explode. "It's like a guilt-by-association situation," she says, "which isn't a strong case." It appears that, while possible, the single-degenerate scenario may be rare.

Twists and Turns

Now that astronomers have determined that both scenarios are at play, there are still a number of other questions — mostly about how the explosion occurs. Does it start at the center of the white dwarf, for example, or does it start at the interface between the core and the envelope? Could there be two explosions, one that starts on the surface that sparks an explosion below?

The possibilities have caused many scientists to argue that perhaps a number of scenarios — each a variant on the single- and double-degenerate scenarios but with a unique explosion mechanism — produce Type Ia supernovae. "I would be surprised if there were just two paths, actually," says Saurabh Jha (Rutgers).

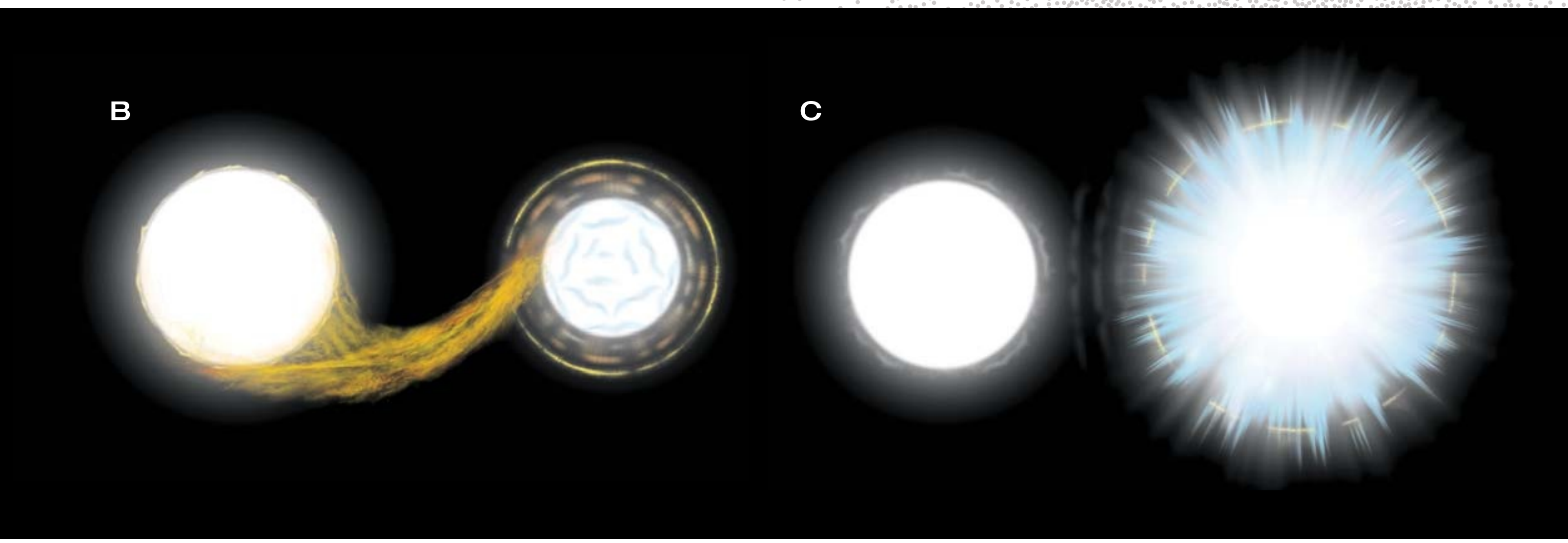
Take a new twist on the double-degenerate scenario. Typically, models suggest that the two white dwarfs spiral toward each other and merge. But Ken Shen (University of California, Berkeley) has been honing a slightly different idea for roughly a decade, one that relies on an often-overlooked element within white dwarfs: helium. White dwarfs are mostly composed of carbon and oxygen, but a thin layer of helium often overlies the bulk. Shen thinks that one white dwarf may steal enough of the other's helium to ignite its outer layer. This detonation squeezes the white dwarf, sending a shock wave deep below that ignites a second explosion — the Type Ia detonation — in the star's core.

With the primary white dwarf annihilated, the companion — which until now had been orbiting the dwarf at rapid speeds — has nothing to hold it in place and shoots off into space. Shen even published a study in 2018 that shows three such white dwarfs speeding through the galaxy. Not only are

DIFFERENT DWARFS

White dwarfs are the dense, naked cores of dead stars, exposed when the aging star shed its outer layers. They're primarily carbon and oxygen. Many have outer helium envelopes, while others have a thin layer of hydrogen. Some show no signs of either. But when they explode, there's usually no sign of hydrogen or helium in their spectra — that's one of the ways astronomers distinguish Type Ia supernovae from other kinds of stellar explosions.

EXPLOSION GRAPHIC: TATIANAZAETS / ISTOCK / GETTY IMAGES PLUS



they quick-moving, but they possess bizarre characteristics that can be perfectly explained if they underwent such a catastrophic event (*S&T:* Dec. 2018, p. 30).

Stuart Sim says this model is his personal favorite. Although other theories also suggest that a white dwarf can siphon matter from a second, less massive dwarf, the scenarios still require that the primary dwarf reaches critical mass in order to detonate its core. But because the helium model relies on an explosion on the surface to squeeze the core, the explosion can occur well before the star hits that mass. Given that there should be more low-mass white dwarfs than high-mass white dwarfs in the universe, which might create duos that never reach critical mass, that’s an attractive feature.

These scenarios might sound wild, and they are: None of these ideas is exactly natural. “If you were to talk to a 17th-century physicist about all the things that happen in the universe, I doubt any of these things would have come to mind,” Sim says. “They have been thought up by people who are scratching their heads thinking about how we can arrange conditions for this rather spectacular but strange thing to occur.”

Blazing Forward

Although scientists do not fully understand the various channels that lead to Type Ia supernovae, the explosions’ role as cosmic milestones is on solid ground. “No one needs to give back their Nobel Prize or anything like that,” Foley says.

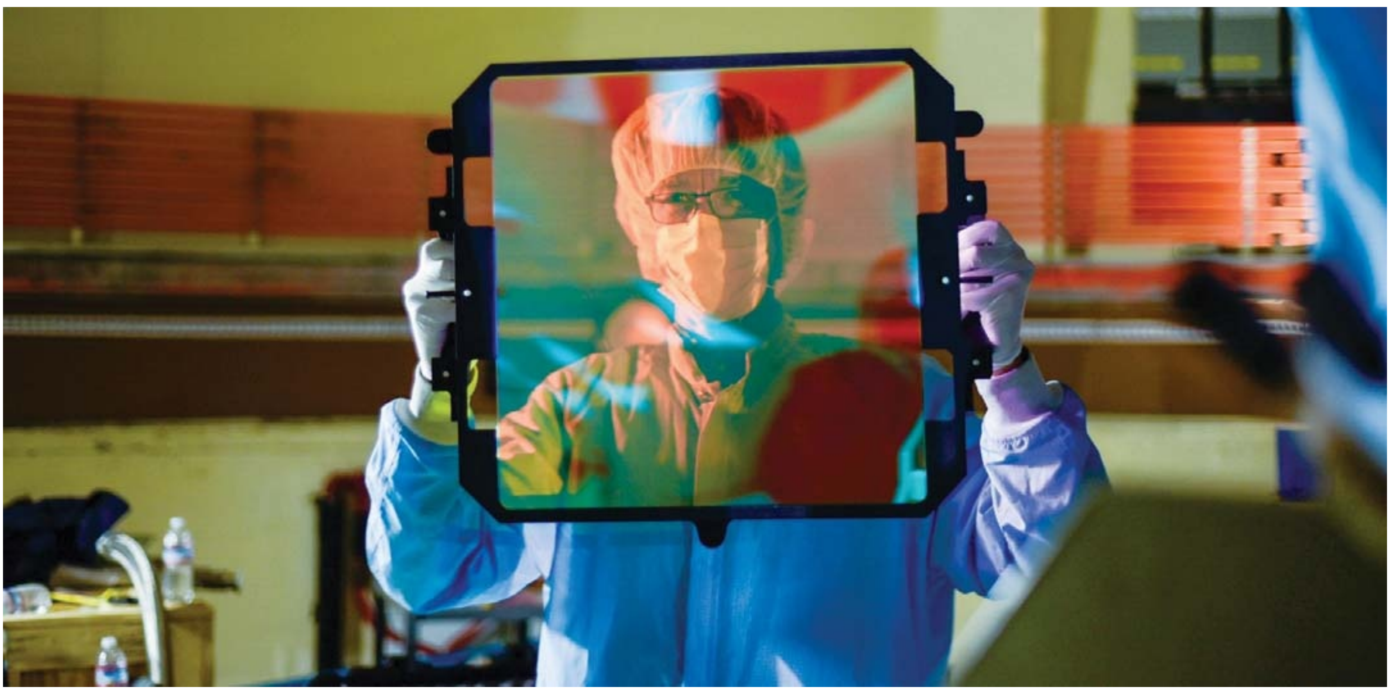
That’s because empirically-speaking, astronomers know the brightness of every Type Ia supernova’s flame fairly well.

Although scientists do not fully understand the various channels that lead to Type Ia supernovae, the explosions’ role as cosmic milestones is on solid ground.

A better understanding of what ignites that flame will only improve the precision of those measurements — especially if those systems change over time.

Currently, astronomers think that double-degenerate systems might take longer to explode than single-degenerate systems, because it can take billions of years after the white dwarfs form for them to spiral in close enough to each other for something explosive to happen. That could explain why so many Type Ia supernovae in today’s universe seem to come from double-degenerate systems, not single-degenerate ones. It also suggests that a larger fraction might have come from single-degenerate systems in the early universe. If one pairing explodes at a slightly different luminosity than the other, then it could affect the precision of our cosmological measurements.

And that precision is crucial in illuminating dark energy, the poorly understood phenomenon that propels the expansion of the universe (*S&T:* May 2018, p. 14). A precise measurement of the expansion rate throughout cosmic history will help astronomers discover whether or not dark



CALTECH OPTICAL OBSERVATORIES

▲ **WIDE-FIELD VIEW** Technical lead Roger Smith inspects one of three wide-field optical filters in the Zwicky Transient Facility’s camera. The survey scans the entire visible sky over three nights with a field of view equivalent to 247 full Moons. Astronomers expect it to find tens of thousands of cosmic explosions of various types each year.

energy has changed over time. If the rate is stable, then a model that relies on the cosmological constant — which suggests that dark energy arises from the short-lived virtual particles and antiparticles within empty space — might be the best explanation. But if it does change, then a model that relies on quintessence — which suggests that dark energy results not from the vacuum of space but from a field that pervades spacetime — might be more appropriate (see page 22).

A better understanding of Type Ia supernovae will help scientists pin down not only dark energy and our cosmic past but also the fate of our universe, which is determined by dark energy's true nature.

Filippenko argues that one way forward is to study the extreme cases. Consider a lesser-known class dubbed Type Iax. These explosions look like Type Ia supernovae but move slower, fade faster, and have less energy overall. You can almost think of them as a miniature stellar blast.

"They're sort of like this different beast," Foley affirms. "But they're similar enough that we know some of the physics has to be shared."

The data scientists have gathered suggest that Type Iax supernovae occur in single-degenerate systems. But in this situtation, the companion star has already lost its outer layer of hydrogen, meaning that the white dwarf accumulates helium instead. Jha speculates that perhaps that's the difference between normal Type Ia supernovae and Type Iax supernovae — one accretes hydrogen and the other helium.

Unfortunately, scientists have very few examples of oddball Type Ia supernovae (see sidebar at right for three types). So they're scouring the skies in search of every system that might soon explode.

Among those efforts is the Zwicky Transient Facility in California, which reached first light in late 2017 (*S&T:* Mar. 2018, p. 13). Like its predecessor, the Palomar Transient Factory (which caught both of the game-changing supernovae in 2011), the ZTF scans the skies nightly and alerts astronomers if any object's brightness has changed. Meanwhile, in the Southern Hemisphere, the future Large Synoptic Survey Telescope in Chile is expected to detect at least half a million supernovae over its lifetime.

But the key isn't simply to find new supernovae; it's to catch them early and then observe them often. In the past, supernovae were often imaged once every 3 or 4 days — time gaps that meant astronomers might miss crucial details. But observatories like the Transiting Exoplanet Survey Satellite (*S&T:* Mar. 2018, p. 22) enable astronomers to observe these explosions every 30 minutes. Follow-up will be done from the ground, including by those in Andrew Howell's Global Supernova Project, a collaboration of 150 astronomers around the world who will gather light curves and spectra when supernovae are discovered.

The Weirdos

While most Type Ia supernovae look strikingly similar to one another, astronomers occasionally stumble upon one of what they call "the weirdos." Some we've discussed in the story — such as the super-luminous and under-luminous supernovae discovered in 1991, and Type Iax — but here are a few more:

Calcium-Rich Supernovae In 2001, astronomers discovered an odd supernova — it was the first in a class of objects that astronomers later realized had a huge amount of calcium in their ejecta. These explosions may occur when a low-mass white dwarf steals enough helium from its binary companion to boost its surface temperature and pressure, igniting a thermonuclear explosion. The blast would blow off at least the outer layers of the white dwarf star — and half of that lost material is calcium.

02es-like Supernovae Similar to Type Iax supernovae, these objects explode with less energy than normal. They're also much cooler. "There aren't that many examples of these, but they are clearly something weird and different, and they almost certainly come from white dwarfs," Foley says.

06bt-like Supernovae These supernovae are true weirdos. They look similar to normal Type Ia events except for some subtle differences, like the fact that their temperatures seem inconsistent with their brightnesses. "Those are the ones that actually trouble me for cosmology," Foley says. That's because with minimal information, they perfectly resemble Type Ia supernovae.

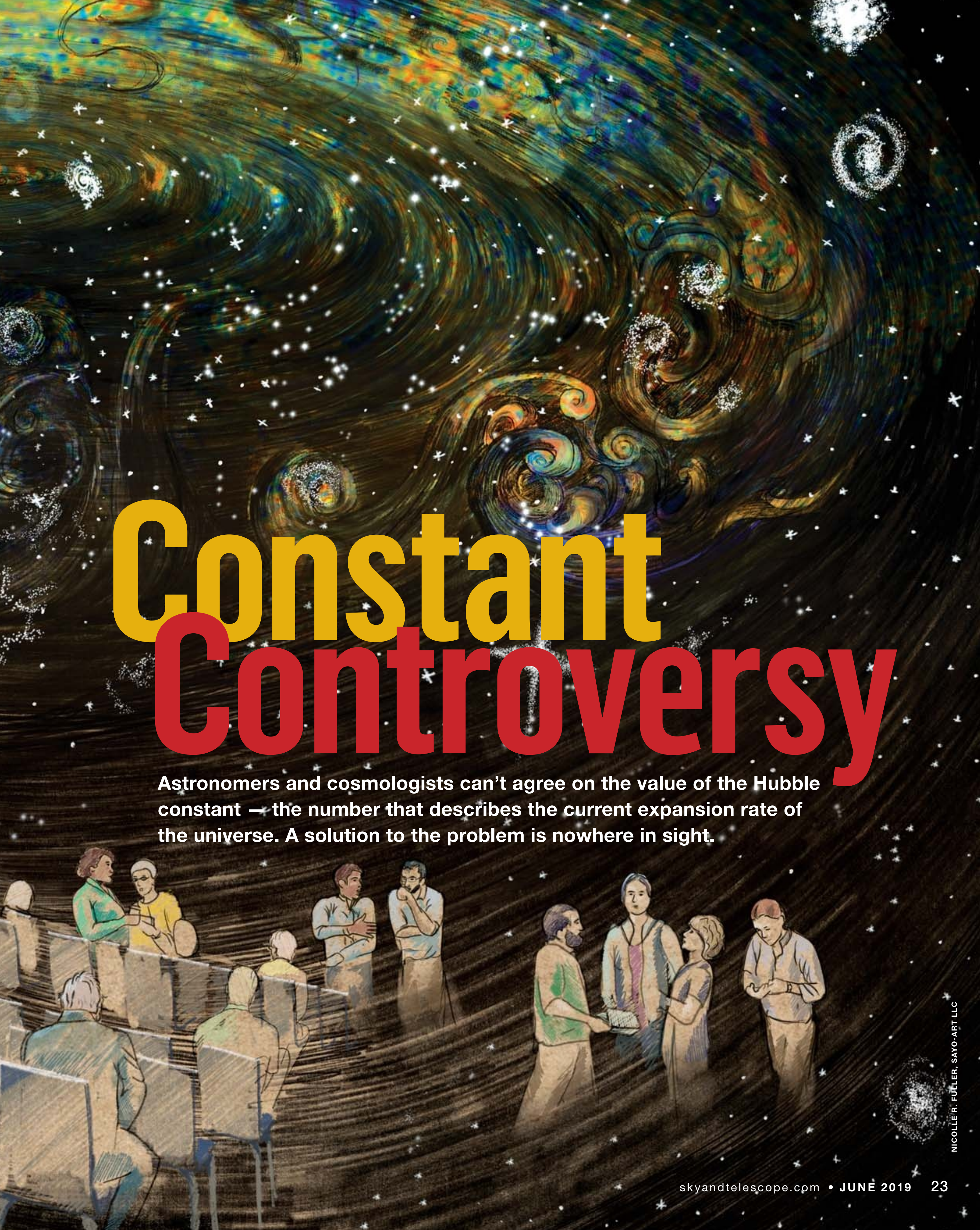
With so many surveys online or in the works, astronomers are optimistic that they'll soon have enough data to pin down what sets these explosions in motion and how often. "No supernova can hide from us now," Nugent says. "We're going to find it during the night or the next night every single time."

■ **SHANNON HALL** is an award-winning science journalist based in the Rocky Mountains. Her favorite supernova remnant to observe is the Crab Nebula, created by a star that exploded in AD 1054.

EXPLOSION GRAPHIC: TATIANAZAETS / ISTOCK / GETTY IMAGES PLUS

Constant Controversy

Astronomers and cosmologists can't agree on the value of the Hubble constant — the number that describes the current expansion rate of the universe. A solution to the problem is nowhere in sight.



NICOLLE R. FULLER, SAYO-ART LLC

In the 1980s, when people in East and West Berlin still lived in two very different universes, politically speaking, Checkpoint Charlie was an intimidating and heavily guarded crossing point between communist oppression and liberal democracy. Today, it is one of the most popular tourist attractions in the capital of united Germany. But 29 years after the Berlin Wall opened in 1989, another insuperable barrier, this time scientific in nature, manifested itself just 600 meters commieward of Checkpoint Charlie, in the Auditorium Friedrichstrasse. On a drizzly Saturday in November 2018, this unadorned Soviet-style building served as the intellectual battleground for a cosmological Cold War.

Some 130 scientists flocked to a one-day symposium here to discuss an unnerving crisis in our understanding of the universe. It was a diverse bunch from all over the world: astrophysicists and cosmologists, observers and theorists, young postdocs and eminent professors. Some of them had spent more time on the plane than they would in the lecture room. Their mutual worry: The universe appears to be expanding too fast, and no one knows why. At the end of the meeting, Brian Schmidt (Australian National University, ANU), co-recipient of the 2011 Nobel Prize in Physics, said: "I'm even more puzzled after today."

Here's what astronomers and physicists alike scratch their heads about: Detailed observations of the cosmic microwave background (CMB, the cooled-down "afterglow" of the Big Bang) yield a very precise value for the current expansion rate of the universe, with an error margin of just 1%. However, measurements of objects in the "local" universe arrive at a number that is also fairly precise, but a whopping 9% higher. "And neither side has obvious weak points," says Matthew Colless (ANU), one of the organizers of the Berlin symposium.

According to co-organizer Matthias Steinmetz (Leibniz Institute for Astrophysics Potsdam, Germany), the determination of the universe's current expansion rate "has a history of crisis and controversy." Indeed, the earliest guesstimates for the Hubble constant (H_0, a measure of the present-day expansion rate) seemed to indicate that the universe was much younger than Earth. And 30 years ago, you'd be offered values that differed by a factor of two, depending on whom you asked.

"The good news is that the controversy was much larger when I started to work in cosmology" than it is now, quips theorist Abraham Loeb (Harvard University). "So in a sense, there's progress in the field."

But Loeb is worried, too. Cosmology has become a high-precision science, and never before has the gap between two different estimates of the Hubble constant been so statistically significant.

Climbing up the Distance Ladder

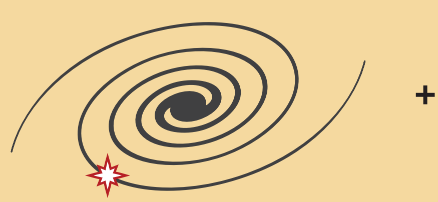
In March 1929, American cosmologist Edwin Hubble published observations that, for the first time, revealed that our universe is expanding. According to Hubble's measurements, distant galaxies appear to be receding from us at a higher velocity than nearby galax-

How Fast Does the Universe Expand?

The expansion of the universe cannot be expressed as a simple velocity. Galaxies are not receding from each other through some imaginary static space. Instead, space itself is expanding, thereby pushing the galaxies away from one another. As a result, the distance between two galaxies increases over time. The more space there is between the two galaxies, the faster their mutual distance is growing, in kilometers per second. In other words, there's no single "velocity value" for the expansion of the whole universe – it all depends on the scale you consider. It's like monetary inflation: The inflation rate for 2018 cannot be expressed in dollars (that would only work for a particular sum of money), but must always be given as a percentage, or a proportionality constant.

Not that the universe is expanding that fast. In fact, cosmic distances increase by only some 0.01% in 1.4 million years. In other words: If the current distance to a remote galaxy is 100 million light-years, it will increase by one light-year every 140 years or so. A "recession" velocity of one light-year per 140 years corresponds to about 2,150 kilometers per second (4.8 million mph). But a galaxy at a distance of 200 million light-years appears to "recede" twice as fast, at some 4,300 kilometers per second. Thus, the "recession" velocity is growing by 21.5 kilometers per second for every additional million light-years, or by some 70 kilometers per second for every additional megaparsec (Mpc; 1 parsec equals 3.26 light-years). There's your proportionality constant, H_0: 70 km/s/Mpc.

How Astronomers Calculate H_0 from Supernovae



Distance: Astronomers spot a standard candle star or supernova in a distant galaxy. They calculate how far away the galaxy has to be in order for the star to look as faint as it does.

H_0 FROM SUPERNOVAE: GREGG DINDERMAN / *S&T*; SPECTRA: VOLKER GAIBLER/HITS, SDSS, ESO; EXPLOSION GRAPHIC: TATIANAZAETS / ISTOCK / GETTY IMAGES PLUS ies — something that (unknown to Hubble at the time) had been predicted to hold in an expanding universe by Belgian cosmologist and Jesuit priest Georges Lemaître two years earlier. The Hubble-Lemaître Law describes this linear relationship between distance and "recession" velocity; the proportionality constant became known as the Hubble constant, or, more precisely, the Hubble parameter, because its value slowly changes with time.

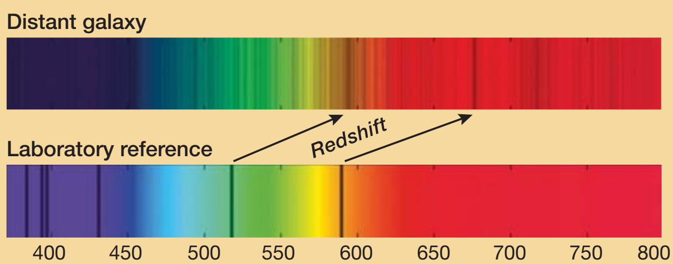
However, the true value of the Hubble constant, measured in kilometers per second per megaparsec (km/s/Mpc, see box "How Fast Does the Universe Expand?"), turned out to be elusive. To determine it, you need to know both the cosmological "recession" velocity of a galaxy and its distance. In principle, the recession velocity (the rate at which a galaxy's distance is increasing due to the expansion of the universe) can be found by measuring the redshift: The more time the galaxy's light waves spend traveling through expanding space on their way to Earth, the more they are stretched to longer (redder) wavelengths. But for a nearby galaxy — one for which it's relatively easy to measure the distance — the redshift measurement is compromised by the galaxy's real motion through space. These spatial velocities can be as high as a few hundred kilometers per second. And for remote galaxies — the ones for which any spatial motion is negligibly small compared to the cosmological recession velocity — it's frustratingly hard to measure their distances.

Over the decades, astronomers have set up an elaborate distance ladder to establish distances to other galaxies. Cepheid variables — luminous pulsating stars — are a key ingredient of this technique. The more luminous a Cepheid is, the slower it pulsates. Henrietta Swan Leavitt at Harvard College Observatory discovered this *period-luminosity relationship* in the early 1900s, and it's now known as the Leavitt Law. So if you find a Cepheid in a remote galaxy, its observed period tells you how luminous it is, and the star's apparent brightness then reveals the galaxy's distance.

Using the eagle-eyed vision of the Hubble Space Telescope, which was designed in part for this work, a team led by Wendy Freedman (now at the University of Chicago) succeeded in identifying Cepheid variables in spiral galaxies at distances of hundreds of millions of light-years. "The final results of our Key Project, published in 2001, yielded a Hubble constant of 72 km/s/Mpc," she says, "but the uncertainty in that value was some 10%." Still, this was a huge achievement: Before the launch of Hubble in April 1990, the best estimates for H_0 ranged from 50 to 100 km/s/Mpc. Moreover, the Hubble results enabled astronomers to calibrate other distance indicators that could be used farther out, where individual Cepheids can't be seen anymore.

One of those standard candles are Type Ia supernovae — the catastrophic detonations of white dwarf stars that become too massive to resist their own gravity, either by accreting matter from a companion star or by merging with another white dwarf (see page 14). Since the temperature and density at which a white dwarf succumbs to gravitational collapse is usually the same, Type Ia supernovae explode and fade in a standard pattern, and from these light curves it's pretty straightforward to deduce their true luminosity. Once calibrated, a comparison with the observed apparent brightness yields a distance estimate. (Some other ways of determining cosmic distances are described in the box on page 27.)

Using Type Ia supernovae as standard candles, two independent teams of astronomers made a startling discovery in 1998: Even though the value of H_0 was not yet known to a high level of precision, the observations of really remote galaxies revealed that the cosmic expansion rate isn't slowing down, as had always been assumed, but is actually speeding up, despite the mutual gravitational attraction of all matter in the universe. This momentous discovery, for which Saul Perlmutter (University of California, Berkeley), Adam Riess (Johns Hopkins University), and Brian Schmidt received the 2011 Nobel Prize in Physics, is now seen as evidence for a



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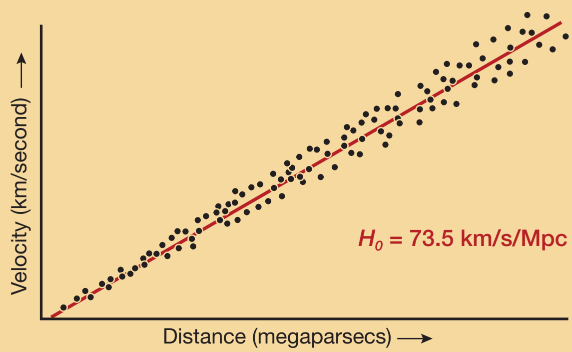


Velocity: The expansion of the universe shifts the standard candle's light to longer, redder wavelengths. The amount of redshift tells astronomers the galaxy's apparent *recession velocity*.

Rate: A plot of the galaxies' distances versus redshifts shows that farther galaxies recede faster. (Simulated data shown.) The slope of the line is the universe's expansion rate.

mysterious dark energy, the true nature of which is one of the biggest mysteries in science (*S&T:* May 2018, p. 14).

Cosmology Crisis

No one realized it at the time, but the discovery of the accelerated expansion of the universe germinated the current crisis in cosmology that was the topic of the Berlin symposium. Not because the concept of dark energy is somehow deficient, but because it works too well.

Over the past 20 years, astronomers have come to realize that we live in a weird universe, dominated by dark energy (denoted by the Greek letter lambda, Λ) and (cold) dark matter (CDM), which is every bit as mysterious (*S&T:* Aug. 2017, p. 28). But although we don't know the true nature of these enigmatic components, the ΛCDM model of the universe successfully accounts for all kinds of cosmological observations, including the large-scale clustering properties of galaxies.

In particular, the ΛCDM model appears to be the only one that is compatible with the observed properties of the cosmic microwave background. The statistical distribution of the "hot" and "cold" spots in the CMB (in fact, temperature differences of less than a ten-thousandth of a degree), as observed in fine detail by the European Planck spacecraft, can only be understood if the universe is largely made up of dark energy and dark matter (*S&T:* July 2015, p. 28). From the 2018 final Planck data release, cosmologists conclude that 68.4% of the matter-energy density of our universe is accounted for by dark energy; 26.5% by dark matter (probably some as-yet-undiscovered type of elementary particle), and no more than 4.9% by ordinary matter, consisting of atoms and molecules. (These fractions don't quite add up to 100% because of rounding and the still-uncertain neutrino mass, among other reasons.)

As Antony Lewis (University of Sussex, UK) told the Berlin audience, these cosmological parameters have now been derived so precisely that it's easy to deduce what the current value of the Hubble constant should be: 67.4 km/s/Mpc, with an error margin of less than 1%. (This deduction takes into account the fact that the cosmic expansion rate first slowed down because of the universe's self-gravity but is now speeding up again, because dark energy started to prevail some 6 billion years ago.) And there appears to be very little wiggle room, says Colless. "It's hard to get rid of [this result] without running into all kinds of other problems."

The same value is arrived at by completely independent results from the Dark Energy Survey (DES). Carried out at

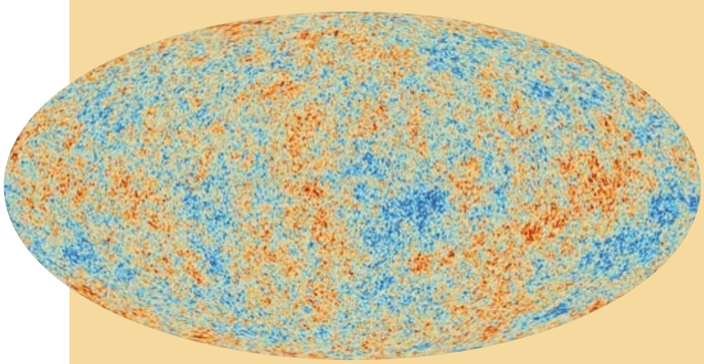
No one realized it at the time, but the discovery of the accelerated expansion of the universe germinated the current crisis.

the Cerro Tololo Inter-American Observatory in Chile, DES looked at the clustering properties of galaxies and at weak lensing — the tiny "shape-shifting" of remote galaxies due to the light-bending gravity of foreground galaxies and clusters (*S&T:* Sept. 2016, p. 34). These results have an error margin of about 2%, says DES theoretical cosmologist Dragan Huterer (University of Michigan).

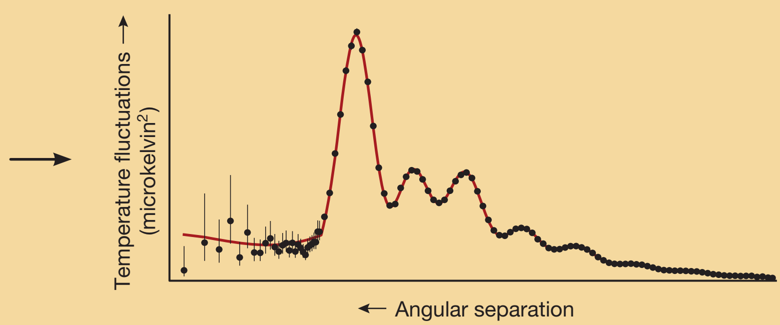
But the lack of wiggle room in these results is causing a problem of its own: They don't jibe with updated "local" measurements of H_0 from Cepheids and supernovae. The 2001 result from Freedman's Hubble Key Project had a large enough range of uncertainty that, at first, there didn't seem to be cause for concern. But over the past years, a team led by Riess has arrived at a much more precise calibration of

H_0 FROM CMB: GREGG DINDERMAN / *S&T*, PLANCK DATA (2): ESA / PLANCK COLLABORATION, GALAXY WEDGE: LEAH TISCIONE / *S&T*; EXPLOSION GRAPHIC: TATIANAZAETS / ISTOCK / GETTY IMAGES PLUS

How Astronomers Calculate H_0 from the CMB



Step 1: Astronomers measure the patchiness of the cosmic microwave background. (Data from Planck shown.)



Step 2: The map gives them the *power spectrum*, which plots how large the temperature differences are between two locations on the sky, depending on how far apart those locations are.

the cosmological distance ladder, and at a correspondingly much more precise value for the Hubble constant. The result: 73.5 km/s/Mpc, with an uncertainty of just 2.2%. "The value hasn't changed very much," he says, "but the uncertainty has come down significantly."

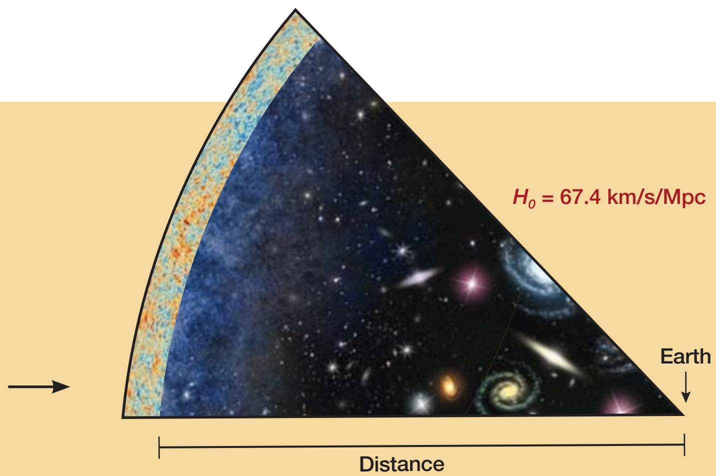
To achieve this high level of precision, Riess's "Supernova, H_0, for Equation of State of Dark Energy" (SH0ES) team determined the parallax, and thus the distance, of 50 Cepheid variables in our own Milky Way Galaxy — a necessary step in accurately calibrating the Leavitt Law. Subsequently, they studied Cepheids in 37 galaxies in which Type Ia supernovae had also been observed. Using the Cepheid distances of these 37 galaxies, the team then calibrated the standard candle properties of Type Ia's. Finally, they derived the Hubble constant from observations of some 300 supernovae in more distant galaxies, for which the redshift is a reliable measure of the cosmological recession velocity.

"Our data set has been re-analyzed by many, many independent groups," Riess says, "and they all arrive at the same value" of 73.5 km/s/Mpc. That's about 9% higher than the value obtained by Planck. Given the precision of both estimates, the statistical significance of this discrepancy is 3.8 sigma, according to Riess. That means the chance of the mismatch being some statistical fluke is about 1 in 7,000. Clearly, there's something amiss.

Huterer agrees. "The Hubble tension is real," he says.

Now What?

While some scientists still think there may be an undiscovered error in either one of the two approaches (or maybe in both!), most believe that the results are solid. But that doesn't



Step 3: Astronomers then deduce the properties the primordial plasma had to have in order to produce this spectrum, including the speed of sound in the plasma and the density of different types of matter. From those, researchers work out what the CMB patterns' true physical size must be. Since they know the apparent size, the comparison provides the distance, which depends on the history of cosmic expansion.

Keep Your Distance

There are various ways to determine the distance to another galaxy:

Variable stars The pulsation period of Cepheids – a particular and easy-to-recognize type of variable star – is related to their peak luminosity. Measuring a Cepheid's period reveals its luminosity; comparing that to its apparent brightness reveals its distance. Similar period-luminosity relationships hold for other types of variable stars, most notably RR Lyrae stars. The relationships need to be calibrated by measuring distances to Milky Way variables by means of the parallax method.

Eclipsing binaries By spectroscopically measuring the orbital speeds of the two components of an eclipsing binary star (a close binary in which the stars mutually eclipse each other), and combining this information with the observed light curve, it is possible to geometrically calculate the physical dimensions of the two stars. Comparing this with their observed temperature and apparent brightness yields a distance. Eclipsing binaries were used in 2013 to determine the distance to the Large Magellanic Cloud to a precision of 2%.

Red giant stars At the end of their lives, Sun-like stars turn into bloated red giants, slowly increasing in size and luminosity. Just before they experience the so-called helium flash, they all produce the same amount of energy. By observing a large number of red giants in another galaxy, it is possible to derive the apparent brightness of this so-called *tip of the red giant branch* (TRGB). Comparing that to the known *absolute* brightness yields the distance. The TRGB method has been calibrated by observing red giants in the Large Magellanic Cloud, which is at a precisely known distance.

Megamasers Excited by X-rays from a supermassive black hole, water molecules in orbiting gas clouds can be stimulated to emit maser light (just like laser, but at microwave frequencies). These maser regions can be seen orbiting the black hole as a disk through very long baseline interferometry (VLBI). Combining the apparent size of the megamaser disk with the actual size that would match the clouds' velocities, derived from spectroscopic observations, yields a precise distance, to within some 3% in the case of M106. Unfortunately, water megamasers are not extremely common, but the technique has proved to be useful in calibrating other "standard candles."

mean they know how to explain the discrepancy. Even very creative theorists like Harvard's Loeb are stumped. "I tried to come up with a solution to present at the symposium," he says, "but I have nothing new to report. It's not a simple problem to solve."

One thing's for sure: The suggestion that our Milky Way Galaxy may sit in a huge local void, which would have a higher-than-average expansion rate (*S&T:* Oct. 2017, p. 12), doesn't work. "That effect is much too small," says Loeb. "Moreover, it would also leave an imprint on the cosmic microwave background."

Riess agrees. "If caused by a local void, the difference between the two estimates of H_0 would be less than a percent, not 9%," he says. Riess is very confident about the high-H_0 results of the SH0ES team, partly because some alternative methods of determining the Hubble constant arrive at a similar value (see box below). "Maybe we're just not creative enough" to solve the riddle, he says.

One far-fetched possibility might be that dark matter has been destroying itself over time, weakening its ability to slow the universe's expansion. But coming up with viable models of decaying dark matter has turned out to be difficult. In Berlin, theoretical physicist Lisa Randall (Harvard University) presented her very preliminary ideas on what she calls a "quintessential solution to the Hubble puzzle," in which dark matter would become less massive over time. "But," she said at the conference, "if the gap remains as large as 9%, this can't be the final solution. It's a very challenging problem to address." Since then she's been able to revise the model to provide "a rather good fit to existing data."

Another potential solution would be a slow change in the "density" of dark energy over cosmological time. Recent X-ray observations of 1,600 distant quasars appeared to indicate just that (*S&T:* May 2019, p. 8). However, "the jury is definitely still out," acknowledges team leader Guido Risaliti (University of Florence, Italy). "We'll have to look at many more models in great detail before we can solve this cosmic conundrum."

Both Randall and Loeb are reluctant to consider speculative theories on modified gravity that might somehow explain away the problem. "That would be unwarranted by common sense," says Loeb. "It would be like killing a fly with an atomic bomb."

Still, according to Freedman, an informal vote amongst scientists during a cosmology conference in Chicago in early October 2018 revealed that the vast majority thought that some form of "new physics" will be needed to solve the mystery. "It's what cosmologists really hope," says Huterer. "Who knows," comments Schmidt, "there might be something fundamentally wrong with our interpretation of the cosmic microwave background."

▶ **THE WALL** Measurements of the cosmic expansion rate bifurcate, with studies that use distance scales set in the early universe favoring lower values than those that use phenomena such as supernovae.

H_0 MEASUREMENTS: GREGG DINDERMAN / *S&T*; EXPLOSION GRAPHIC: TATIANAZAETS / ISTOCK / GETTY IMAGES PLUS

Other Ways to Measure the Hubble Constant

The current expansion rate of the universe can be derived from precise measurements of distances and "recession" velocities of remote galaxies, or calculated from cosmological models and the observed properties of the cosmic microwave background — both approaches are discussed in the main story. But there are other ways to measure the Hubble constant, H_0:

Gravitational lensing The light from remote galaxies and quasars can be split into multiple images by the gravity of a massive foreground object, such as a huge elliptical galaxy or a galaxy cluster. Brightness changes in the lensed object (for example, a supernova explosion in a galaxy, or the temporary flickering of a quasar core) arrive at Earth at different epochs, because each light path has its own associated travel time. From the time differences — and a precise model of the mass distribution of the foreground lens — it is possible to calculate the distances traveled, measuring the Hubble constant to a precision of some 3%, according to Sherry Suyu (Max Planck Institute for Astrophysics, Germany). Her team's latest results yield a value for H_0 between 70.2 and 74.6 km/s/Mpc, in fair agreement with the "local" Cepheid/supernova method.

Baryon acoustic oscillations (BAOs) Some 370,000 years after the Big Bang, free electrons combined with atomic nuclei, and the universe became transparent to radiation. Large-scale pressure waves in the primordial gas, produced by the earlier photon pressure, suddenly froze out. As a result, every high-density lump of matter was surrounded by a sphere with a higher-than-average density at a characteristic distance of something between 400,000 and 500,000 light-years. Consequently, the chance of two galaxies forming at this mutual distance was higher than average. According to Matthew Colless (Australian National University), it's a small effect, invisible to the eye, but statistical studies of the current three-dimensional distribution of 1.5 million galaxies do reveal it, albeit at a much larger characteristic scale, thanks to the expansion of the universe (*S&T:* Apr. 2016, p. 22). The "peak" now appears at a mutual distance of 147 megaparsecs (480 million light-years), and from this value, a Hubble constant of 67 km/s/Mpc can be derived, in accordance with the "cosmological" method.

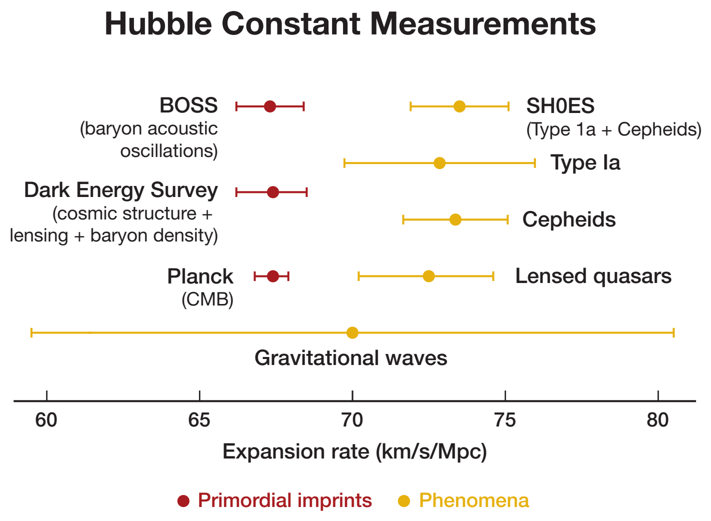
Clarity Will Come

In the closing session of the symposium, Schmidt stoically observed that "clearly, we have not solved things today." The hope is that new and better observations will shed light on the Hubble constant controversy. Astronomers look forward to more precise parallax data from the European astrometric satellite Gaia, to detailed supernova observations by the James Webb Space Telescope, to high-precision measurements of the CMB by the future Simons Observatory in northern Chile, and to planned surveys of the large-scale structure of the universe at various look-back times in cosmic history.

By far the best, however, would be a direct measurement of the expansion of the universe. "It's hard, but worth it," says Rachel Webster (University of Melbourne, Australia). The idea would be to precisely measure the redshift (and, thus, the recession velocity) of a distant quasar, and then to repeat the measurement ten years later, to determine how much it has increased. The expected change in redshift would be on the order of one part in a billion, but with future facilities like the European Extremely Large Telescope (ELT) or the Square Kilometre Array (SKA), this is "potentially doable," according to Webster.

Colless, like most of his colleagues, remains optimistic. "The nice thing about this field is that many outstanding questions will be answered in due time, unlike the situation with cosmic inflation or string theory," he says. "Five years from now, we'll have a much clearer view."

■ *S&T* Contributing Editor **GOVERT SCHILLING** writes about astronomy and space science from his hometown of Amersfoort, The Netherlands. Since he was born, the universe has expanded by about 0.00000044%.



"That would be unwarranted by common sense," says Loeb. "It would be like killing a fly with an atomic bomb."

Clustering and weak lensing Combined with baryon acoustic oscillations and the density of baryons, observations of the clustering properties of galaxies over time and measurements of so-called weak lensing yield an independent, pretty precise value of the Hubble constant. This approach has been followed by the Dark Energy Survey — a comprehensive survey of the positions, redshifts, and shapes of a few hundred million galaxies, carried out with the 520-megapixel Dark Energy Camera on the 4-meter Blanco Telescope at Cerro Tololo, Chile. Preliminary results, published in November 2018, arrive at a value for H_0 of 67.4 km/s/Mpc — again, in good agreement with the "cosmological" estimate.

Gravitational waves In August 2017, astronomers and physicists detected a burst of gravitational waves — minute ripples in spacetime — from a pair of colliding neutron stars (*S&T:* Feb. 2018, p. 32). From the detected wave patterns, it was possible to deduce the masses of the colliding stars and the corresponding energy that was emitted in the form of gravitational waves. Because the waves' amplitude shrank as they traveled, measuring the amplitude in the detectors here on Earth then provided an independent distance estimate for the host galaxy of the merger (NGC 4993): 143 million light-years, with an error margin of 15%. Combining this with the known redshift of the galaxy yields a (rather imprecise) value for the Hubble constant of 70 km/s/Mpc, smack in the middle of the "local" and "cosmological" values. However, according to Bernard Schutz (Cardiff University, UK), future gravitational-wave detectors like the Einstein Telescope and the Cosmic Explorer will be able to "see" every binary neutron star merger in the observable universe, and eventually, the precision of this method may improve to 0.1%.

GALAXY AND STARS
You might not be able to resolve NGC 4030's spiral arms when you observe it, but this galaxy is pleasing nevertheless. It's delightfully bracketed by two 11th-magnitude stars.

Hunting Elusive

You've probably marveled at the grand spiral structure in the Whirlpool Galaxy, teased out the ethereal pinwheel of M101, and traced the delicate branches of Triangulum's grandest showpiece, M33. Few deep-sky objects elicit as much awe as these open-faced spiral galaxies with their spectacular arching arms. The Messier list contains several other examples, and you've no doubt enjoyed at least the brightest of them.

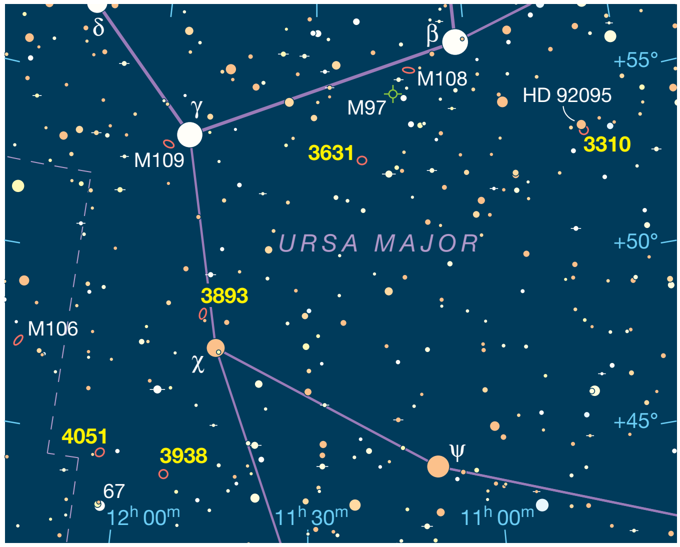
Are there more of these majestic marvels lying just off the well-worn track? The challenging targets on our tour of open-faced spirals from the *New General Catalogue of Nebulae and Clusters of Stars* might reward the patient and careful observer with some delightful surprises. They are all well placed in the June sky.

Learning to eke out faint spiral structure is a useful skill to cultivate. First, of course, one should employ all of the tried-and-true techniques for pushing the envelope of visual detection. You'll want the darkest site you can find on a night of decent sky conditions. Dark adaptation is paramount; take the time to achieve it and take precautions to preserve it. Large aperture will be a plus, but don't discount your chances just because your telescope is of modest aperture. Experiment with magnification; finding the optimum contrast is essential. Most important, however, is simply learning to consider that there may be faint structure visible beyond what is initially evident. You're apt to miss what you don't look for. And, as with any faint deep-sky object, the longer you look the more you'll see.

Some observers like to view a photograph of an object first. It's quite helpful to know exactly where to look for the fainter components of a galaxy. The danger, of course, is in imagining you see something just because you know it's there. I prefer to check the photographs after noting these fainter features to confirm that what I suspected was really there.

NGC 3310 (Arp 217) lies about 4.5° southwest of the Big Dipper's bowl and about 10′ south-southwest of a 5.6-magnitude star (HD 92095). A first impression is of an abruptly bright core within a much fainter halo. Further study reveals a more mottled appearance, and eventually a small north-reaching arm becomes visible. A southern arm is less continuous, comprising a string of bright knots, or stellarings.

The term *stellaring* was probably coined by Brian Skiff and Christian Luginbuhl in their 1990 publication, *Observ-*



▲ **STELLAR NURSERY** NGC 3310 in Ursa Major is an example of a starburst galaxy, where stars are being born at a prodigious rate, especially along the spiral arms.

NGC 4030: ESO / P. GROSBØL; NGC 3310: NASA / ESA / HUBBLE HERITAGE TEAM / STSCI / AURA

Prey

Face-on spiral galaxies are among the most graceful objects to behold and thus are totally worth the bit of effort they require to observe.

▲ **WOOLLY GALAXY** Some galaxies, such as NGC 3521 in Leo, are members of a class of objects known as *flocculent galaxies*. They are so named for their soft, woolly appearance.

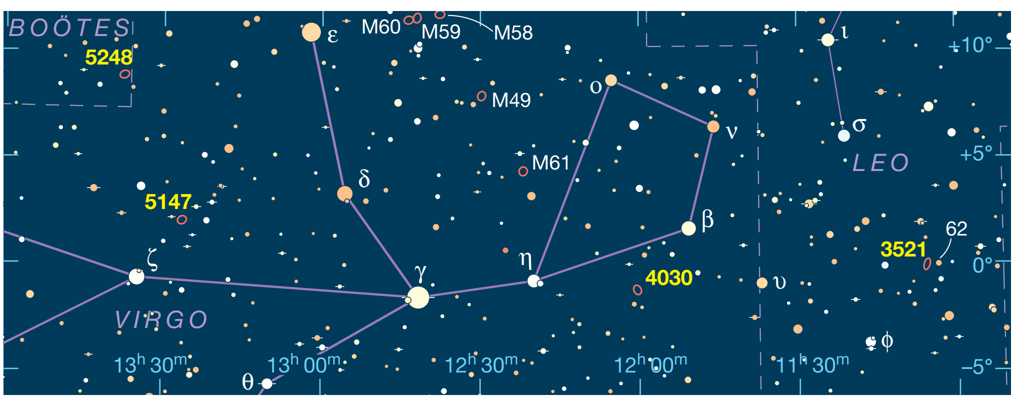
▲ **TAKE A LONG LOOK** The graceful spiral NGC 3938 in Ursa Major requires deeper examination to tease out its structure — but you'll be richly rewarded by the galaxy's delicate spiral arms with their brighter knots.

ing Handbook and Catalogue of Deep-Sky Objects. It perfectly evokes the image of the dense, starlike knots that populate some nebulous objects. The arms of NGC 3310 are short, barely more than stubs, but studying the galaxy until they become detectable will establish the technique you'll employ for the rest of this tour. Owners of large-aperture scopes might pull even more out of this small galaxy, as some very faint and wispy outer arms extend out to the northwest.

Often one has the unmistakable impression of stellar structure even without being able to trace out and separate the individual arms of an object. **NGC 3521** in Leo is a good example. Located in the same field as 6th-magnitude 62 Leonis, this is a rather large spiral tilted at an oblique angle to our line of sight. NGC 3521 is often described as a *flocculent galaxy* — its multiple branching arms give the halo a fleecy appearance. The arms seem to blend together, becoming distinct only at their extreme ends. This is a remarkable object with a great deal to offer the persistent observer, so give it some time. A very subtle dust lane can be detected on its western edge with the faintest hint of nebulosity beyond it.

We might think of the spiral arms as a population of stars orbiting a galaxy as a structured group, but that's not the case. One theory proposes that the arms are essentially density waves that orbit the galactic core independent of the stars within them. Stars move through the arms as they orbit the galaxy. Orbiting gas clouds also move through the arms, where they get squeezed and compressed by the denser gravity there, leading to star formation. Indeed, most of a spiral galaxy's starbirth occurs in the arms, and it's this starburst activity that highlights them.

Also situated below the bowl of the Dipper, **NGC 3631** is a bright face-on spiral with a small bright core and loosely wound spiral arms. At least two major arms wrap around the core counterclockwise. One arm flattens out into a straight band that stretches to the east. The arms can be traced out rather easily by the numerous stellarings that highlight their mottled form. These dense knots suggest regions of star formation where we are seeing the combined light of illuminated or radiating clouds of gas and dust and the hot young stars within them. Regions of star formation in our own neighborhood, like M42 or M17, would likely appear similar to an observer in a far-off galaxy.



About 1° northeast of Chi (χ) Ursae Majoris, **NGC 3893** isn't quite face-on to us. It has one large arm that wraps around its southern edge and stands out prominently to the east of the core. NGC 3893 is smaller than our Milky Way and about 49 million light-years distant. It's likely interacting with tiny NGC 3896, which is in the same field of view. Photographs of the

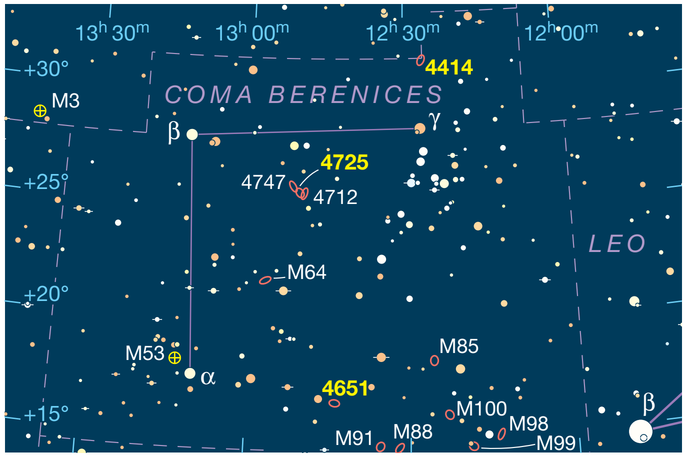
NGC 3521: ESA / HUBBLE / NASA / S. SMARTT;
NGC 3938: TED WOLFE

graceful galaxy show a smaller northern arm that isn't at all apparent in the eyepiece.

NGC 3938 deserves a very long look. This remarkable face-on spiral will stingily hide its structure from the casual observer, who will see only a rather faint round object with a brighter center. A much deeper examination will enable its branching arms to emerge. A delicate network of brighter knots defines this graceful grand spiral's swirling arms. Perhaps no other object on our tour is better proof of the effectiveness of careful, prolonged study. It's located 2° northwest of 5th-magnitude 67 Ursae Majoris.

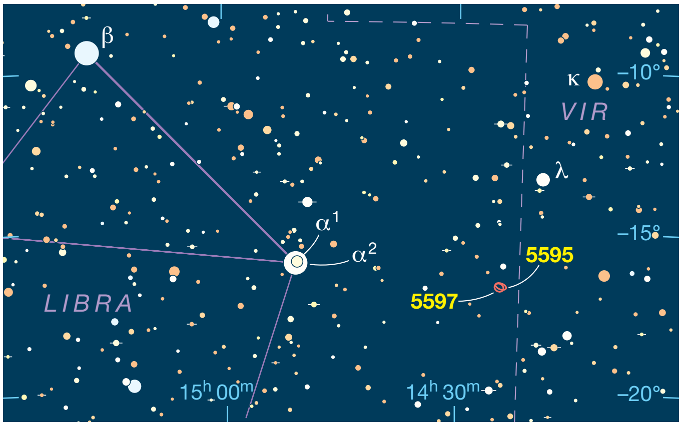
The spiral structure in **NGC 4030** may elude you as well, but this galaxy is worth the effort to find. Look for it 3° 45′ southeast of Beta (β) Virginis. It lies pleasingly nestled among a number of stars, including two of 11th magnitude that border its west side, one north and one south of the extended halo. In the eyepiece, I detect some faint mottling that extends beyond the obvious central core and gives the unmistakable impression of spiral arms, but I'm not sure we actually resolve them.

▼ **UMBRELLA GALAXY** Likely interactions with a smaller galaxy resulted in the stream of material seen emanating to the right of NGC 4651. The stream won't be visible in backyard telescopes, but when you spot the galaxy in your eyepiece, bear in mind this extraordinary structure.



MAGNIFICENT SPIRAL Another splendid example of a flocculent galaxy, NGC 4414 in Coma Berenices highlights how these objects have older and more red and yellow stars at their centers. New stars are constantly being born in the spiral arms, which is why these outer regions look bluish.

NGC 4651: R. JAY GABANY / CC BY-SA 3.0; NGC 4414: HUBBLE HERITAGE TEAM / AURA / STSCI / NASA / ESA



▲ **TWO FOR ONE** A medium-power eyepiece will help you catch this pair of barred spirals in the same view. NGC 5595 and NGC 5597 lie in Libra at similar distances and may be interacting.

Common in spiral galaxies, including our own Milky Way, are elongated central features we call *bars*. As many as two-thirds of spirals have bars. The cores of barred spirals can appear as bright bands that taper off into their largest spiral arms. You might detect such a bar in **NGC 4051**, lying 1.5° north of 67 Ursae Majoris and about 2° east-northeast of NGC 3938, which we visited earlier. A faint arm emerges from the southern end of the elongated core and sweeps north along the east side of the galaxy. A few bright knots appear on the opposite end of the bar hinting at a northern arm. The north arm doesn't stand out as separate from the core, however.

NGC 4414, a flocculent galaxy in Coma Berenices, sits on the border with Canes Venatici about 3° north of 4th-magnitude Gamma (γ) Comae Berenices. It's a bright, tightly wound spiral that gives just a hint of swirling arms wrapping around its bright core.

▼ **ONE-ARMED SPIRAL** NGC 4725 is an odd galaxy in that it only has one spiral arm that loops around the core and then itself. As with other spiral galaxies, the yellowish central bar region contains older stars, while bluer star-forming regions dot the winding arm.

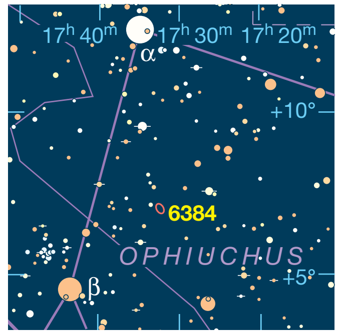
The Umbrella Galaxy is the nickname by which **NGC 4651** (Arp 189) in Coma Berenices is known. The name refers to an oddly shaped remnant of a long-ago interaction with another galaxy that manifests itself as a faint stream of material. This tidal stellar stream is likely the remains of a dwarf companion shredded by the larger galaxy's gravity. As with many nicknames, it refers to structures that are not visible in backyard telescopes. Instead, in the eyepiece, NGC 4651 appears like a bright oval core surrounded by several patchy arms that comprise its mottled halo. A denizen of the Virgo-Coma Cluster, it has eluded reliable determinations of its distance, with estimates ranging from 35 to 75 million light-years. It's located at the end of an arc of 4th- and 5th-magnitude stars leading westward about 6.5° from Alpha (α) Comae Berenices.

Large, bright, and impressive, **NGC 4725** adorns northern Coma Berenices about 5° east of the bright cluster that lends its ancient identity to its parent constellation. The galaxy's sole spiral arm winds tightly around a bright oval core. It shares the field with several stars and two 13th-magnitude companion galaxies, NGC 4712 and NGC 4747. NGC 4747 may be at a similar distance to NGC 4725 and thus a true neighbor, but NGC 4712 is very much farther away. A few of the galaxies on our list are *Seyfert galaxies*, and NGC 4725 is among them. Seyfert galaxies are powered by supermassive black holes just like quasars, but unlike quasars, their host galaxies are detectable. Visually, it's comparable to M94, similar in size, and only a little less bright, but I find its spiral structure easier to discern.

Virgo's **NGC 5147** lies in front of Abell 1733, a galaxy cluster that is about four times more distant. Initial impressions of the galaxy are skewed by a foreground star that sits near and outshines the galactic core. An irregularly bright halo is the evidence of stellar structure in this example of a nearly face-on spiral. Involved stars make for a pretty view but may distract the eye from noticing the variations in brightness that trace out its hidden structure.

You may know **NGC 5248** in Boötes as Caldwell 45. Famed British astronomer Sir Patrick Caldwell-Moore (better known as Patrick Moore) compiled a catalog of non-Messier objects in the December 1995 issue of *Sky & Telescope*. The 109 objects in that article have become a popular target list of many amateur deep-sky sleuths and the subject of a popular observing program of the Astronomical League. It's large, bright, and easily visible in small apertures. The spiral structure may require larger instruments. Two bright arms, one to the east arching north and one to the west tending south, are outlined in numerous bright stellarings — in this case, bright H II regions that dot the arms along their entire length. It's located in a rather blank area on the border between Boötes and Virgo almost 14° southwest of Arcturus and a little more than 9° north of Zeta (ζ) Virginis.

The barred spirals **NGC 5595** and **NGC 5597** are two very similar galaxies in the same medium-power field in Libra that make for a very interesting view. They're at similar distances from us, and they may even be interacting. NGC 5595 is irregular looking with a small bright core and one fairly bright arm that loops over its north end. NGC 5597 is just 4′ to the southeast and appears a bit fainter and mostly round. It has a small, bright, almost rectangular core and a faint outer halo that's challenging to resolve into its discrete parts but that leaves the unmistakable impression of spiral structure. They're found near Libra's border with Virgo, about 6.5° west of Alpha Librae.



NGC 6384 is a barred spiral in Ophiuchus situated about 3° 40′ northwest of Beta Ophiuchi, lying among many superimposed stars. A faint outer halo leads the observer to just suspect its delicate spiral arms. If we accept its distance of 86 million light-years, it would span 150,000 light-years in diameter, half again as large as the Milky Way!

There are so many more! To varying degrees, the majority of open-faced spirals in our sky have the potential to yield up their delicate, swirling structure to visual detection. To be successful at seeing it, both the eye and the mind must be trained to pick it up. Observers who develop the habit of considering the existence of features beyond the obvious bright core and faint halo will be richly rewarded.

■ Contributing Editor **TED FORTE** maintains a backyard observatory outside of Sierra Vista, Arizona, and is the operations director at another observatory on the Sierra Vista campus of the University of Arizona.

Face-On Spiral Galaxies

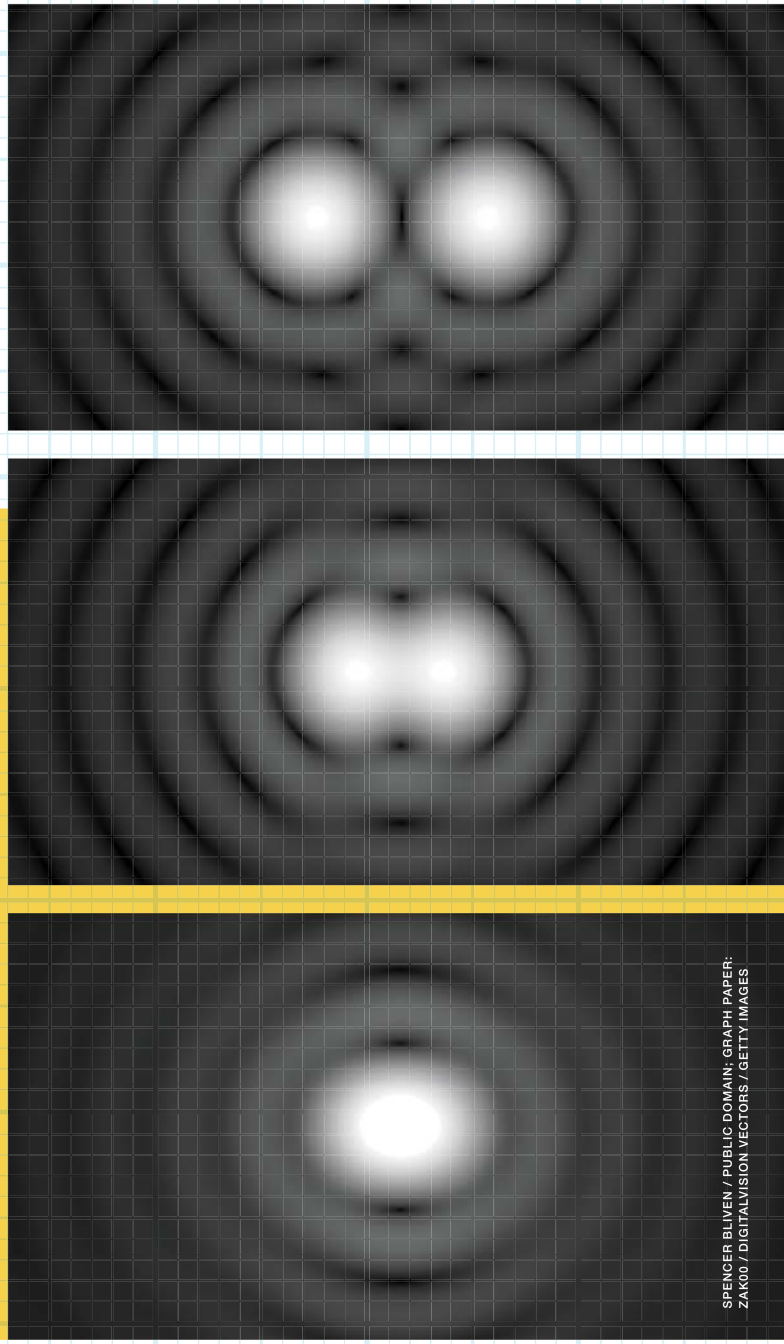
Object	Constellation	Surface Brightness	Mag(v)	Size/Sep	PA (°)	Distance (million l-y)	RA	Dec.
NGC 3310	UMa	12.8	10.8	3.1′ × 2.4′	156	50	$10^h 38.8^m$	+53° 30′
NGC 3521	Leo	13.3	9.0	11.0′ × 5.5′	163	32	$11^h 05.8^m$	–00° 02′
NGC 3631	UMa	13.4	10.4	5.0′ × 3.7′	114	59	$11^h 21.0^m$	+53° 10′
NGC 3893	UMa	13.1	10.5	4.5′ × 2.8′	165	49	$11^h 48.6^m$	+48° 43′
NGC 3938	UMa	13.8	10.4	5.4′ × 4.9′	0	41	$11^h 52.8^m$	+44° 07′
NGC 4030	Vir	13.2	10.6	4.2′ × 3.0′	27	65	$12^h 00.4^m$	–01° 06′
NGC 4051	UMa	13.3	10.2	5.2′ × 3.9′	135	36	$12^h 03.2^m$	+44° 32′
NGC 4414	Com	12.8	10.1	4.4′ × 3.0′	155	35	$12^h 26.5^m$	+31° 13′
NGC 4651	Com	13.2	10.8	4.0′ × 2.6′	80	35–75	$12^h 43.7^m$	+16° 24′
NGC 4725	Com	14.0	9.4	10.7′ × 7.6′	35	58	$12^h 50.4^m$	+25° 30′
NGC 5147	Vir	12.8	11.8	1.9′ × 1.5′	120	50	$13^h 26.3^m$	+02° 06′
NGC 5248	Boo	13.8	10.3	6.2′ × 4.5′	122	54	$13^h 37.5^m$	+08° 53′
NGC 5595	Lib	12.9	12.0	2.2′ × 1.2′	50	127	$14^h 24.2^m$	–16° 43′
NGC 5597	Lib	13.3	12.0	2.1′ × 1.7′	95	126	$14^h 24.5^m$	–16° 46′
NGC 6384	Oph	13.8	10.4	6.2′ × 4.1′	30	86	$17^h 32.4^m$	+07° 04′

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.

The Dawes Limit

The author finds that two of his telescopes have somewhat different — lower! — Dawes' limits than what theory predicts.

Distinguishing the binary nature of a star at the Dawes limit is a stringent test of visual acuity at the telescope's limit of resolution, with atmospheric conditions playing no small role. Phillip Kane's "Find Your Dawes Limit" (*S&T:* Sept. 2016, p. 30) provided the catalyst for me to find closure on unresolved double star issues that had accumulated for decades. His "grand list of test stars" is outstanding and was almost up-to-date. I decided to accept his challenge.



SPENCER BLIVEN / PUBLIC DOMAIN; GRAPH PAPER: ZAK00 / DIGITALVISION VECTORS / GETTY IMAGES

The Dawes and Sparrow Limits

Observers use the ability to separate double stars as a proxy for a telescope's resolving power. Enlarged images of close double stars as seen in a telescope without a central obstruction at decreasing separations are simulated at right. According to the *Dawes criterion*, resolution is predicated on the perception of a drop in the light intensity (dark notches) flanking the closely merged star images. In his *Catalogue*, Dawes concludes this is the closest that two stars can overlap and still be recognized as individual objects. The criterion culminates in his famous Dawes' limit equation

$$r = \frac{4.56''}{a},$$

and Beyond

Selecting the Targets

Some of the closely merged 6th-magnitude stars I observed resembled the elongated image representing stars at the Sparrow limit (bottom image, see sidebar). Others, which had components of unequal magnitudes ($\Delta_{mag} \leq 1.0$), presented ovate or peanut-shaped images. These forms can also be distinguished (as opposed to resolved) since:

- One can infer two stars are involved by the irregularity of the image.
- The shape of the first diffraction ring usually mimics the inequality of the merged stars and provides a recognizable signature.
- The fainter star of the image generally points toward the requisite position angle.

So, in addition to establishing a personal Dawes' limit for my telescopes (a 3½-inch and a 7-inch), I also addressed a lower limit of distinguishability. I included this feature, hoping to bring attention to the practice of claiming a Dawes' limit resolution for an elongated shape (meaning the stars aren't resolved at all) that in fact falls within the purview of the Sparrow criterion. I observed stars with separations progressively smaller than the conventional Dawes' limit, to a point where I could no longer detect any elongation, and recorded the components' separation (fifth column in the tables overleaf). There was nothing to measure; everything was subjective and limited to specific telescopes. In the end, I chose 18 sixth-magnitude double stars, each meeting at least some of the specifics mentioned.

where r is the resolution of a telescope, 4.56″ is Dawes' empirically derived constant, and a is the aperture of the telescope in inches. If a is given in millimeters, the constant is 116″.

Double stars are just separated if they meet the *Rayleigh criterion*. In this scenario, the centers of the two stars' Airy disks (the bright central source of the star's diffraction pattern) are exactly one disk radius apart. The more stringent Dawes criterion was developed from "five and thirty" years of observations and embodies Dawes' concept of resolution. The centers of the Airy disks at the Dawes limit are separated by about 0.84-disk radii, as shown in the middle panel.

J. B. Sidgwick's *Amateur Astronomer's Handbook* describes overlapping stars with separations closer than the Dawes limit. These appear in the eyepiece as a single elongated star with no drop of light intensity (see bottom image). Sidgwick adds that the normal eye can detect this elongation when the separation is more than about $r/2$. This leads to the *Sparrow criterion*, which describes the appearance of the merged stars as prolate or rodlike, with centers about 0.78-disk radii apart. This form shows no notching and the stars can't be considered resolved. The separation of the stars in arcseconds where the elongation can no longer be visually detected with a given telescope comprises the *Sparrow limit*.

◀ **SIMULATING DOUBLE STARS** In order to describe what close double stars look like through a telescope, simulations such as the one at left can be generated. The top panel shows two Airy disks, fully separated. The middle panel is representative of the Dawes limit, while the bottom panel simulates the Sparrow limit.

SOURCES

I relied on the U.S. Naval Observatory (USNO) for double star data. The ephemerides of the Sixth Catalog of Orbits of Visual Binary Stars (https://is.gd/usno_orb6) generally matched those data provided by the Washington Double Star Catalog (https://is.gd/usno_wds), but there were exceptions.

I used my venerable 3½-inch and 7-inch Questar telescopes for this project. Working high power for the instruments is 160× and 320×, which I can double using internal Barlow lenses if conditions permit. The conventional separation at the Dawes limit for each telescope is 1.3″ and 0.65″; these values are approximately the separations of **53 Aquarii** and **STF 2244** (Σ2244), respectively.

Putting My Telescopes to the Test — the 3½-inch

In 2016, since 53 Aquarii approximated the separation encountered at the Dawes limit for a 3½-inch telescope, the star pair should have presented a notched, elongated Airy disk. Instead, I saw two stars separated by ample dark sky. Ditto for its *doppelgänger*, **Kappa[1] Sculptoris**. With a separation of 1.1″, **STF 749** (Σ749) also showed an expanse of darkness between its components. These stars gave me my first evidence that a sub-Dawes-limit resolution was possible with this telescope.

There are doubts on the binary nature of **24 Ophiuchi**. It doesn't have a calculated orbit and probably is an optical double, but its bluish components certainly invite inspection. Early in this study, I saw 24 Oph as two touching stars.

On the other hand, **HWE 28** (Howe 28) is a *bona fide* physical double and showed a darkly notched, oblong image at 260× during moments of better seeing at its declination of almost –36°. The WDS separation was listed at about 1.0″.

One of the rare doubles whose attributes (6th-magnitude components with $\Delta_{mag} = 0.04$) almost exactly meet the Dawes criterion is **52 Orionis**. It displayed the symmetrical, notched, oblong entity associated with Dawes' limit at an estimated separation of about 1.0″.

▲ **THE TELESCOPES** The author determined the Dawes limit of two telescopes, a 3½-inch and a 7-inch Questar.

While not separable with this telescope, **14 Orionis** ($\Delta_{mag} = 0.9$) gave a peanut-shaped image while **STF 2** (Σ2; $\Delta_{mag} = 0.2$) presented an ovate image. Both were easily distinguished.

The lower distinguishable limit for the 3½-inch telescope may well have been defined when I compared **STT 410** (OΣ410) and **16 Vulpeculae**. The pale blue, elongated image of STT 410 (0.87″ separation) was distinctive at 260×, while the image of 16 Vul with 0.85″ separation remained mostly round and showed only an occasional hint of duality.

Separations Using a 3½-inch Telescope

Object	RA	Dec.	Mag(v)	Size/Sep	PA (°)	Year Observed	Comments
53 Aqr	$22^h\ 26.6^m$	–16° 45′	6.3, 6.4	1.33″	78	2016	Separated
Kappa[1] Scl	$00^h\ 09.4^m$	–27° 59′	6.1, 6.2	1.31″	258	2017	Separated
STF 749	$05^h\ 37.1^m$	+26° 55′	6.5, 6.6	1.11″	319	2017	Separated
24 Oph	$16^h\ 56.8^m$	–23° 09′	6.2, 6.3	1.02″	304	2015	Touching stars
HWE 28	$13^h\ 53.5^m$	–35° 40′	6.3, 6.4	1.01″	315	2017	Classic, notched
52 Ori	$05^h\ 48.0^m$	+06° 27′	6.0, 6.0	0.99″	222	2015	Classic, notched
14 Ori	$05^h\ 07.9^m$	+08° 30′	5.8, 6.7	0.95″	286	2017	Peanut-shaped
STF 2	$00^h\ 09.3^m$	+79° 43′	6.7, 6.9	0.92″	15	2017	Ovate
STT 410	$20^h\ 39.6^m$	+40° 35′	6.7, 6.8	0.87″	4	2016	Elongated
16 Vul	$20^h\ 02.0^m$	+24° 56′	5.8, 6.2	0.85″	127	2016	Round image

Angular sizes and separations are from recent catalogs. When necessary, the author interpolated to reflect closest observation year. Right ascension and declination are for equinox 2000.0.

TELESCOPES: DAWN SCHWIRTZ; GRAPH PAPER: ZAK00 / DIGITALVISION VECTORS / GETTY IMAGES

Putting My Telescopes to the Test — the 7-inch

The 7-inch telescope showed **STF 2244** (Σ2244) with dark sky between its components instead of a fused dumbbell of merged stars. Similarly, **STF 2173** (Σ2173; September 2016 observation) and **BU 395** showed darkness in their interstices. These three stars mirrored the sub-Dawes-limit resolution trend established by the 3½-inch telescope.

However, in September 2017 I decided there was no dark sky between the stars of STF 2173. Instead, they appeared to be just touching. I may have witnessed the two star images merging during the six-week observation period, as initially I imagined that I could see a small gap between them. Try as I might, there was no relating these stars (0.54″ separation) to the Rayleigh criterion.

Another matched (Δ_{mag} = 0.02) 6th-magnitude double star that fits the Dawes criterion nicely is **52 Arietis**. My observation from January 2017 with the 7-inch telescope yielded a classic Dawes' resolution image at an estimated separation of 0.5″. An observation by another astronomer from approximately the same time undertaken using a 10-inch f/5 reflecting telescope on a Dobsonian mount distinctly showed two separate components (see **https://is.gd/Dawes52Ari**). Unlike in the image from the 10-inch scope, I didn't see any space between the symmetrical pair. The notching convinced me it represented Dawes' limit.

It is a point of considerable interest to determine the separating power of any given telescopic aperture. Having ascertained about five and thirty years ago, by comparisons of the performance of several telescopes of very different apertures . . . I examined with a great variety of apertures a vast number of double stars . . . in order to ascertain the separating power of those apertures, as expressed in inches of aperture and seconds of distance.

—Rev. W. R. Dawes, *Catalogue of Micrometrical Measurements of Double Stars* (1867)

The effect a small difference in magnitude has on star images is also demonstrated by ovate **51 Aquarii** (Δ_{mag} = 0.2) and peanut-shaped **59 Hydrae** (Δ_{mag} = 0.6). Again, both were easily distinguished.

BU 311 had a listed separation of 0.43″ and was deemed close to the lower distinguishable limit. At times, its image seemed ovate but kept regressing to a round image. Having identical separation, **BU 932** yielded the same spotty results. Each suggested a lower limit of distinguishability for the 7-inch telescope.

Separations Using a 7-inch Telescope

Object	RA	Dec.	Mag(v)	Size/Sep	PA (°)	Year Observed	Comments
STF 2244	$17^h 57.1^m$	+00° 04′	6.6, 6.9	0.64″	101	2017	Separated
BU 395	$00^h 37.3^m$	–24° 46′	6.2, 6.6	0.60″	118	2018	Separated
52 Ari	$03^h 05.4^m$	+25° 15′	6.2, 6.2	0.50″	258	2017	Classic, notched
51 Aqr	$22^h 24.1^m$	–04° 50′	6.5, 6.6	0.46″	31	2016	Ovate
59 Hya	$14^h 58.7^m$	–27° 39′	6.2, 6.8	0.46″	14	2016	Peanut-shaped
BU 311	$04^h 26.9^m$	–24° 05′	6.7, 7.1	0.43″	157	2016	Ovate?
BU 932	$13^h 34.7^m$	–13° 13′	6.3, 7.3	0.43″	66	2016	Peanut-shaped?

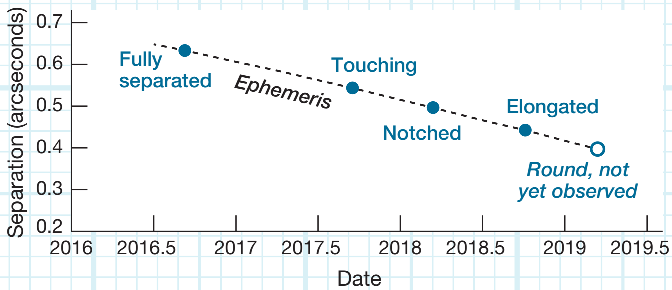
Angular sizes and separations are from recent catalogs. When necessary, the author interpolated to reflect closest observation year. Right ascension and declination are for equinox 2000.0.

STF 2173: Separations Using a 7-inch Telescope

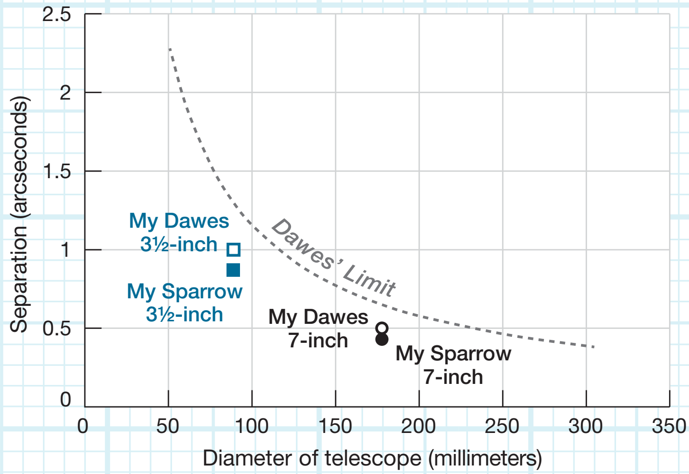
Object	RA	Dec.	Mag(v)	Size/Sep	PA (°)	Year Observed	Comments
STF 2173	$17^h 30.4^m$	–01° 04′	6.1, 6.2	0.63″	142	Sept 2016	Separated
				0.54″	139	Sept 2017	Just touching
				0.50″	138	Mar 2018	Classic, notched
				0.44″	134	Oct 2018	Elongated
				0.40″	*130*	*Mar 2019*	*Round image*

Angular sizes and separations are from the author's interpolations. The last value is a projection. Right ascension and declination are for equinox 2000.0.

Not only did the larger telescope halve the Dawes resolution of the smaller telescope, but this effect was replicated when investigating the strictly subjective lower distinguishable limits, the Sparrow limit.



▲ **OBSERVATIONS OF STF 2173** The author has been observing STF 2173 since September 2016, when the two components were fully separated. He has been following their ever-decreasing separation and projected the March 2019 result to be of a fully round image.



▲ **PERSONAL DAWES' LIMITS** The graph above summarizes the author's findings. The open square is the average of the separations of HWE 28 and 52 Ori, while the open circle is the average of 52 Ari and STF 2173. The solid square and solid circle represent the Sparrow limit for the two telescopes, derived from STT 410 and BU 311.

Separations for this study were, by necessity, obtained piecemeal from various double stars at various positions in their orbits. But in 2016, the companion of STF 2173 was positioned in its 46.4-year, grade-1 orbit (**https://is.gd/usno_orb6**) to offer a seamless investigation from fully separated stars to Dawes' limit to unseparable in a three-year period.

I observed STF 2173 in September 2016 as two stars with visible dark sky (0.63″) between the components. A year later, the yellow stars were just touching with an interpolated gap of 0.54″. The pair reached a separation of 0.50″ in March 2018 and, when observed one frosty morning before dawn, displayed a notched, gold infinity symbol with the smaller lobe pointing towards the vicinity of 140°. In early October 2018, I could still distinguish an elongated image with the components separated by about 0.44″. Soon, the fast-moving stars will merge beyond the distinguishable limit of my 7-inch telescope, then pass into the daylight sky. At the time of writing, the next available viewing of the round image of STF 2173 will be in March 2019.

I called this endeavor "The Lazy Astronomer's One-Star Dawes Limit and Beyond Determination."

Summary

The double stars that showed Dawes' limit resolutions significantly less than 4.56″/*a* were HWE 28 and 52 Orionis with the 3½-inch and 52 Arietis and STF 2173 (March 2018 observation) with the 7-inch telescope.

I couldn't discern elongation or other image irregularities with smaller separations than those of STT 410 and BU 311. Their separation values were at the lower limits of distinguishability for the 3½-inch and 7-inch telescopes, respectively. Neither value approached the $r/2$ established by Sidgwick.

Not only did the larger telescope halve the Dawes resolution of the smaller telescope (0.5″ vs. 1.0″), but this effect was replicated when investigating the strictly subjective lower distinguishable limits, the Sparrow limit (0.43″ vs. 0.87″).

My personal Dawes' limit (rp) for both telescopes is

$$rp = \frac{3.5''}{a}.$$

When a is given in millimeters, the constant is 89″. My value of Dawes' constant is considerably (23%) smaller than the conventional 4.56″. The significance is debatable.

Next August, I will celebrate my eighty-fourth birthday. Perhaps it's time to note at what point stars are nicely separated and enjoy the images and not worry about egg shapes or fused nuclei or other subtleties. There are few sights lovelier than a double star that looks like matched diamonds suitable for a Bond film. The star STF 3050 (Σ3050) in Andromeda comes to mind.

■ **DON FERGUSON** is a retired chemist whose interests include planetary nebulae, the history of astronomy, Enceladus, and — his first love — double stars. *S&T* published his article on planetary nebulae in April 1995. You can email Don at **dferg28571@aol.com**.

OBSERVING
June 2019

1 **DAWN:** Look toward the east-northeast before sunrise to see Venus. Can you spot the slim sliver of the waning lunar crescent some 6° right of the planet?

4 **DUSK:** As twilight deepens, the Moon, one day past new, sets in the west-northwest with Mercury 6° to its right. Find Mars upper left of the Moon, deep in Gemini.

5 **DUSK:** A thicker waxing lunar crescent, Mars, and tiny Mercury are all in Gemini and form a line 17° long before sunset.

6 **EVENING:** The Moon is now in Cancer. Wait for it to get dark enough to spot the Beehive Cluster (M44) some 4° from the fattening crescent.

10 **ALL NIGHT:** Jupiter arrives at opposition. Throughout the month, the majestic planet will be somewhat bigger and brighter than it has been in the past five years.

15–16 **NIGHT:** The waxing gibbous Moon, Jupiter, and Antares form a triangle in the southeast shortly after sunset. The following evening, the almost-full Moon has moved to the other side of Jupiter, and the trio is now arranged in a shallow arc some 14° from tip to tip. You can follow them as they wheel across the sky and set in the southwest at dawn.

17–18 **DUSK:** Look toward the west-northwest after sunset and tease Mercury and Mars out of the gloaming — they'll be a mere ½° apart. The two planets are less than 2° from each other for a couple of evenings prior and several evenings after.

18 **EVENING:** After Mercury and Mars have set, turn to the southeast to see the Moon, one day past full, and Saturn rise in tandem 1° apart.

21 **THE SHORTEST NIGHT OF THE YEAR** in the Northern Hemisphere. Summer begins at the solstice, 15:54 UT (11:54 a.m. EDT).

30 **DAWN:** Taurus rises in the east shortly before sunrise, cradling the Moon in the Hyades, directly below the Pleiades. See if you can spot Aldebaran some 3° from the waxing lunar crescent.

— DIANA HANNIKAINEN

▲ Noctilucent clouds are most often seen at twilight during summer months at latitudes between 50° and 70° (in both hemispheres). They lie very high up, at around 80 km, and are composed of water-ice crystals.

P.-M. HEDÉN

JUNE 2019 OBSERVING

Lunar Almanac

Northern Hemisphere Sky Chart

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

NASA / LRO

MOON PHASES

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

NEW MOON
June 3
10:02 UT

FIRST QUARTER
June 10
05:59 UT

FULL MOON
June 17
08:31 UT

LAST QUARTER
June 25
09:46 UT

DISTANCES

Perigee	June 7, 23^h UT
368,504 km	Diameter 32′ 26″
Apogee	June 23, 08^h UT
404,548 km	Diameter 29′ 32″

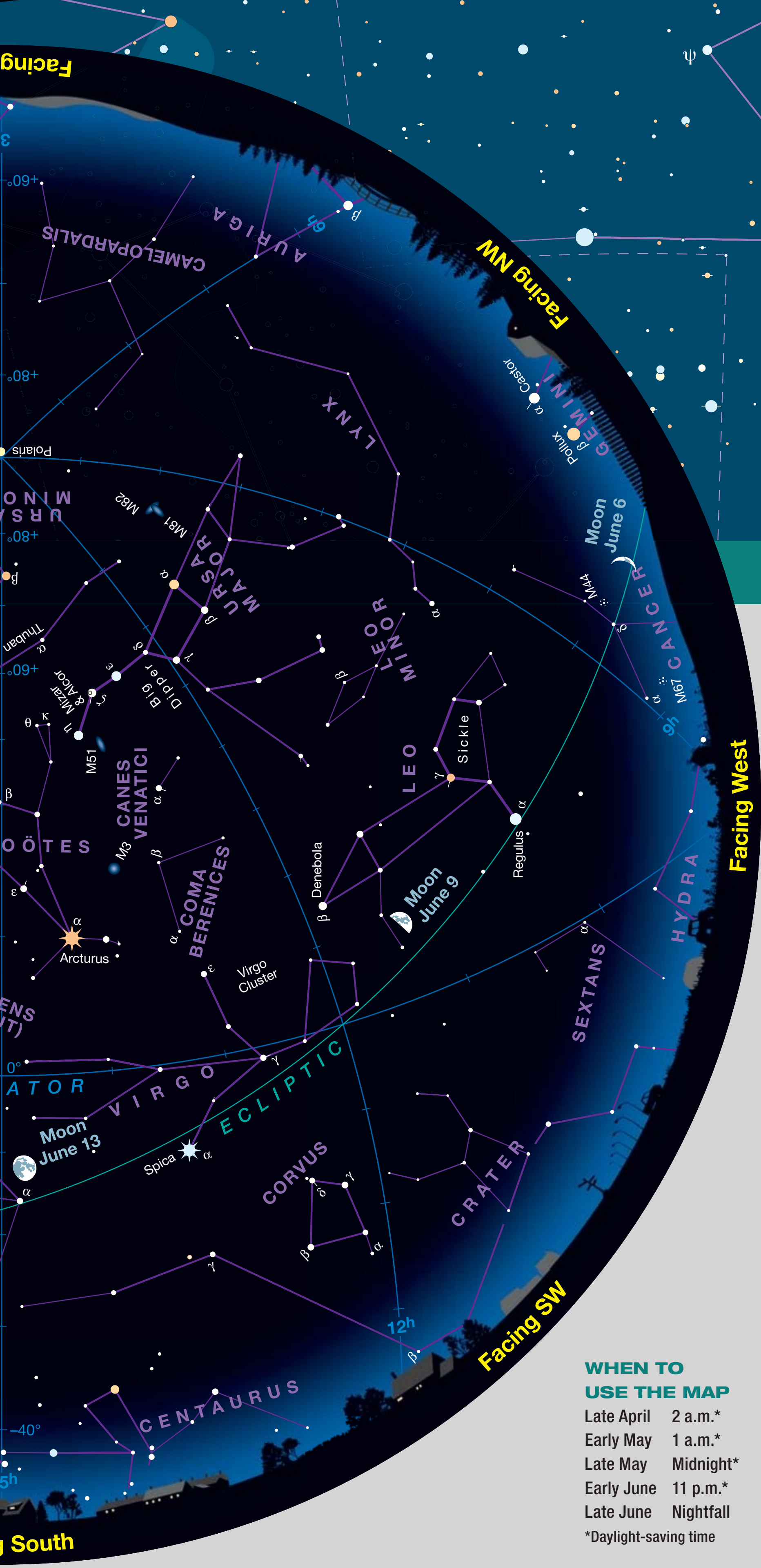
FAVORABLE LIBRATIONS

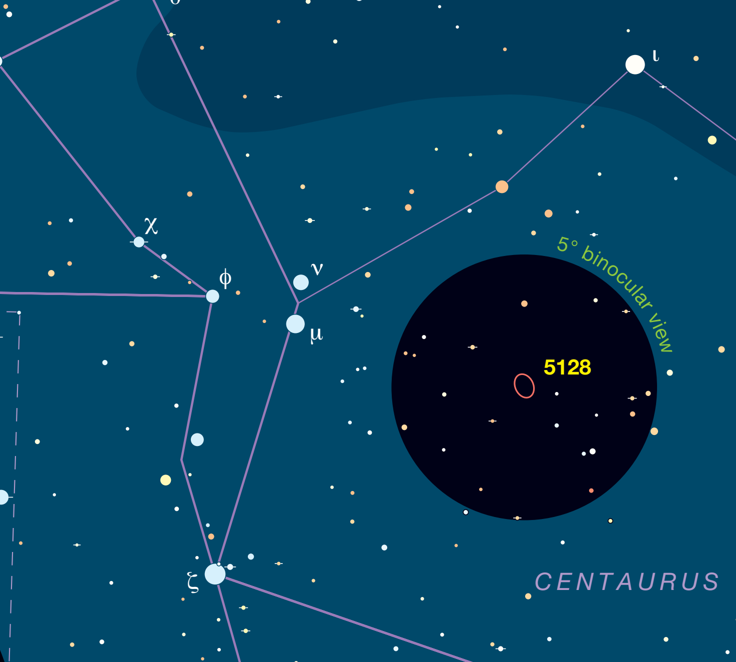
- Neumayer Crater June 11
- Abel Crater June 17
- Repsold Crater June 27
- Ulugh Beigh Crater June 30

Planet location shown for mid-month

USING THE NORTHERN HEMISPHERE MAP

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





Binocular Highlight by Mathew Wedel

Elusive Giant

This month's target is nearby galaxy **NGC 5128**, also known as Centaurus A, in the heart of the celestial centaur. The first recorded observation of the galaxy was by Scottish astronomer James Dunlop, who discovered it in 1826 from his observatory in New South Wales, Australia. In 1949, NGC 5128 was determined to be the host of the "Centaurus A" radio source. That discovery was made by a team led by John Gatenby Bolton, who, like James Dunlop a century earlier, was British-born but living and working in Australia.

To observe NGC 5128 yourself, you too will need to go south — minimally in the sky, and possibly also geographically. At declination –43°, NGC 5128 is pretty darned far south, and that makes it a challenging object for observers at mid-northern latitudes. If you've poked around in that part of the sky, it was probably to have a look at Omega Centauri (NGC 5139), which lies another 4° south of NGC 5128. Omega Centauri has been observed from as far north as southern Canada, but at magnitude 3.9 it's many times brighter than 7th-magnitude NGC 5128.

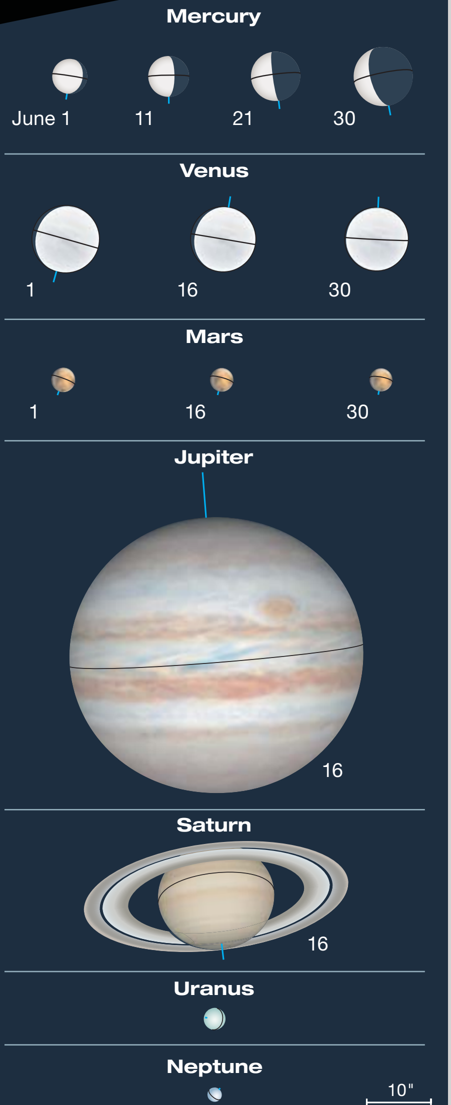
I've observed NGC 5128 with 50-mm binoculars from Texas and southern California, but I've never tried from farther north. I assume there's a tipping point, at which the thickening atmosphere near the horizon dims NGC 5128 to invisibility even though it's still above the horizon. But I don't know where that point might lie. I encourage you to try for it, wherever you might be, and if you catch the galaxy in binoculars from farther north than the 34th parallel, I'd be grateful for a report (**mathew.wedel@gmail.com**). Good hunting!

■ **MATT WEDEL** loses almost as much sleep thinking about objects just below the southern horizon as he does observing the ones above it.

WHEN TO USE THE MAP

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

*Daylight-saving time



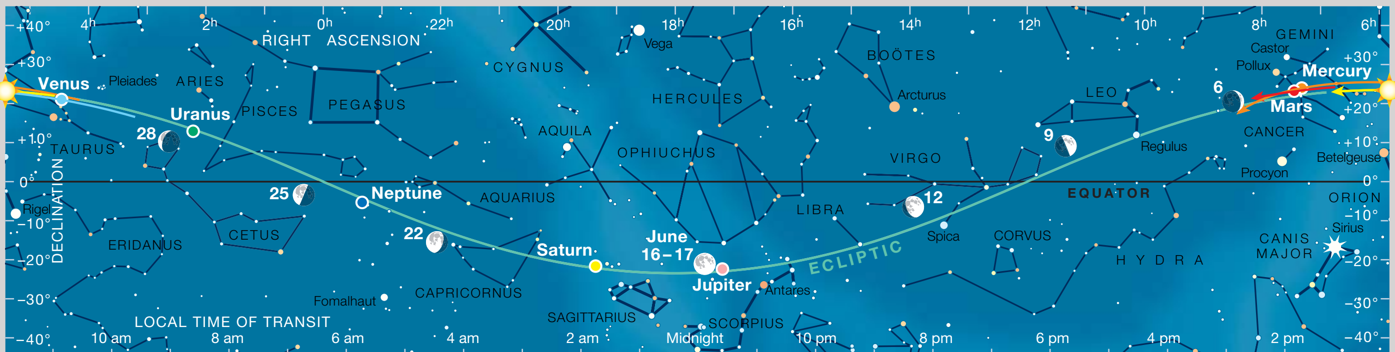
PLANET DISKS have south up, to match the view in many telescopes. Blue ticks indicate the pole currently tilted toward Earth.

PLANET VISIBILITY Mercury: visible at dusk all month • **Venus:** visible at dawn all month • **Mars:** visible at dusk through the 29th • **Jupiter:** rises very early evening, visible until dawn • **Saturn:** rises before midnight, visible until dawn

June Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	$4^h\ 33.4^m$	+21° 57′	—	–26.8	31′ 33″	—	1.014
	30	$6^h\ 33.5^m$	+23° 13′	—	–26.8	31′ 28″	—	1.017
Mercury	1	$5^h\ 26.0^m$	+25° 00′	12° Ev	–1.1	5.5″	87%	1.231
	11	$6^h\ 45.9^m$	+25° 04′	21° Ev	–0.4	6.4″	64%	1.058
	21	$7^h\ 44.4^m$	+22° 22′	25° Ev	+0.2	7.7″	45%	0.875
	30	$8^h\ 15.5^m$	+19° 06′	24° Ev	+0.9	9.2″	29%	0.732
Venus	1	$3^h\ 11.3^m$	+16° 29′	20° Mo	–3.8	10.5″	94%	1.588
	11	$4^h\ 00.8^m$	+19° 38′	17° Mo	–3.8	10.3″	95%	1.625
	21	$4^h\ 52.1^m$	+21° 56′	15° Mo	–3.8	10.1″	97%	1.656
	30	$5^h\ 39.5^m$	+23° 08′	12° Mo	–3.9	9.9″	98%	1.680
Mars	1	$6^h\ 43.7^m$	+24° 13′	30° Ev	+1.8	3.9″	98%	2.428
	16	$7^h\ 25.4^m$	+23° 10′	25° Ev	+1.8	3.7″	98%	2.502
	30	$8^h\ 03.4^m$	+21° 37′	21° Ev	+1.8	3.7″	99%	2.560
Jupiter	1	$17^h\ 18.5^m$	–22° 30′	170° Mo	–2.6	45.8″	100%	4.302
	30	$17^h\ 03.0^m$	–22° 15′	159° Ev	–2.6	45.5″	100%	4.330
Saturn	1	$19^h\ 24.0^m$	–21° 40′	141° Mo	+0.3	18.0″	100%	9.249
	30	$19^h\ 16.3^m$	–21° 57′	170° Mo	+0.1	18.4″	100%	9.047
Uranus	16	$2^h\ 11.9^m$	+12° 45′	49° Mo	+5.9	3.4″	100%	20.491
Neptune	16	$23^h\ 19.1^m$	–5° 30′	96° Mo	+7.9	2.3″	100%	29.815

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



The Sun and planets are positioned for mid-June; 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.

Islands of Night

As spring gives way to summer, you may have to stay up later to catch celestial delights. But it's worth it.

▲ **ANCIENT CLUSTER** Messier 5 (M5) is one of the Milky Way's oldest globular clusters, with most of its stars clocking in at 12 billion years old or even older. However, astronomers have spotted young, blue stars in M5, which they think may have arisen through stellar collisions or mass transfer between binary stars. While scanning the June skies, see if you can spot this globular in Serpens.

ESA / HUBBLE / NASA

Good things sometimes take a while. And it's well to keep that in mind as we astronomers at mid-northern latitudes wait through the longest days of the year — and the longest evening twilights, too — for the starry night to arrive.

By the way, if you're more than about 50° north of Earth's equator in June, you'll have to wait *weeks* for full night to come. The darkest you can get is astronomical twilight, when the solar depression angle is between 12° and 18° (that is, the Sun is between 12° and 18° below the horizon). At least you can look for noctilucent clouds!

In any case, if your sky gets reasonably dark by the times listed on the all-sky map on pages 42–43, you'll see beauties well worth waiting for.

From Arcturus to Vega. The first stars to come out in the June dusk are, of course, the brightest of this sky — Arcturus and Vega. Arcturus is usually classified as a spring star — yet as spring formally ends and most of us are already experiencing summer weather and culture, it's barely past the meridian on our map. In the month most associated with roses, Arcturus is a star that an old friend of mine once said shines with the hue of "champagne shot with roses." Most remarkably, Arcturus may be — cue up the old sci-fi thriller movie music — "the star from another galaxy." The highly inclined orbit of Arcturus with respect to our galaxy's equatorial disk was the first clue that the star may have belonged to a galaxy that collided with, and was cannibalized by, our Milky Way.

While Arcturus is high in the south on our map, the ever-so-slightly less bright Vega is already well up the eastern sky. The other two members of the Summer Triangle, Altair and Deneb, are much lower now — certainly part of their heyday (or should we say "heynight"?) is in late summer or even early autumn. If you're observing in early June, our map portrays the sky at 11 p.m. and hopefully your personal — real-life! — version of that sky is dark enough for you to enjoy two major stops on the journey between Arcturus and Vega: the semi-circle of Corona Borealis and the Keystone of Hercules.

These asterisms are ⅓ of the way and ⅔ of the way, respectively, along the line from Arcturus to Vega. Corona Borealis is adorned with its 2nd-magnitude gem of a star, known as Gemma or Alphecca. The Northern Crown offers us legendary variable stars to keep an eye on and double stars for us to split. It doesn't offer us something that the Keystone does, though: a spectacular globular cluster. In fact, Hercules holds the most famous and most-observed globular cluster of all, M13.

Globulars and galaxies — and so much more. Three of the four greatest globular clusters visible from mid-northern latitudes — M13, M3 of Canes Venatici, and M5 of Serpens — are now all rather near the meridian. (The fourth of the globular greats, M22, is barely above the horizon as Sagittarius rises in the southeast.) But most of us forget that as we begin the season of globular clusters most of spring's bounty of galaxies is still pretty high (the Virgo Galaxy Cluster, in particular, is well up in the southwest, not that far from Arcturus).

Ursa Major is still fairly high, the front half of Scorpius is creeping towards the meridian, underappreciated Libra, the Scales, is balanced on the meridian, and Draco is coiling (back-half first) towards the meridian. They're all part of the start of your visit to June's wonderful island of night in the midst of the ocean of long days. And this island vacation called June nights is well worth the wait.

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

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

Plentiful Planets

All five bright planets are on display this month — four accompany us during the evening hours, and one greets us at dawn.

Four bright planets adorn the sky during evening twilight in the latter half of June. Mars hangs low in the west-northwest in evening twilight this month, with much brighter Mercury passing close by. Jupiter reaches opposition on June 10th and so is visible all night at its brightest and biggest. Saturn trails Jupiter by about two hours and rises as little as 30 minutes after the Sun sets at month's end. Venus gives us a last good look in the brightening dawn sky before the Morning Star fades from view in late July.

DUSK

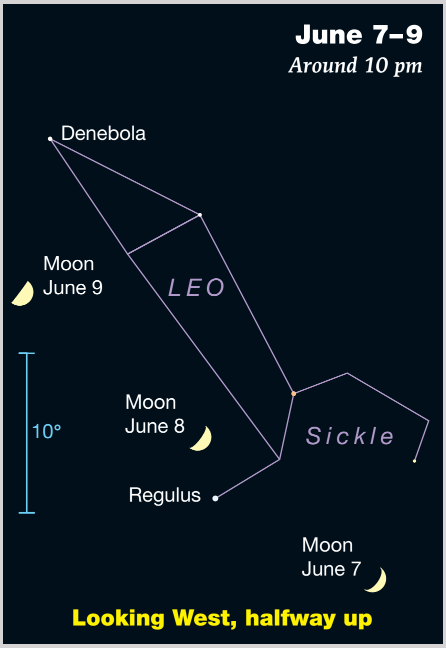
Mars and **Mercury** are a fascinating pair in the west-northwest at evening twilight in June. Mars remains at magnitude 1.8 all month, and the interval between sunset and Mars-set shrinks from about 2¼ to 1¼ hours during June. As Mars appears a little lower at any given time in dusk with each passing day, Mercury appears higher. The tiny world starts the month far below Mars, setting about 65 minutes after the Sun but shining at magnitude –1.0. Mercury fades to magnitude +0.1 by June 17th when it appears just ¼° from Mars. The next evening, Mercury is even closer to Mars. By the 19th, the gap between the planets has increased to ¾°. On these dates, Mercury is about half-lit and a bit more than 7″ across.

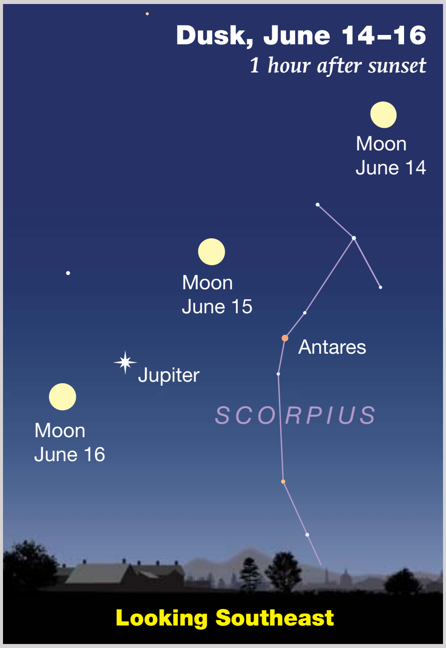
Find Mercury about 6° lower left of much dimmer Pollux on June 20th (Mars is the same distance lower left of Pollux on June 22nd). Mercury reaches a greatest eastern elongation of 25° from the Sun on June 23rd. You'll no doubt need binoculars near month's end to spot Castor and Mars as the latter moves into a nearly horizontal line with Mercury (magnitude 1.0 as June ends), Pollux, and Castor.

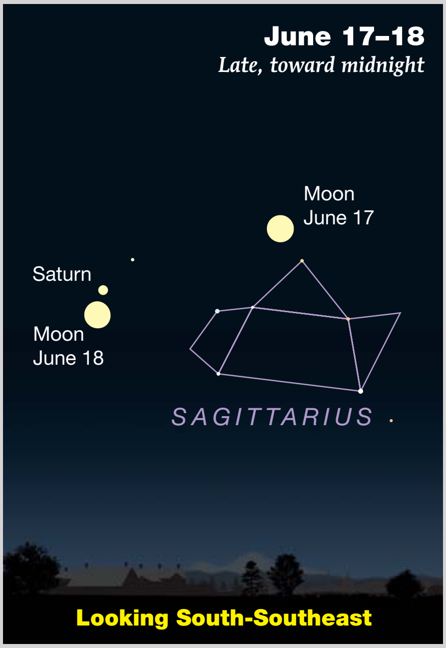
DUSK TO DAWN

Jupiter reaches opposition on June 10th and so rules the entire night with its brilliance and, in telescopes, its size this month. Throughout June, Jupiter burns at magnitude –2.6 and its globe measures about 46″ wide. This is a little brighter and bigger than the king of the planets has been in five years.

The only negative factor in this month's (and year's) display of Jupiter for observers at mid-northern latitudes is the extreme southerliness of the



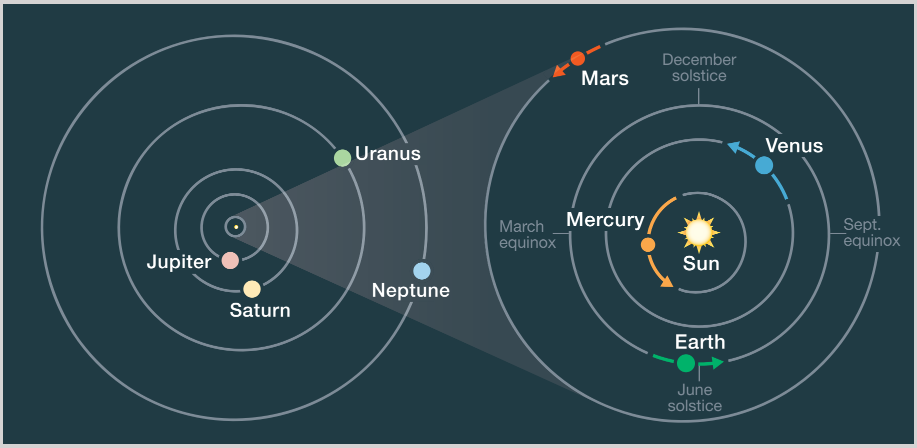




planet. At its highest in the middle of the night, Jupiter is barely high enough for its image to likely be steady and sharp. Even so, there is so much to look for in Jupiter's cloud features — and the events of its large Galilean satellites. (For the timings of Great Red Spot central passages and Galilean moon phenomena, see pages 50–51.)

Jupiter spends June retrograding just above the body of low Scorpius. At least this is a rich and beautiful section of the heavens. Also, we can enjoy watching Jupiter's separation from Antares shrink from about 12° to less than 9° during June. Meanwhile, Jupiter's retrograde is much faster than Saturn's, so the former increases its separation from Saturn by 2° in June, carrying Jupiter out to almost 31° from its splendor-ringed rival.

Saturn rises about 2½ hours after sunset as June opens but very early in evening twilight as the month closes. The deep-gold-colored world brightens from magnitude +0.3 to +0.1 (rivaling Vega) during June. Saturn shines left or upper left of the large Teapot asterism of Sagittarius and just below the little Teaspoon asterism. Saturn is at its highest several hours after midnight (daylight-saving time), so that's the best time to observe its globe and rings in the telescope. The globe of Saturn grows to an apparent equatorial diameter of more than 18″ during June. Saturn will arrive at opposition on July 9th.



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

START OF DAWN

Neptune and **Uranus** are best seen in the sleepy hours during this month's long morning twilights (if you live around latitude 40° north or far enough south to even have full night at any time in June). Neither is yet well-placed for observation, but if you want to take a crack at them check out finder charts at **https://is.gd/urnep**.

DAWN

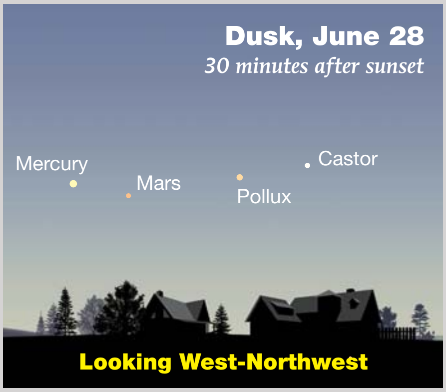
Venus rises less than an hour before the Sun this month. On June 18th Aldebaran will be about 5° lower right of the magnitude –3.8 planet. Even with binoculars this is a hard catch, but it's well worth a try.

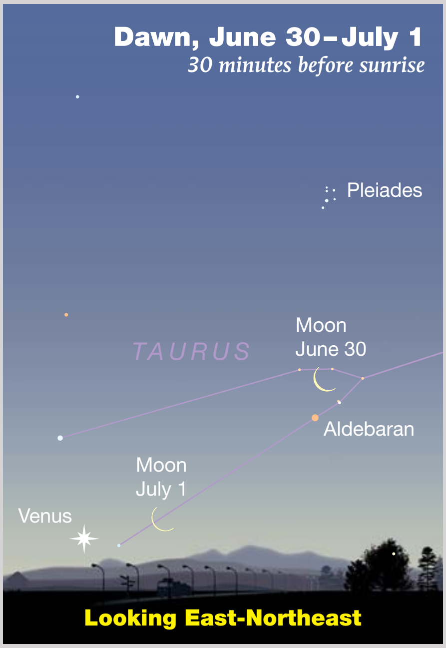
SUN AND MOON

The Sun arrives at the June solstice at 11:54 a.m. EDT June 21st, making this the longest day of the year in North America. The June solstice marks the start of summer in the Northern Hemisphere and the start of winter in the Southern Hemisphere.

The Moon is a slender waxing crescent some 6° upper left of Mars at nightfall on June 5th and at the end of a long arc with Castor and Pollux the next night. A thicker lunar crescent hangs less than 4° above Regulus on the evening of June 8th. A heavily gibbous Moon forms a fairly large, nearly equilateral triangle with Jupiter and Antares on the evening of June 15th. The next night, the Moon is closer to Jupiter, to the brilliant planet's lower left or left. Late on the evening of June 18th, the night after full Moon, the round lunar orb is less than 2° below Saturn. On the last day of the month, the waning lunar crescent is in the Hyades.

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

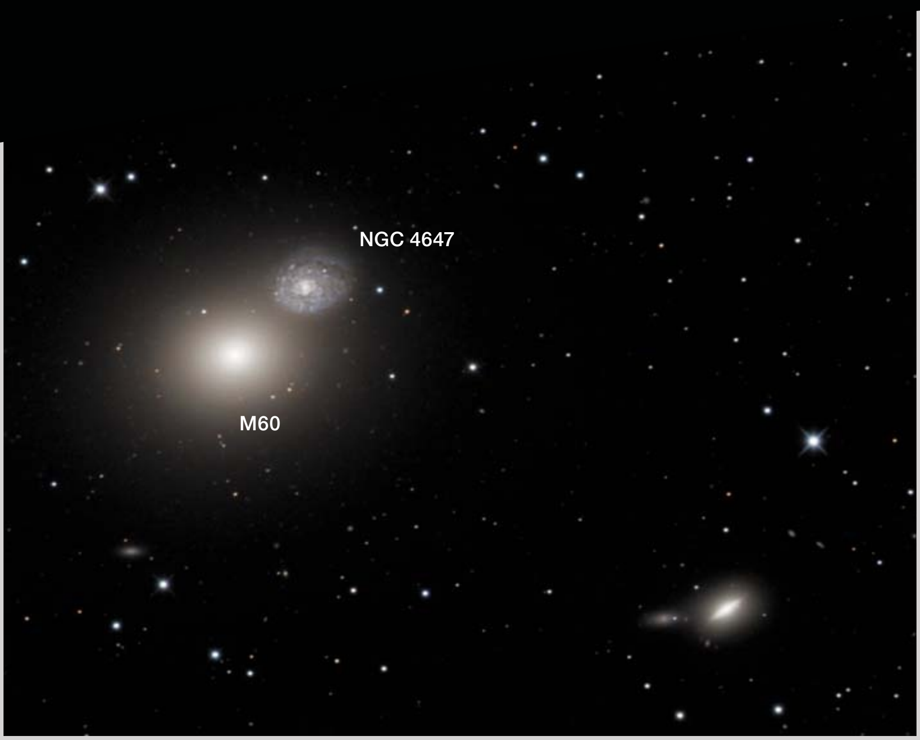




■ FRED SCHAAF teaches astronomy at Rowan University and Rowan College at Gloucester County.

The Last Rites of Spring

Ignore the call of summer to explore the spring's best galaxy cluster.



This deep-sky image reveals the complex structure of the spiral galaxy NGC 4647. Seemingly on the verge of touching the brilliant elliptical galaxy M60, NGC 4647 shows few signs of interaction with its galactic "neighbor".

DAN CROWSON

It's true that June is the month of solstice, when summer begins for the Northern Hemisphere, but I often spend the month finishing up my spring observing plans. Yes, the temptations of summer are rising in the east, but the vernal constellations haven't yet disappeared in the west. And since spring weather often cuts short my observing sessions — or eliminates them altogether — I'm willing to postpone summer to spend a few more hours with the Virgo Cluster (sometimes called the Virgo-Coma Cluster).

Just a glance at a star chart covering the sky between Gamma (γ) Virginis and Gamma Comae Berenices shows the potential of this celestial hunting ground. The Virgo Cluster contains as many as 2,000 galaxies, of which about 150 fall within range of small scopes. My 5-inch f/5 reflector does a solid job picking out the cluster's brightest members (and under very dark skies I can nab some with the 90-mm refractor and averted vision), but the 10-inch f/4.5 reflector makes the pursuit noticeably less strenuous.

The brightest galaxies in the Virgo Cluster are those included in the Messier catalog. Most of these can be found in the stretch between Epsilon (ε) Virginis and Beta (β) Leonis; a notable exception is M64, which lies deep in Coma Berenices. If this is your first dive into the cluster, the Messiers are a good place to start.

A few caveats. First, though the chart on the facing page makes it seem as if the sky is lousy with galaxies, it takes a careful star-hop to land one of these beasts in the eyepiece. Randomly pointing your scope toward a populous patch seems as if it should turn up something, but keep in mind that your eyepiece field of view is small compared to the amount of sky covered in our chart.

Second, magnitude can be a little misleading when it comes to galaxies — surface brightness (brightness per unit area) can be a better indicator of visibility. If a galaxy's light is spread out over a large area, its surface brightness is lower. All other things being equal, if you're looking for two 10th-magnitude galaxies, the one with the more favorable surface brightness (lower number) will probably be easier to find. It's not a perfect system, but if your atlas lists both magnitude and surface brightness, use them to guide your observing choices.

Third, most of these galaxies aren't showpieces. While the Virgo Cluster offers its share of spirals (M90 in Virgo, M88 and M64 in Coma Berenices) and lenticulars (M104, south of Gamma Virginis on the Virgo-Corvus border), most of what you'll be chasing are ellipticals, which look like blurry rice puffs in the eyepiece. But it's the number of galaxies gathered near the cluster's core that's important, not the aesthetics.

There are several ways to approach the Virgo Cluster. Beta Leonis is a sensible starting point for a star-hop to 6 Comae. The edge-on spiral galaxy M98 is about ½° west of this 5th-magnitude star, and the pair shares a field of view at low magnifications. The face-on spiral M99 lies less than 1° southeast of 6 Comae. A line drawn from 6 Com to M99, then extended about 2⅓° beyond the galaxy takes you right to the M84–M86 galaxy pair. These two ellipticals, which form the western end of the "galaxy asterism" known as Markarian's Chain, make ideal jumping-off points for star-hops to most of the remaining Messier and not a few NGC galaxies.

Since M60 is my favorite galaxy in the area, I prefer to start my observing session at Epsilon Virginis and move west into the cluster. To find M60, move 5° west-southwest from Epsilon to 5th-magnitude Rho (ρ) Virginis. M60, with M59 in the same low-power field of view, is 1⅓° north-northeast of Rho.

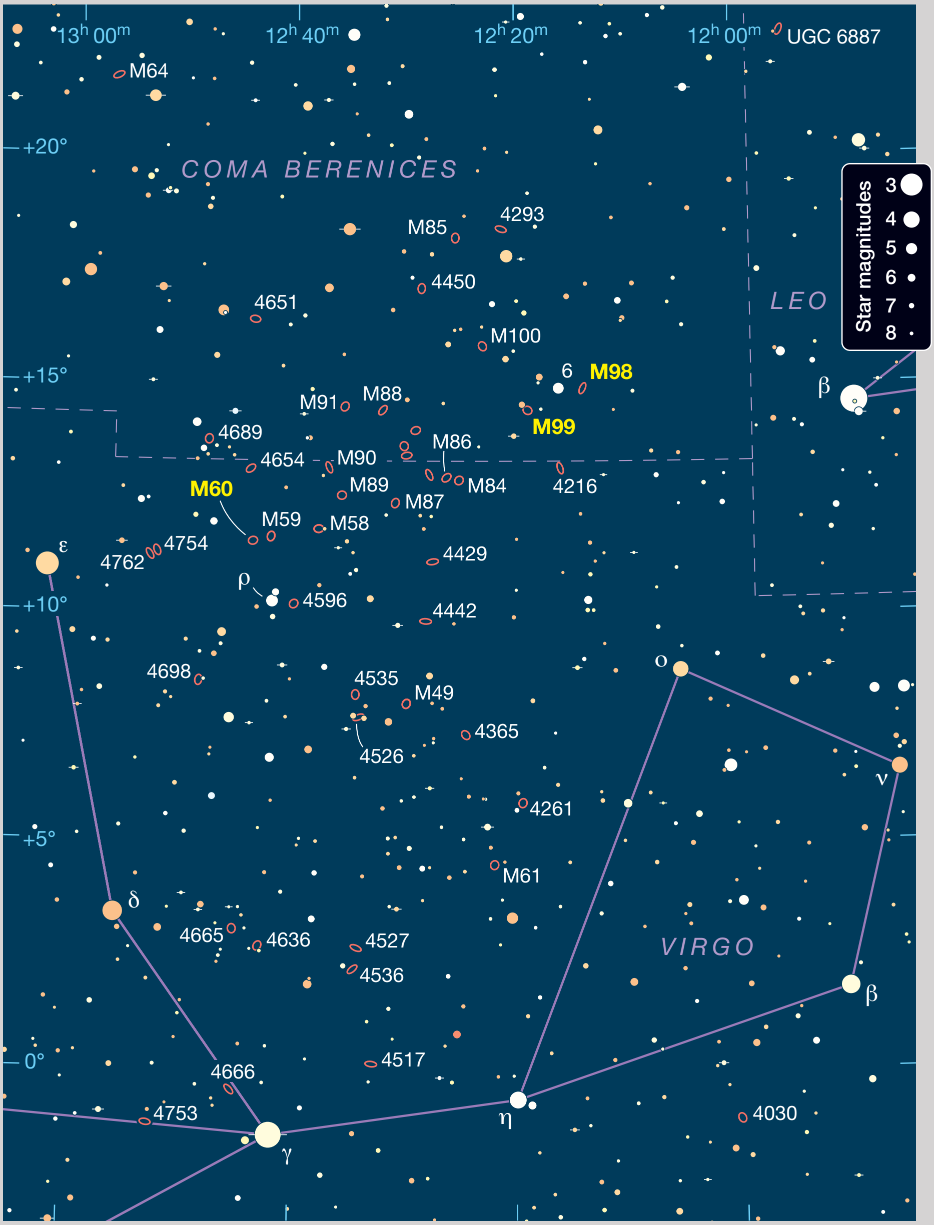
Discovered in 1779 by Johann Gottfried Koehler, M60 is the third brightest galaxy in the Virgo Cluster. Studying it in his 18-inch reflector, Contributing Editor Steve Gottlieb described M60 as "very bright, fairly large, [with a] diffuse halo, slightly elongated approximately east-west." M60's bright core is certainly detectable in the 10-inch, but it appears to be surrounded by a circle of fluff that thins at the edges but otherwise lacks distinguishing features.

This lackluster description notwithstanding, the reason M60 gets my favor is its context: In the eyepiece, M60 looks as if it's being trailed by a shadow of itself. That fainter ball of fuzz is NGC 4647, a spiral galaxy that doesn't give up much detail in a scope. It's just a more diffuse version of its neighbor. Deep-sky images make it appear as if M60 is preparing to get lost in NGC 4647's spiraling embrace, but there's little evidence to indicate the two galaxies are interacting, no matter how pretty a picture they paint. It's possible some very early tidal interactions have begun, but star formation due to mutual disturbance is still in the future tense.

Space-based observations of M60 reveal it to be an elliptical galaxy with a central supermassive black hole, dark matter halo, and X-ray halo. Recently, a team led by Vincenzo Pota (University of California Observatories) released a new catalog of the globular clusters associated with the galaxy — all 431 of them. The distribution, rotation, and velocities of the globulars helped lead the team to the conclusion that M60 formed via a merger between two gas-poor galaxies, followed by a period of satellite accretion.

The Virgo Cluster is well-placed for observation through June from mid-northern latitudes — if you're willing to stay up late, that is. For example, on June 5th, when the Moon is just two days old, M60 is comfortably placed more than halfway up the sky for observers near latitude 40° north when true darkness falls near 10:30 p.m. daylight-saving time. It takes a good three hours for the galaxy to drop to an altitude of 20° on that night. Around June 20th, three nights after full Moon, M60 stands 10°–11° lower at the end of astronomical twilight, so descends to an altitude of 20° in only two hours. Observers around latitude 30° north will have longer observing hours (add an additional hour to the windows for the dates mentioned above) with the target higher in the sky, while observers to the north will have to hustle to do their galaxy-hopping. At latitude 50° north, darkness won't arrive until midnight, and even on June 5th, M60 will only stand 38° high at that time. By the 20th, you'll have 30 minutes at most to catch M60 in a dark sky, and that's only if you have a very clear horizon and excellent seeing.

However long you get to spend with the Virgo Cluster, you'll find yourself wanting more. One galaxy inevitably leads to another, and even if you find your favorite, the pull toward further exploration will keep you coming back to these spring sights even as the calendar invites you to turn toward summer.



Jupiter Goes Big

JUPITER REACHES OPPOSITION — opposite the Sun in the sky from our vantage point on Earth — on June 10th, when it will be easily spotted with the naked eye from dusk to dawn. Appearing low in the southeast out of evening twilight, Jupiter rises with Ophiuchus to shine at its highest in the south an hour after local midnight on that date. Admittedly, high isn't very high for northern observers, since Jupiter's path is following a southern line at declination –22°. At opposition, Jupiter climbs only to a peak altitude of 28° above the horizon. Finding the steady skies needed for observing could be a challenge.

But at least the Planet King is a showoff, already shining at magnitude –2.6 when the month opens and sporting an apparent diameter of 46″. Jupiter's moons, too, show their best — or at least their largest — selves when the parent planet is at opposition.

Any telescope shows the four big Galilean moons, and binoculars usually show at least two or three. In binoculars, the moons are all but indistinguishable from one another. They orbit Jupiter at different rates, changing positions along a 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 time and date.

▲ Citizen-scientist Kevin M. Gill created this image of Jupiter's South Equatorial Belt brown barge (a bar-shaped cloud) from data returned by NASA's Juno spacecraft.

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

In a telescope, variations between Jupiter's natural satellites in color and apparent diameters are more obvious. Io and Europa are the brighter of the tetrad. Callisto has the darkest surface; this becomes particularly obvious whenever Callisto transits (passes across the face of) Jupiter. The differences in the moons' sizes are subtle but can be detected under magnification. At opposition, Io will appear 1.2″ wide, Europa 1.0″, Ganymede 1.7″, and Callisto 1.6″.

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

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

May 1: 2:37, 12:33, 22:28; **2:** 8:24, 18:20; **3:** 4:15, 14:11; **4:** 0:06, 10:02, 19:58; **5:** 5:53, 15:49; **6:** 1:44, 11:40, 21:36; **7:** 7:31, 17:27; **8:** 3:22, 13:18, 23:13; **9:** 9:09, 19:05; **10:** 5:00, 14:56; **11:** 0:51, 10:47, 20:43; **12:** 6:38, 16:34; **13:** 2:29, 12:25, 22:20; **14:** 8:16, 18:12; **15:** 4:07, 14:03, 23:58; **16:** 9:54, 19:50; **17:** 5:45, 15:41; **18:** 1:36, 11:32, 21:27; **19:** 7:23, 17:19; **20:** 3:14, 13:10, 23:05; **21:** 9:01, 18:57; **22:** 4:52, 14:48; **23:** 0:43, 10:39, 20:34; **24:** 6:30, 16:26; **25:** 2:21, 12:17, 22:12; **26:** 8:08, 18:03; **27:** 3:59, 13:55, 23:50; **28:** 9:46, 19:41; **29:** 5:37, 15:33; **30:** 1:28, 11:24, 21:19; **31:** 7:15, 17:10.

June 1: 3:06, 13:02, 22:57; **2:** 8:53, 18:48; **3:** 4:44, 14:40; **4:** 0:35, 10:31, 20:26; **5:** 6:22, 16:17; **6:** 2:13, 12:09, 22:04; **7:** 8:00, 17:55; **8:** 3:51, 13:47, 23:42; **9:** 9:38, 19:33; **10:** 5:29, 15:24; **11:** 1:20, 11:16, 21:11; **12:** 7:07, 17:02; **13:** 2:58, 12:54, 22:49; **14:** 8:45, 18:40; **15:** 4:36, 14:32; **16:** 0:27, 10:23, 20:18; **17:** 6:14, 16:10; **18:** 2:05, 12:01, 21:56; **19:** 7:52, 17:48; **20:** 3:43, 13:39, 23:34; **21:** 9:30, 19:26; **22:** 5:21, 15:17; **23:** 1:12, 11:08, 21:04; **24:** 6:59, 16:55; **25:** 2:50, 12:46, 22:42; **26:** 8:37, 18:33; **27:** 4:28, 14:24; **28:** 0:20, 10:15, 20:11; **29:** 6:07, 16:02; **30:** 1:58, 11:53, 21:49.

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

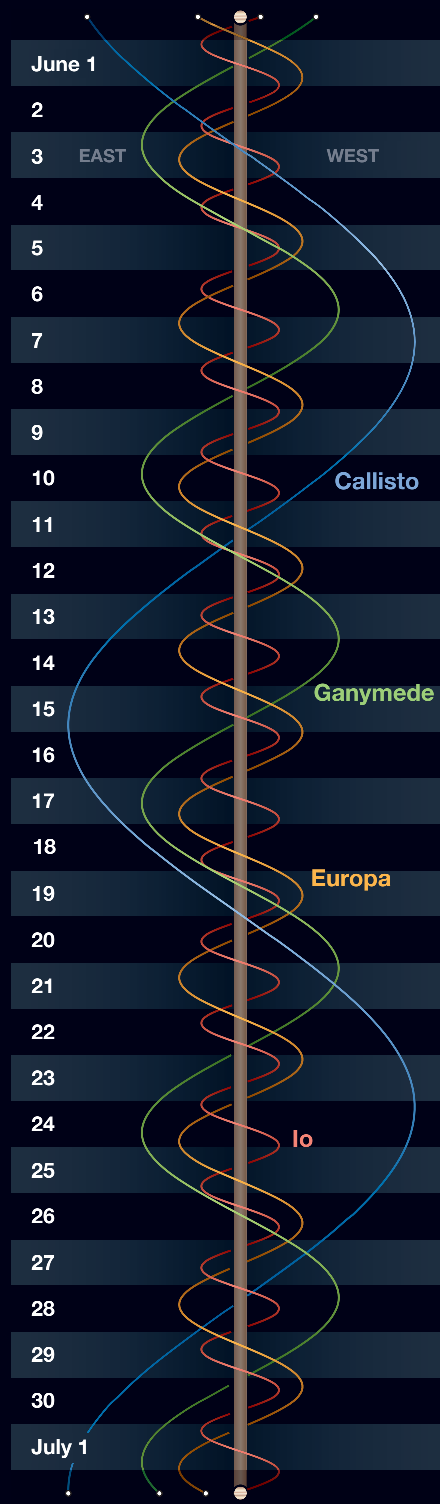
Features on Jupiter appear closer to the central meridian than to the limb for 50 minutes before and after transiting. It's good advice to use a filter opposite in color to the feature you're trying to highlight in the eyepiece. A light blue or green filter slightly increases the contrast and visibility of Jupiter's reddish and brownish markings, like the Great Red Spot and the equatorial belts. Red filters can make Jupiter's bluish features easier to distinguish, while yellow or yellow-green filters can enhance contrast at the planet's polar regions.

Phenomena of Jupiter's Moons, June 2019

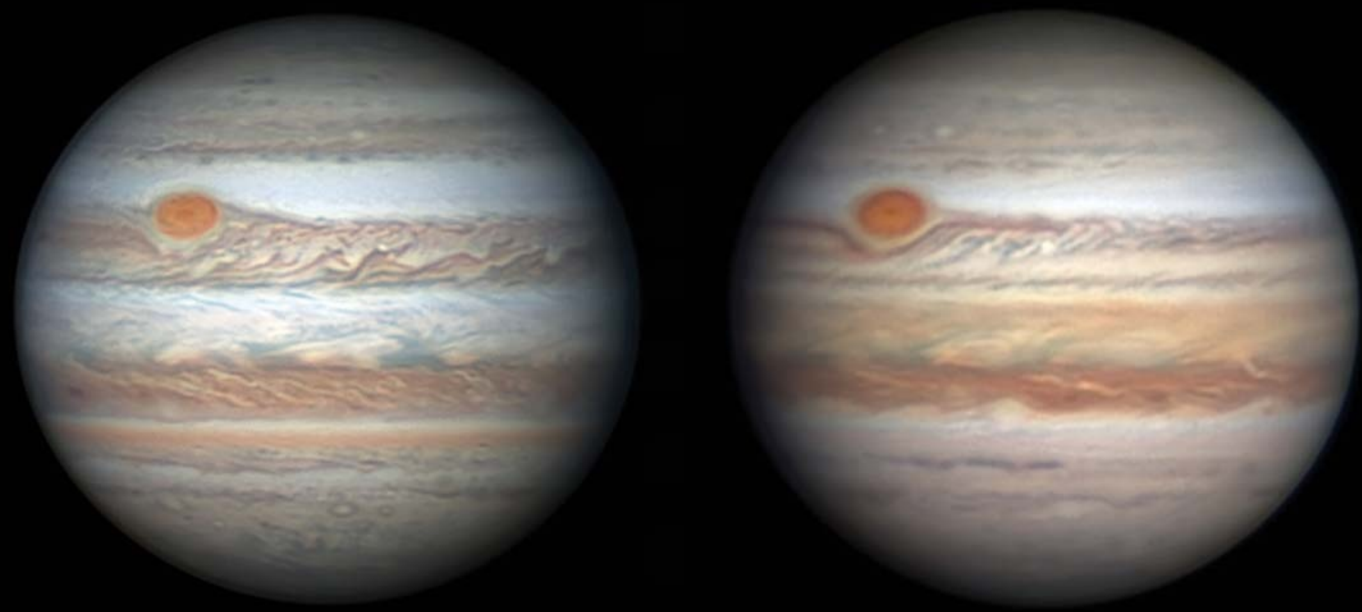
June 1	9:42	III.Ec.D
	11:32	I.Sh.I
	11:46	I.Tr.I
	12:53	III.Oc.R
	13:44	I.Sh.E
	13:57	I.Tr.E
June 2	8:41	I.Ec.D
	11:05	I.Oc.R
	15:25	II.Ec.D
	18:15	II.Oc.R
June 3	6:01	I.Sh.I
	6:12	I.Tr.I
	8:13	I.Sh.E
	8:23	I.Tr.E
June 4	3:10	I.Ec.D
	5:31	I.Oc.R
	9:38	II.Sh.I
	9:57	II.Tr.I
	12:05	II.Sh.E
	12:22	II.Tr.E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

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.



Christopher Go's images capture the normal pearly white Equatorial Zone in May 29, 2017 (left) and its intensifying color this year on February 21st. South is up in both photos.

Old Wine in New Bottles

A recurring change in Jupiter's Equatorial Zone brings color to the historical record.

The cloudscape of Jupiter is divided into alternating bright zones and dusky belts that run parallel to its equator, giving the planet its characteristic striped appearance. The contrast between the zones and belts arises from localized differences in the vertical motion and temperature of the planet's upper troposphere. Jupiter's upper troposphere is cooler in zones and warmer in belts. Zones are sites where atmospheric upwelling of ammonia-rich air expands and cools, forming a dense layer of brilliant white clouds of frozen ammonia crystals at high altitudes. Within the belts air warms as it descends, causing the ammonia clouds to evaporate and exposing lower cloud layers that display a rich palette of warm colors imparted by compounds of phosphorus, sulfur, and carbon.

Late last year, a team led by Arrate Antuñano (University of Leicester, U.K.) published a study that revealed a cycle of large-scale meteorological changes in Jupiter's Equatorial Zone, or EZ (*S&T:* May 2019, p. 10). Based on more than three decades of data acquired using NASA's 3-meter infrared telescope atop Mauna Kea in Hawai'i, the work sheds new light on a recurring phenomenon that has captivated Jupiter observers for a century and a half.

The broad EZ, which extends from latitudes 7°S to 7°N, occupies almost a third of Jupiter's visible disk. For visual observers it is usually the brightest and whitest part of the planet. However, at wavelengths of several microns (μm) in the thermal-infrared region of the spectrum, the EZ normally appears dark because its overlying canopy of cold ammonia ice clouds insulates and obscures Jupiter's warm internal glow.

Every six or seven years the ammonia clouds that top the EZ suddenly dissipate for a period of a year or more, causing the entire region to appear bright in thermal infrared but dark and colorful in visible light. As Jupiter emerged from solar conjunction in the closing days of 2018, dedicated predawn observers reported signs that the clearing was already underway.

John Rogers, director of the British Astronomical Association's Jupiter Section, coined the term "EZ coloration events" to describe these episodes. His summary of their appearance and evolution is an excellent guide to the developments that Jupiter observers may witness in coming months:

> *The color typically develops over a few months, simultaneously at all longitudes . . . Sometimes the color begins as a pure yellow, but evolves within a few months to a darker, less pure color such as ochre or tawny or merely brown. Sometimes the evolution continues as the colored material concentrates over a year or two into a massive dark belt, passing from yellow/orange through brown to grey. However, some episodes have begun with dull grey or brown color and only later become more vivid. And some episodes end with a gradual brightening back through yellow to white.*

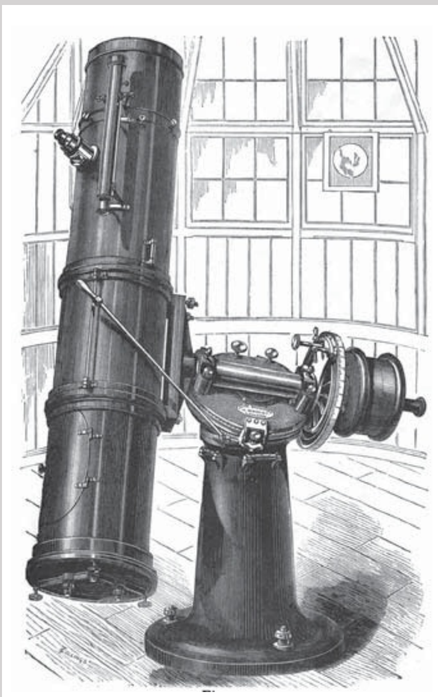
While the colors may be more pronounced at some longitudes, they never show any distinct structure. Rogers notes that the fading of the adjacent South Equatorial Belt usually accompanies EZ coloration events. Conversely, the intensity of the North Equatorial Belt seldom diminishes and sometimes even increases.

About ⅓ of EZ coloration events produce intense displays of color. The spectacular EZ coloration event of 1961–65 was unusually prolonged and arguably the darkest on record. In 1964 Sergei Vsekhsviatskii, then director of Kiev Observatory, reported that Jupiter's overall brightness in visible light had decreased by almost 15%. This estimate was based on careful visual comparisons with naked-eye reference stars at the same apparent sky elevation.

The first well-documented EZ coloration event occurred during the years 1869–73. In October 1869 John Browning, a prominent English maker of scientific and medical instruments, reported that Jupiter's EZ had taken on an extraordinarily deep-yellow tint. The vivid descriptions of these intensifying hues of the EZ by Browning and a host of observers during the following years included amber, orange, ochre, salmon, ruddy, rosy, coppery, faint chocolate, and rich dark brown.

In 1920 Arthur Stanley Williams, a British solicitor who was the leading Jupiter observer of his era, published a review of the sparse observational record prior to 1869 that uncovered unmistakable evidence of EZ coloration events dating back as far as the late 18th century. Four drawings of Jupiter made by Charles Messier in 1767 depict a single dark broad band at Jupiter's equator. William Herschel reported that the Equatorial Zone displayed "a yellow cast" in 1790 and appeared "brownish grey" in 1792. The Bavarian physician Franz von Paula Gruithuisen recorded a reddish-brown EZ in the spring of 1839 and a bright, colorless EZ the following year. Williams suggested that EZ coloration events occur at 12-year intervals (about half the frequency derived from the recent thermal-infrared data), but he cautioned that there were many gaps in the record and that "the observations are seldom sufficient to fix exactly either the beginning or end of the period of visibility or the real time of maximum intensity of the tawny coloration."

▼John Browning produced many impressive Newtonian reflectors like the instrument shown below. He extolled the superiority of reflectors over the era's achromatic refractors for discerning the true colors of planetary features.



▲Browning's depiction of Jupiter's distinctly yellow EZ on the evening of July 31, 1870.

JUPITER: JOHN BROWNING / WIKIMEDIA COMMONS / PUBLIC DOMAIN; TELESCOPE: JOHN BROWNING / *A PLEA FOR REFLECTORS* 1876

Well into the 20th century many astronomers imagined that EZ coloration events were caused by upwelling dark material spreading over the bright white clouds. Yet even as the EZ coloration event of 1870 was unfolding, the English astronomer Richard Anthony Proctor correctly interpreted them as clearings rather than obscurations. In his popular 1870 book *Other Worlds Than Ours* he wrote:

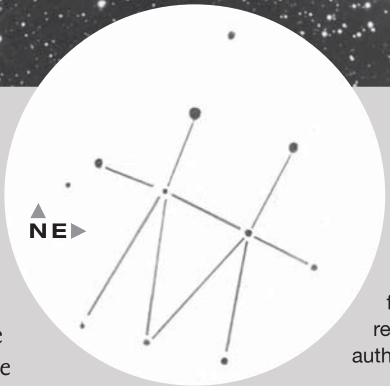
> *Suppose we regard the ordinary white light of the equatorial belt as indicative of the existence of enormous masses of cloud reflecting ordinary solar light to us, then we should regard the appearance of any other color over this region as an indication that these cloud masses had been, through some unknown cause, either wholly or in part swept away.*

Jupiter has been called "the amateur's planet" because amateur observers discovered the planet's principal atmospheric currents and have systematically monitored its ever-changing appearance since the Victorian era. The long-term data they have amassed will continue to play a vital role in unlocking the secrets of weather patterns and climate variations on the solar system's largest and most dynamic planet.

■ **THOMAS A. DOBBINS** observes the denizens of the solar system from his home in Gainesville, Florida.

No NGC Clusters

Look beyond the pages of the classic catalog to find these star clusters.



The open cluster Dolidze 27 seems almost bereft of stars, but its brighter members form a Gemini-like asterism. The sketch illustrates the figure as shown in the mirror-reversed view through the author's 105-mm refractor.

Most of the star clusters we amateur astronomers observe are included in the famed *New General Catalogue of Nebulae and Clusters of Stars* (NGC), but that compilation includes no object discovered after 1887. Since then many more clusters have been found that are well within the reach of backyard scopes, so let's visit some of these oddities in the world of open clusters and learn who found them.

Our featured deep-sky wonders dwell within the realm of the all-sky chart at the center of this magazine, but since we're just entering the celestial bailiwick of open clusters in June, they congregate east of the centerline. I'll introduce our quarry from west to east so that each succeeding cluster climbs higher as you eyeball the one before. In case you prefer to stalk clusters by constellation, that info is given in the table on page 56.

In 1961 Madona Dolidze published lists of possible clusters noted during her spectral studies at the Abastumani Astrophysical Observatory. These groups seemed to hold either stars with a cluster-like distribution of spectral type versus brightness or else hot young stars with similar magnitudes.

Dolidze 27 in Ophiuchus is a sparse cluster, but I'm fond of it anyway. It brings to mind a simplified version of the Gemini stick figure drawn on many charts. My 105-mm refractor at 17× shows a shallow curve of three stars that's easy to spot 1.6° north of Zeta (ζ) Ophiuchi in the same field of view. At 76× the northernmost star in the curve glows orange and lies just outside the northwestern border of the group's nominal 25′ span. The other two stars belong to Do 27 and mark the heads of the mini-Gemini twins, the western one yellow and the eastern one orange. The sketch illustrates the figure as seen in my mirror-reversed view.

Robert Trumpler published a study of open clusters in 1930, including 37 anonymous groups that were later named for him. The following year Per Collinder produced a catalog of open clusters. The vast majority were previously known, but all now bear Collinder designations.

Our next two objects come from these catalogs. The overlapping clusters **Collinder 316** and **Trumpler 24** are fascinating to skygazers mostly because they make up the curved tail of the False Comet. This remarkable object is nicely visible to the unaided eye when gazing across the ocean from the Florida Keys, but various observers interpret it in different ways. For some the bright and tight cluster NGC 6231 forms the pseudo-comet's head, while others see it as Zeta^1 and Zeta^2 Scorpii. No matter which strikes your fancy, you'll find the tail fanning out to the northeast. With binoculars I've been able to enjoy the "comet" brushing the horizon even from the northern Adirondack Mountains at a latitude of 44.4°N.

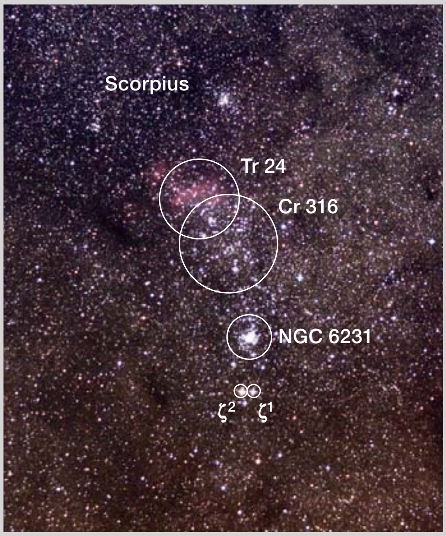
The origin of the term False Comet is something of a mystery. Some propose that it was so dubbed by John Herschel, largely to commemorate his ship's landing in False Bay, South Africa, near which he conducted observations of the southern sky. Others claim a more recent origin by amateur astronomers based solely on appearance. There's some evidence *S&T* Contributing Editor Alan Whitman inspired the name by pointing out the "comet-like Milky Way patch in southern Scorpius" at the 1983 Texas Star Party. Others think the term may have been coined by Southern Hemisphere observers.

Resting 27′ northeast of the 4th-magnitude star 45 Ophiuchi, **Trumpler 26** is a fine cluster through my 130-mm refractor. At 23× four brighter suns, laid out like the hub and tips of a three-bladed propeller, overlay a grainy backdrop of threshold stars. At 164×

DO 27: MARTIN GERMANO; SKETCH: SUE FRENCH the hub star is a nice double, and I can pick out 20 stars in a 7′ gathering with indefinite borders.

Much farther north in Ophiuchus, **IC 4665** is centered 1.3° north-northeast of yellow-orange Beta (β) Ophiuchi. Seen through the 105-mm scope at 28×, it's a loose but obvious bunch of stars 7th magnitude and fainter. About 22 stars occupy the main bunch, which spans 40′. Stars wrapped more sparsely around those double the count and extend the cluster to a diameter of 70′. My 10-inch scope at 43× reveals a mixture of 60 bright and faint stars spattered across 45′. The brightest pose in oddly deliberate-looking lines, arcs, and geometric shapes. The cluster's IC designation springs from the second *Index Catalogue*, a supplement to the *New General Catalogue*.

Dolidze-Dzimselejsvili 9 is a pretty aggregation of loosely strewn stars perched 40′ west of the orange star 104 Herculis. Its coordinates differ from source to source, but visually it seems to lie at those in the table. Through the 105-mm scope at 17×, about 25 stars, 8th magnitude and fainter, assemble in a ½° collection widely framed by three bright field stars. Many cluster members roughly outline a five-pointed star with its center nearly barren and most of its southeastern point snapped off. At 36× about 40 stars bedeck the group, some colorful. The bright pair in the north shines yellow-orange and pale yellow. The dimmer star of a similar pair south of center glows yellow-orange, as do the middle star in a line of three to its west and a bright star near the cluster's northwestern edge.



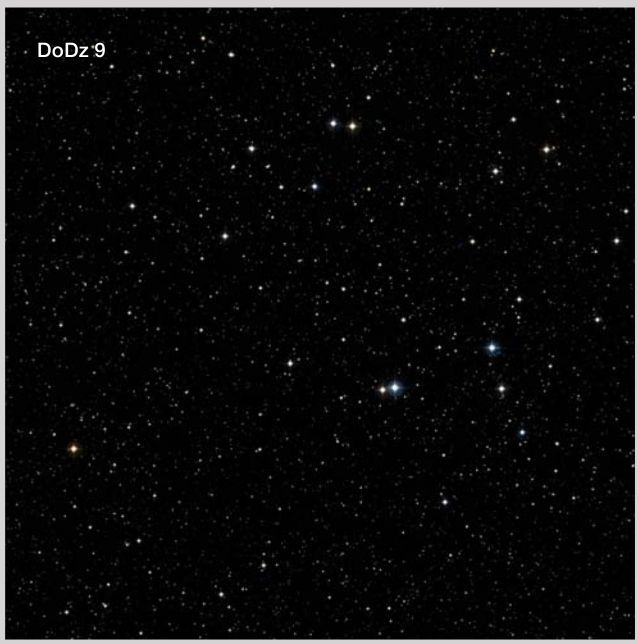
◀ The region near Zeta^1 and Zeta^2 Scorpii makes for good observing. The tight open cluster NGC 6231 shines almost directly north of the stars, while the overlapping clusters Trumpler 24 and Collinder 316 stretch to the northeast. Together, these objects combine to mimic a comet, with NGC 6231 or the Zetas forming its head and Trumpler 24 and Collinder 316 shaping an imaginary tail. Deep-sky images reveal the emission nebula IC 4628, which envelopes Trumpler 24.

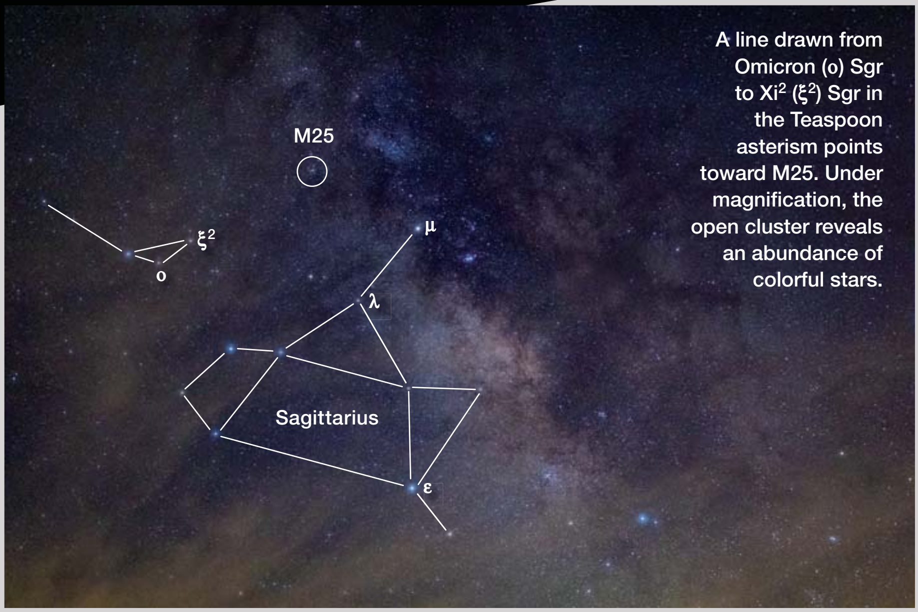
The 11 Dolidze-Dzimselejsvili objects appeared in a 1966 Astronomicheskii Tsirkulyar paper by Madona Dolidze and Galina Jimsheleishvili, a better transliteration of the second author's name than the one commonly adopted in catalogs.

Although discovered by Jean-Philippe Loys de Chéseaux circa 1745–46, **Messier 25** wasn't included in the *New General Catalogue*, which gives me an excellent excuse to include this spectacular cluster in our non-NGC tour. My latest visit to M25 was with the 105-mm scope. At 36× this 30′ beauty flaunts 55 mixed bright and faint stars displayed in arms flung out in all directions. It also boasts several colorful stars. The brightest one in the northeast glows yellow-orange, and the one in the

CR 316 AND TR 24: MICHAEL A. COVINGTON; IC 4665: BOB FRANKE; DODZ 9: POSS II / CALTECH / STSCI / PALOMAR OBSERVATORY

▼ *Left:* IC 4665 forms an obvious grouping 1.3° north-northeast of Beta Ophiuchi. Despite being an easy sight to see, it wasn't included in either Messier's lists or the NGC. In fact, it wasn't even included in the 1895 update to the NGC, the Index Catalogue (IC), but had to wait until the second IC was issued in 1908. *Right:* The open cluster DoDz 9 lies 40′ west of 104 Herculis. Look for the two yellow-orange star pairs, one at the cluster's north, one south of center.





A line drawn from Omicron (o) Sgr to Xi^2 (ξ^2) Sgr in the Teaspoon asterism points toward M25. Under magnification, the open cluster reveals an abundance of colorful stars.

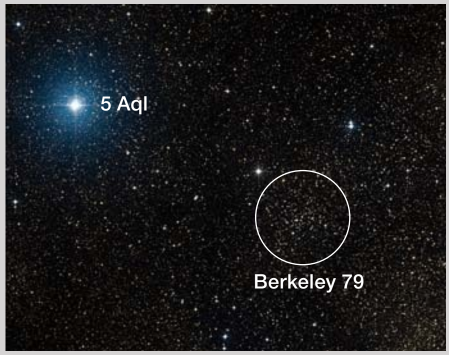
northwest gleams yellow. The luminous star just east of center shines yellow, and the next brightest to its east wears a yellow-orange hue. Two stars smolder orange: one in the southeastern edge, and another of similar brightness 8′ south-southwest of the cluster's center. Besides the color, number, and diversity of its stars, M25 holds another charm — a cute little D of seven faint stars rests at its heart.

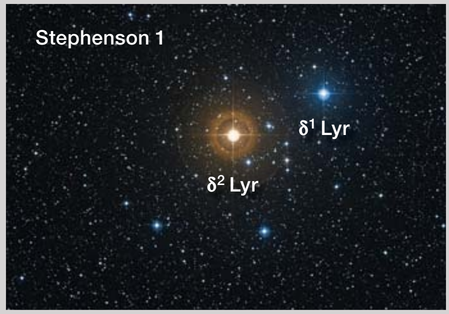
Pointing the 130-mm scope to the bright double star 5 Aquilae, the granular haze of **Berkeley 79** shares the field of view and sports one faint star at 37×. At 117× four dim stars emerge: three in a southward-pointing triangle and one to its east. The northwestern triangle star looks elongated at this power, but going to 164× proves it to be a pair. Some extremely faint stars also pop into view. In the 10-inch at 68×, I see a fairly large patch of mist sprinkled with very faint stars, and 5 Aquilae exposes three components in a little arc. At 187× Berkeley 79 reluctantly surrenders a central clump of 10 stars plus perhaps 20 corralled into a 10′ halo around it. Berkeley clusters debuted in a two-part, 1962 paper by Arthur Setteducati and Harold Weaver of the University of California, Berkeley.

Beyond the NGCs

Object	Const.	Mag(v)	Size/Sep	RA	Dec.
Dolidze 27	Oph	6.3	25′	16^h 36.5^m	−08° 56′
Collinder 316	Sco	3.4	105′	16^h 55.5^m	−40° 49′
Trumpler 24	Sco	8.6	60′	16^h 55.8^m	−40° 43′
Trumpler 26	Oph	9.5	7′	17^h 28.5^m	−29° 30′
IC 4665	Oph	4.2	70′	17^h 46.2^m	+05° 43′
Dolidze-Dzim 9	Her	6.2	34′	18^h 08.8^m	+31° 32′
Messier 25	Sgr	4.6	30′	18^h 31.8^m	−19° 07′
Berkeley 79	Aql	—	10′	18^h 45.0^m	−01° 09′
Stephenson 1	Lyr	3.8	40′	18^h 54.5^m	+36° 54′

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.





▲ *Top:* The 6th-magnitude star 5 Aquilae shares a field of view with the somewhat dim Berkeley 79, which resembles a meek pile of caster sugar in the eyepiece. More aperture and higher magnification reveals individual stars. Look for the central gathering of about a dozen suns. *Bottom:* Many of us have probably looked at Stephenson 1 without realizing it was a star cluster. The orange Delta^2 Lyrae, which shines at the cluster's center, is surrounded by 30 to 40 stars as dim as 9th magnitude. Blue-white Delta^1 is also a cluster member.

We'll finish our tour with **Stephenson 1**, the fetching splash of stars surrounding Delta^2 (δ^2) Lyrae. This orange star pins the cluster's heart and offers a pretty contrast with bluish-white Delta^1 to the west-northwest. About 30 to 40 mixed bright and faint stars embellish a patch of sky at least ½° across. The group was proposed as a possible cluster in a 1959 paper by Charles Stephenson.

Although some of these clusters may ultimately prove to be mere asterisms of unrelated stars, stargazers usually judge their worth by how interesting they appear. I hope a few of them will catch your attention and add bit of variety to your observations of the sky we love.

■ Contributing Editor **SUE FRENCH** would like to thank everyone for the kind farewells, and she hopes to meet you under the stars.

M25 SAGITTARIUS: STEPHEN RAHN / PUBLIC DOMAIN; BERKELEY 79 & STEPHENSON 1: POSS II / CALTECH / STSCI / PALOMAR OBSERVATORY

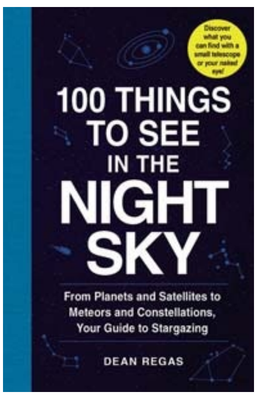
Step by Step to Success

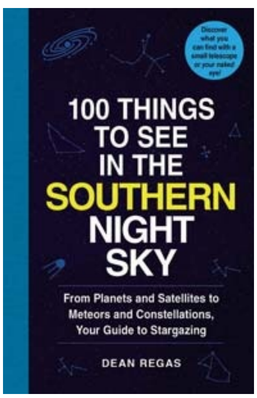
100 THINGS TO SEE IN THE NIGHT SKY

Dean Regas
Adams Media, 2017
224 pages, ISBN 9781507205051
$15.99, soft cover.

Southern Edition
Adams Media, 2018
224 pages, ISBN 9781507207802
$15.99, soft cover.

I'M OFTEN ASKED ABOUT resources for novice amateur astronomers. More and more, my replies center on the digital — stargazing apps, websites, planetarium programs, and so on. But nothing fosters interest in observing more than a good book written specifically for the beginner. By good, I mean a book that's not just well written and free from errors, but organized in a way that systematically builds skills and knowledge without overwhelming the reader. Ideally, observing should leave us feeling content much more often than it leaves us feeling frustrated. (Let's save the frustration for those 12th-magnitude faint fuzzies that just won't be found.) A strong introductory observing manual should also include more advanced material to challenge the curious and expanding mind. A well-considered bit of history that places an object or constellation in its cultural context and/or a lucid summary of a scientific study of a particular target makes a book even better.





ADAMS MEDIA

Dean Regas, Astronomer at the Cincinnati Observatory, co-host of the television program *Star Gazers*, and *S&T* Contributing Editor, has written a book that ticks all the boxes. *100 Things to See in the Night Sky* is more than a lengthy list of interesting celestial objects. It's also a step-by-step guide to deciphering the constellations and a primer for observing the Sun, Moon, and planets. Many of these objects can be viewed with the naked eye, but Regas also includes suggestions for using small telescopes and binoculars for lunar and planetary observing. Safe solar observing habits are also emphasized.

In addition to the introduction, the book has three parts. Part One covers the Sun, Moon, and naked-eye planets. Part Two is dedicated to the stars and constellations, and is further subdivided by season. Basic diagrams show and connect the constellations' brightest stars; if you're giving this book as a gift, consider pairing it with a planisphere or an all-sky chart to give more context to the stick figures. Part Three goes "beyond stargazing" to discuss artificial satellites, meteor showers, eclipses, northern lights, and other celestial phenomena. Regas ranks each sight in terms of difficulty (easy, moderate, difficult), guiding the reader to improvement from night to night.

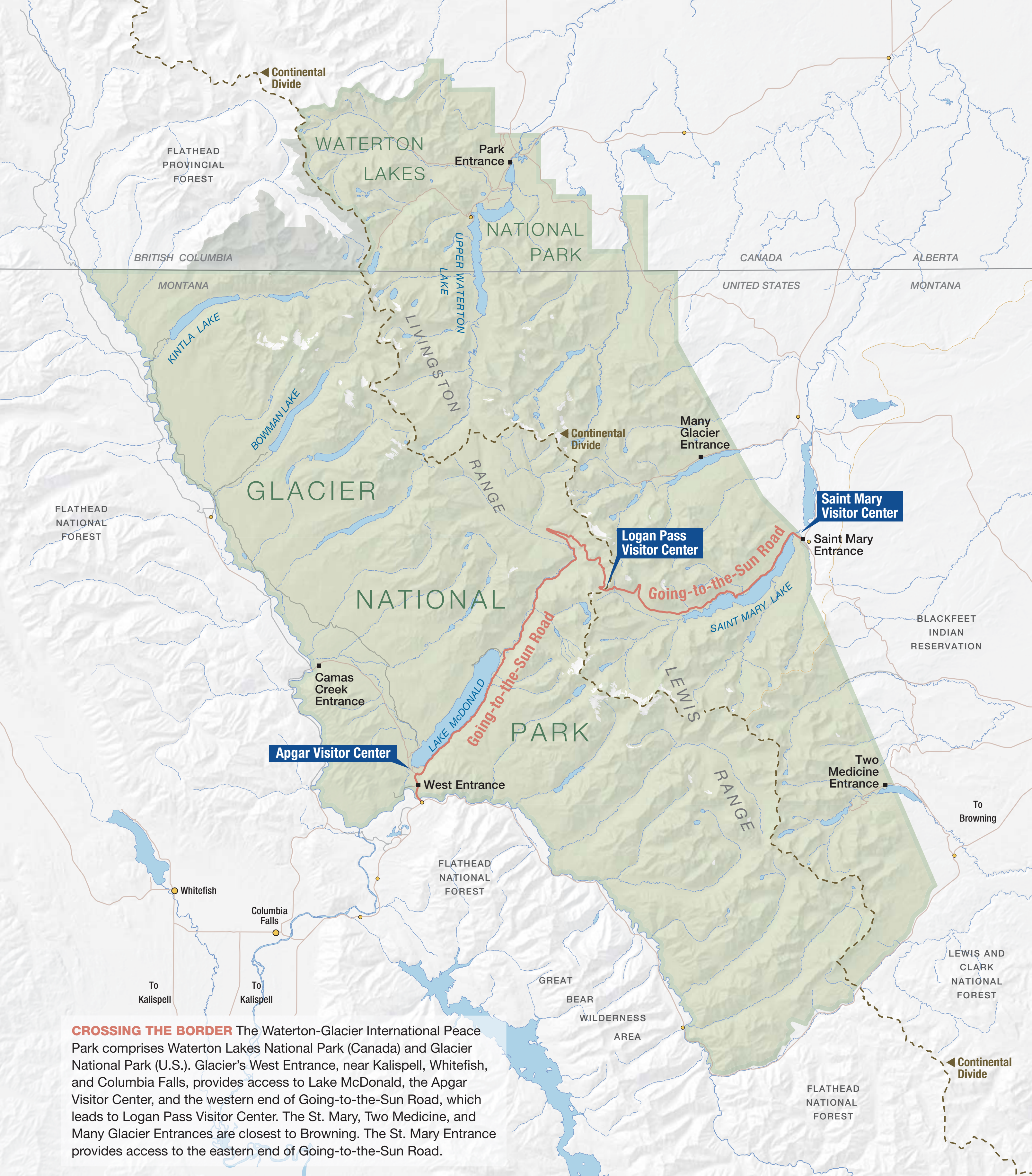
The design of *100 Things to See in the Night Sky* is clean and sharp. The constellation diagrams are easy to read, the table of contents detailed, and the index comprehensive. The use of blue ink on white paper adds a touch of jazziness to the page, but perhaps higher-contrast black ink would have been a better choice. There's plenty of white space, so bring a pencil to scribble notes in the margins while observing. The book is lightweight but sturdy, meant to be taken outside and perhaps thrown in the bin of camping equipment. The book's corners are rounded to avoid unnecessary paper stabs in the dark.

> Dean Regas, Astronomer at the Cincinnati Observatory and co-host of the television program *Star Gazers*, has written a book that ticks all the boxes.

Regas has thoughtfully prepared two editions of this book. *100 Things to See in the Night Sky* is intended for observers in most of North America, Europe, northern Africa, and most of Asia (roughly between latitudes 25° and 55° north). *100 Things to See in the Southern Night Sky* is written for viewers in Australia, New Zealand, South Africa, and South America (latitudes 15° to 45° south). A few constellations and asterisms have been added to (or inverted in) the southern edition, and the seasons reversed between editions, but most of the content is identical, so you won't be missing out if you only purchase the book for your local sky.

■ Associate Editor **S. N. JOHNSON-ROEHR** suggests taking your book outside.

PARK IN THE DARK by Amy Grisak



CROSSING THE BORDER The Waterton-Glacier International Peace Park comprises Waterton Lakes National Park (Canada) and Glacier National Park (U.S.). Glacier's West Entrance, near Kalispell, Whitefish, and Columbia Falls, provides access to Lake McDonald, the Apgar Visitor Center, and the western end of Going-to-the-Sun Road, which leads to Logan Pass Visitor Center. The St. Mary, Two Medicine, and Many Glacier Entrances are closest to Browning. The St. Mary Entrance provides access to the eastern end of Going-to-the-Sun Road.

Seeing Stars in Glacier

The first cross-border International Dark Sky Park offers everything a stargazer needs for a fulfilling night under the stars.

"Stunning" and "breathtaking" fall short as descriptors when talking about the majesty of towering mountains and sweeping vistas in Montana's Glacier National Park. But as gorgeous as the daylight hours are, Glacier truly shines at night. Mountain peaks frame the view of the northern lights or the Milky Way, and the surrounding silence, without the din of human existence, makes every night feel like a once-in-a-lifetime experience.

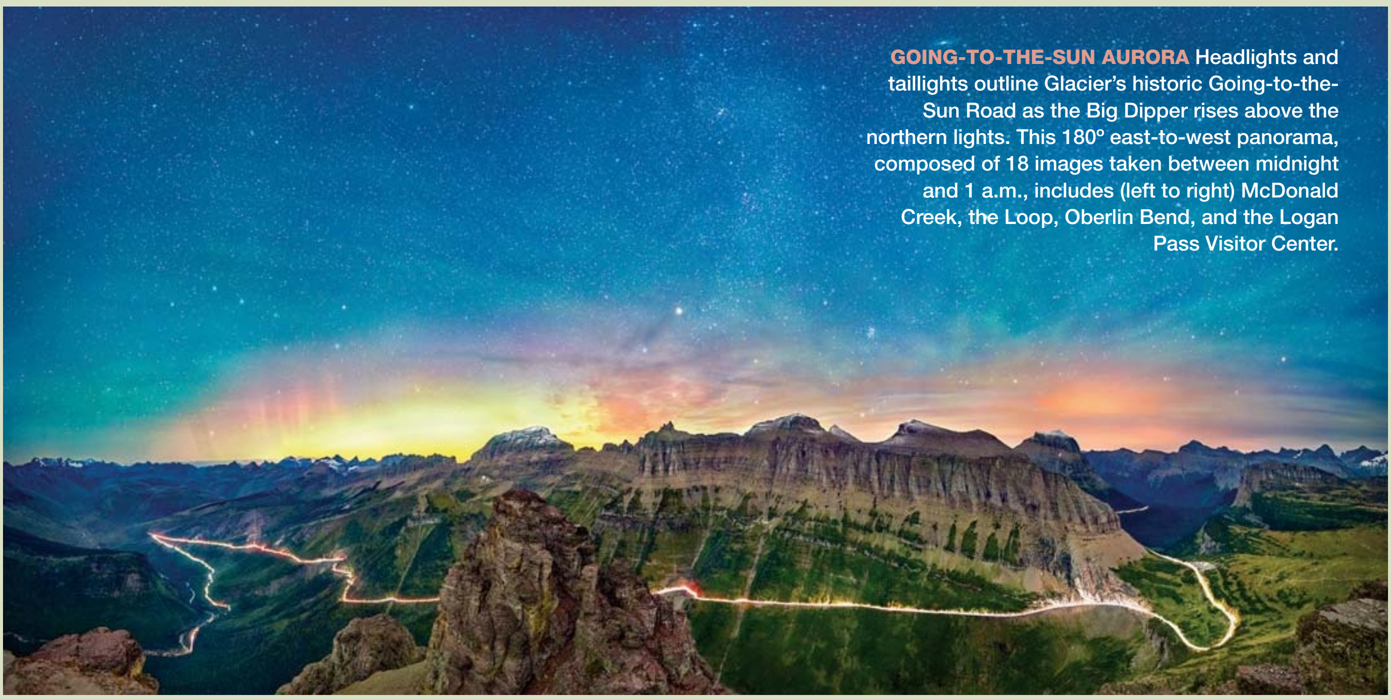
Going to Dark Places

It's a given that viewing the night sky without extraneous light enhances the experience, and, fortunately, Glacier and its sister park, Waterton Lakes National Park in Alberta, Canada, are doing their best to protect this resource for future generations. Though administered separately, the two parks were brought together under the moniker Waterton-Glacier International Peace Park in 1932. In 2017, the joint park received a provisional Gold Tier designation from the International Dark-Sky Association (IDA) as the first transboundary International Dark Sky Park, and it's well on its way to complying with the requirements.

"We have until 2020 to get our lighting to 67% IDA compliance," explains Mark Biel, Natural Resources Program Manager for Glacier National Park. "We are anticipating meeting, and exceeding, the 67% compliance requirement by the end of 2019 if anticipated funding is received and employees can be hired to install the lighting."

Dark skies are an increasingly precious resource, but they weren't priorities until recently.

"No National Park, yet, has ever been set aside for the dark skies," says Mark Wagner, retired Interpreter for the Hudson Bay District in Glacier, as well as one of the found-



GOING-TO-THE-SUN AURORA Headlights and taillights outline Glacier's historic Going-to-the-Sun Road as the Big Dipper rises above the northern lights. This 180° east-to-west panorama, composed of 18 images taken between midnight and 1 a.m., includes (left to right) McDonald Creek, the Loop, Oberlin Bend, and the Logan Pass Visitor Center.

GLACIER MAP: GREGG DINDERMAN / *S&T*, SOURCE NATIONAL PARKS SERVICE; U.S. AND CANADA MAP: FREE VECTOR MAPS; PANORAMA: JOHN ASHLEY ers of the park's astronomy program. Rather, parks have been established to preserve natural or cultural landmarks, with dark-sky designations awarded later by organizations such as the IDA. He points out that when Glacier was established in 1910 administrators didn't recognize the value of the night skies because light pollution wasn't an issue. Fortunately, we still have dark skies at Glacier to show the next generation.

Join the Party

"The key thing in Glacier is it's one of the truly dark sky places in America," says John Donovan, chairman of the board of the Glacier National Park Conservancy, the non-profit arm of the park that funds a multitude of programs and projects. Because they recognize the importance of the night sky, they enthusiastically fund the astronomy efforts.

"The astronomy programs are among the most popular things the park does," notes Donovan. Each season, nearly 30,000 people attend either daily solar viewing or nighttime stargazing, as well as special star parties. The Conservancy understands the need to do more.

Jewel in the Crown of the Continent

Building on this realization, Glacier will reveal its newest addition to the astronomy program in the early summer of 2019. With the blessing of the National Park Service and funding by the Glacier National Park Conservancy, a 12.5-foot-diameter SkyShed POD Max dome observatory was set up just beyond the parking lot boundary at the St. Mary Visitor Center.

Lee Rademaker, lead Interpreter in the Hudson Bay District based out of St. Mary, is a fixture of the astronomy programs and is equally enthusiastic about the new equipment. "Our telescope is a PlaneWave 20-inch CDK," he says, "and that will tour around the night sky on top of a Paramount ME II robotic telescope mount. We will use a MallinCam SkyRaider DS10c to feed two 55-inch monitors mounted on the outside of the observatory with high-resolution images of the night sky."

"People are going to be awe-struck with it," enthuses Russ Lucas, a volunteer park astronomer and member of the Big Sky Astronomy Club who has been with the program since its inception. "None of us can wait. This is going to be the jewel."

The telescope will be powerful enough to see into deep space, and the plan is to focus on more

Blackfeet Star Stories

Long before we could peer into deep space, the indigenous people who have called Glacier home for generations looked at the sky with a unique vision. Members of the Blackfoot Confederacy were, and still are, intertwined with the world above us, and their daily lives honor and renew these connections when they are retold.

Helen Augare Carlson and Melissa Weatherwax of the Blackfeet Community College in Browning, Montana, share these stories as part of Glacier National Park's star parties, where attendees have the opportunity to immerse themselves in the night sky and ancient lessons.

"[Glacier National Park] is all part of the territory," says Carlson. "We see it all as special. All of our land has a purpose."

Carlson explains that star stories are part of their oral tradition, therefore there is no set "right" way to tell them. They're often told using different details depending on the storyteller, audience, and the context of what needs to be taught in that particular instance.

"One story connects to the rest," she says. "It's connected on [the theme of] how to learn to live a good life. It's not a religion. It's a way of life. The knowledge is still there. All these stories of how indigenous people understood their environment go back to the energy of the place."

Melissa Weatherwax shares a story of Ursa Major:

Naatosi (the Sun) and Kokomiikiisom (the Moon) had a falling out. Kokomiikiisom was angry with Naatosi and their seven sons, who ran from their mother in her anger. To slow Kokomiikiisom, Naatosi gave each son a special gift. Each time Kokomiikiisom drew near, they could use that gifted power to escape. As a result, they created the canyons, rivers, lakes, mountains, weather, and forests. When Kokomiikiisom came close to the youngest brother, he propelled himself and his brothers into the sky, forming what is now called Ishkitsi-kammiks, or Ursa Major.

To fully appreciate these stories, attend one of the star parties where members of the Blackfoot Confederacy share their history and lessons, bringing us all together under the night sky.

THE MAGIC HOUR The Milky Way stretches across a darkening sky above Logan Pass.

NPS / JACOB W. FRANK / PUBLIC DOMAIN

advanced scientific projects. Wagner says educational opportunities will be available to students of all levels throughout the world.

The observatory will also offer a completely different experience for park visitors. “Now we have this amazing tool where we can show off the night sky in St. Mary,” says Rademaker. As the camera projects images on screens for visitors, it allows them to see well beyond the capabilities of the naked eye looking through an eyepiece. “Our astronomers will be able to talk in detail about the events being displayed.”

More Opportunities

While the new telescope will offer an unparalleled experience, dedicated volunteers, including members of the Big Sky Astronomy Club in nearby Kalispell, will continue to share the night sky through the lenses of multiple telescopes, including solar, in order to introduce people to the world above.

“The astronomer in me loves this,” says Lucas. “I meet people in Glacier from all over the world. We live in different parts of the world, but we all see the same sky.”

Lucas says the programs, which are held multiple times per week at the Apgar and St. Mary Visitor Centers, usually begin by the first half of July (depending on when Going-to-the-Sun Road is plowed open). He recommends that visitors check the bulletins at the information kiosks or ranger stations for specific details.

Although the evening programs often don’t begin until nearly 10 p.m., the early-to-late evening hours offer excellent opportunities to observe the brightest planets and stars until the sky is dark enough to gain a better view of deeper objects. Dark skies finally settle fully upon the landscape closer to midnight.

In July, August, and early September, special star parties are held at Logan Pass, which, situated at an altitude of 6,647 feet, feels within reach of the stars. Tickets to the event are free (although a $5 donation to the Glacier National Park Conservancy is welcomed), and can be picked up at the Apgar or St. Mary Visitor Centers the day before, or even the day of, the event.

Attendees should be at the parking lot at Logan Pass around 9–9:30 p.m. and plan to remain there until midnight since the headlights of any cars leaving will spoil the stargazers’ night vision. After an introduction, visitors are broken into groups where an astronomer offers a laser-guided tour of the night sky as it darkens, before everyone filters out to various telescopes for an up-close view. Star enthusiasts can even bring their own scopes for a front-row seat.

“It’s about the experience of seeing things in the truly dark sky,” explains Wagner. “We try to get people to make personal connections.”

Backcountry Seats

Offering views not every park visitor can witness, backcountry campgrounds are some of the best places to stargaze, whether you pack a telescope or opt for a pair of binoculars. A

LIFE GOALS At latitude 48.6° north, Lake McDonald lies south of the typical auroral oval, but in times of elevated geomagnetic activity, Waterton-Glacier is a top spot for viewing the northern lights.

BRAVING THE ELEMENTS Comet Lovejoy (C/2013 R1) crosses the winter skies above the fire lookout on Mount Brown on December 7th, 2013. It took four nights in subfreezing temperatures before Moon phase (new), cloud cover (none), and comet all aligned. On this night the air temperature was –9°F, not counting the wind chill.

AURORA: NPS / JACOB W. FRANK / PUBLIC DOMAIN; COMET LOVEJOY: JOHN ASHLEY

Volunteers Make It Happen

The amazing programs within Glacier don't come without challenges — primarily a lack of knowledgeable people to help keep them going. The Big Sky Astronomy Club members are an integral part of the program, and the park is always looking for more volunteers.

"The numbers are growing more and more," says Lucas. "It's hard to find people to help. It's the most challenging thing the park has to do. We could expand this program and make it even better than it is. It's really tough for us when we get 90 people (per night at the Apgar or St. Mary stargazing events) and there are two of us running the telescopes," he says.

Wagner shared the sentiment. "I love the volunteers. They are great. If you take the volunteers out, you have zero programs."

For those who wish to step up and into this rewarding role, specific information is available at **https://is.gd/GlacierAstro**.

▲ **PUBLIC PROGRAMS** Nearly 30,000 people attend stargazing or solar parties in Glacier National Park each year. Because of the northerly location of the park, summertime darkness doesn't fall until around 10 p.m. local time, but once it arrives, the skies are pristine, barring bad weather and smoke. Darkness arrives earlier in winter, but cold-season observing requires dedication and planning.

JOHN ASHLEY

good portion of the backcountry campgrounds have excellent views of the sky, and aligning geographical features with the celestial ones creates a one-of-a-kind experience.

Spaces are limited in the backcountry sites, but there are a couple options for securing a spot. Potential backpackers can apply for a permit via the backcountry advanced reservation system, which opens on March 1st for large groups (9–12 campers) and March 15th for standard groups (1–8 campers) (**https://is.gd/GlacierAdvance**). As the date is sometimes referred to as "IT Armageddon" because the system occasionally crashes due to the high volume of requests, have your application ready to submit, with several itinerary choices for the best chance of securing a site. Applicants are typically notified by mid-April whether their application was successful.

If planning ahead isn't an option, or a reservation wasn't obtained, showing up in person at one of the backcountry offices can sometimes secure a site since there are a certain number held for walk-in backpackers. Line up early (some begin the wait as early as 5 a.m.) for the 7 a.m. opening, and talk to the helpful rangers to see what spaces are available. This can be done a day in advance or the same day.

Living the Night Life

If spending the night under the stars isn't in the cards, another option is to be strategically positioned for the dark hours. John Ashley, biologist, photographer, and author of *Glacier National Park After Dark: Sunset to Sunrise in a Beloved Montana Wilderness*, spends innumerable days coordinating astronomical events with the weather and the scenes he envisions in his mind. To obtain these shots he notes when comets, Moon phases, or a particular meteor shower will be visible and where he wants it in relation to the landscape before venturing into the darkness.

"I never just go out with a camera and hope to find something," he says. "There are some alignments I've chased unsuccessfully for multiple years and they're still on my calendar."

While not everyone will snowshoe up a ridge to line up a perfect shot of the full Moon, astronomically minded visitors can often drive to suitable viewpoints, especially along Going-to-the-Sun Road where the best visibility is above the treeline. Use the pullouts on the east side of Logan Pass, particularly above Siyeh Bend, or higher than the hairpin curve known as "The Loop" on the west side.

Hiking to less accessible vantage points is also an effective way to gain a better perspective of the night sky, but it's not necessarily advised. Glacier, besides having a reputation for amazing scenery, is also one of the largest strongholds of grizzly bears in the lower 48. While hiking up to Siyeh Pass, for example, will undoubtedly offer exceptional night viewing, it's probably not worth the risk of bumping into a bear. Surprise encounters are the number-one reason for human-bear conflicts within the park, and hiking at night increases the probability dramatically. On a practical note, no matter when you're hiking, day or night, always bring bear spray and know how to use it, make noise as you travel down the trail, and preferably hike in groups of at least four.

For those who don't want to venture out very far at night, they needn't hike into the wild areas in order to gain a phenomenal perspective of the night sky. Standing at the southern edge of Lake McDonald near Apgar offers amazing views of the northern lights (when they're active), as well as a large swath of the night sky. Kintla and Bowman Lake are equally stunning in the North Fork valley, and standing at the base of Rising Wolf Mountain in Two Medicine is just as remarkable. It's not difficult to find a good place to look up.

◀ **DANGEROUS REALITY** Forest fires are a fact of life in Glacier National Park, and the threat and presence of fire has only increased in recent years. Wildfires often cloak the landscape in dense smoke, but occasionally their glow can lend an unplanned element to the scene, as in this view captured of the 2015 Thompson Fire from Hidden Lake Nature Trail at Logan Pass.

Be Ready for Anything

Just because Glacier is blessed with dark skies doesn't mean stargazing is a sure thing.

"Trying to stargaze in the mountains is a delicate dance between starlight, moonlight, and clouds," says Ashley. But stargazers can use the Moon to their benefit at times. "If you want to learn the constellations, go out with a lot of moonlight. It washes out the dimmer stars and makes the brighter ones stand out," he says.

In more recent years smoke from wildfires has been increasingly problematic. "Smoke can make an astronomical event exceptional or keep you from even seeing it," Ashley says. "It can add a reddish color, or it might make (stars) invisible."

Ashley believes that the smoke from western fires is going to be the new reality for stargazing in the park, particularly later in the summer. There have been fires in Glacier nearly every year since 1910, but the magnitude of the fires has increased over the past several years. It's a consideration visitors need to understand when they're planning their trip.

Regardless of the season, Glacier National Park is a special place at night. You might have to contend with the extended sunlight during the glorious summer days, brave the brisk but long winter nights, or visit in the shoulder seasons when the weather is a wild card. But every visit brings a new perspective and greater appreciation of the spectacular scenery above us.

■ **AMY GRISAK** is a freelance writer and photographer specializing in gardening, cooking, and sustainable lifestyles, as well as anything to do with the beautiful Montana outdoors.

▼ **OPTICAL ILLUSION** The night sky appears to circle around Polaris, the North Star, in this time-lapse image over Lake McDonald. But it's really the Earth's rotation that creates the circular star trails.

FIRE: NPS / JACOB W. FRANK / PUBLIC DOMAIN; STAR TRAILS: JOHN ASHLEY

 by Ron Brecher

The Quest for Round Stars

Great deep-sky imaging begins with well-tracked exposures.

We all marvel at gorgeous pictures of galaxies, nebulae, and star clusters, and strive to make our own astrophotos just as inspiring. But many things can go amiss during the long exposures needed to make them. Some things we can't control — atmospheric seeing, variable sky transparency, or gusty winds, for example. But other factors that affect our images we can control. One is mechanical jerkiness in our mounts that can cause every star to look like streaks or even double stars. Another is poor collimation of our optics. This can produce weird star images in different parts of the field, indicating a problem that can sometimes be difficult to diagnose.

The stars in our images serve as excellent diagnostic tools to help us identify and correct problems in our imaging techniques. Capturing stars that are as round as our setups will permit makes post-processing easier and improves our overall results. Here are some common problems and how we can deal with them on an off night.

Collimation

Perhaps the first thing to check with any imaging setup is its collimation. A system is collimated and performing at its best when everything is properly aligned and the light coming into the center of the telescope or lens reaches the center of

PERFECT GUIDING Perhaps the most critical step in deep-sky astrophotography is ensuring well-tracked images. This detailed image of NGC 7000 (left) and IC 5067 (right) includes more than 16 hours of perfectly tracked, unguided exposures using a Takahashi FSQ-106ED astrograph and a Moravin G3-16200 CCD camera. Unless otherwise noted, all photos are courtesy of the author.

the sensor. Fast optics (those with a low f/ratio) are particularly sensitive to imperfect collimation.

In astrophotography, not only must the optics be aligned, but the camera's sensor must be properly positioned. Heavy cameras and filter wheels can cause some focuser drawtubes to sag, introducing misalignment. One clue that a focuser on a refractor or Cassegrain telescope is sagging is when stars appear round across a photo only when the telescope is pointed straight up towards the zenith and gravity is pulling the focuser holding a heavy camera square to the optical axis. You can solve this sagging issue by tightening up any loose rails or

▲ **POOR COLLIMATION** Ensuring your collimation is spot-on is an important step, particularly when shooting with fast Newtonian astrographs with coma correctors. This image of van den Bergh 15 displays comatic stars along the right side. These are particularly visible in the top right.

▲ **UNWANTED TRAILS** While some star elongation doesn't detract from wide-field nightscape images, the same can't be said for deep-sky astrophotography. If your results look like the image above, plan on spending some time identifying the cause of the tracking problem.

▲ **HALF IN FOCUS** Diagnosing the source of sensor tilt — seen in this image as the right half of the frame is out of focus, while the other side is not — can be tricky. Take an exposure pointed at the zenith then another pointed about halfway towards the horizon to make sure the problem isn't due to a sagging focuser drawtube.

COLLIMATION: SEAN WALKER / *S&T*

bearings in the focuser, or by replacing it with an after-market model that can better support the camera's weight.

You can distinguish the effects of miscollimation from other problems by comparing the stars in short and long exposures. Its appearance in images is unaffected by exposure length, which can help to eliminate other issues such as poor tracking or field rotation.

An additional concern with deep-sky imaging is ensuring a camera's sensor isn't tipped within the focal plane of the imaging telescope. Large sensors are more sensitive to these tiny misalignments that mimic the effects of poor collimation but aren't corrected by adjusting the optics or the focuser. Images affected by sensor tilt appear the same regardless of where the telescope is pointed. Some astronomical cameras equipped with large detectors include a push-pull adjustment plate on the front of the camera that permits you to tweak the alignment of the sensor.

Most refractors and Maksutov-Cassegrains are collimated at the factory and don't require collimation by the user (although the camera and focuser may require adjustment as noted above). See articles on collimating a Schmidt-Cassegrain (*S&T:* Feb. 2018, p. 28) and Newtonian reflectors (*S&T:* April 2019, p. 68). Specialized collimating tools such as those offered by Hotech (**hotechusa.com**) permit collimation of Newtonian and Cassegrain optics during the day.

Polar Alignment

Even the finest equatorial mount won't produce images with round stars if it isn't properly aligned. Polar alignment is when the polar axis of the telescope is made parallel with the rotational axis of Earth. Our planet rotates around this axis, making stars appear to spin around the north or south celestial pole. As an object moves through the sky from east to west, a properly aligned mount will cancel out this movement, keeping the object centered in the telescope. Misaligned equatorial mounts (and alt-azimuth Go To mounts) can keep an object centered for visual observation but will slowly introduce field rotation, which makes such setups unsuitable for long-exposure astrophotography.

So how accurate does polar alignment need to be for tracked images to have round stars? The answer depends on several factors, such as the length of the exposure, the target's location in the sky, the telescope's focal length and pixel scale, and even the difference in pointing angle between the guide star and the imaging target. Richard Hook published equations concerning polar alignment in the February 1989 issue of *The Journal of the British Astronomical Association*. One of these equations tells us how well-aligned a mount needs to be for a given setup:

$$E = \frac{45{,}000 \times S \times \cos D}{T \times F \times A}.$$

In the equation, E is the maximum permitted polar alignment error in arcminutes, and S represents the tolerance for field rotation in microns. D is the declination of the target, while T is the exposure duration in minutes. Focal length (in millimeters) is represented by F, and A is the angle in degrees between the guide star and the opposite edge of the field.

This equation confirms that short exposures and short focal lengths combined with larger pixels are more tolerant of imperfections in polar alignment. In other words, the higher your pixel-per-arcsecond ratio is, the longer you can expose with less-than-perfect polar alignment.

If you know how accurately polar aligned your mount is, the equation can be rearranged to answer the question "Given my current polar misalignment and equipment, what's the longest exposure I can achieve before stars appear elongated?" like this:

$$T = \frac{45{,}000 \times S \times \cos D}{E \times F \times A}.$$

When shooting with an image scale of 1 to 4 arcseconds per pixel, polar misalignment by as much as 3 arcminutes is adequate for exposures up to about 15 minutes long.

Some telescope-control software and autoguiding software programs include tools that make precise polar alignment relatively simple. Hardware tools such as the QHYCCD PoleMaster are also available (*S&T:* July 2018, p. 62). The tried-and-true manual method of drift alignment takes longer but works well even if you don't have a clear view of the celestial pole. Numerous drift alignment tutorials are available online.

▶ **AUTOGUIDING** Most astrophotography rigs require autoguiding to keep the telescope pointing exactly at the target throughout the entire exposure. This setup includes a 10-inch ASA f/3.8 Newtonian astrograph that has a piggybacked 80-mm refractor for autoguiding.

Autoguiding

While good polar alignment, tracking, and collimation can improve the roundness of the stars in our images, many telescope mounts require a little help staying on target. This is because most mounts use gears that produce a repeating error known as *periodic error* (PE), which causes a slight oscillation of the field. This often is represented in the technical specifications of your mount as, for example, a PE of +/- 3 arcseconds. Some high-end mounts reduce this error to near-imperceptible levels below one arcsecond, which permits long, unguided exposures at moderately long focal lengths. For most of us, though, long-exposure imaging requires guiding on a field star near your target and correcting these small periodic errors.

Guiding used to be performed manually using a reticle eyepiece, your own eye, and copious amounts of both time and patience. Thankfully, technology eliminated the need for manual guiding almost three decades ago. Autoguiders are small, inexpensive CCD or CMOS cameras that you use to monitor a star and make the corrections necessary during a long exposure.

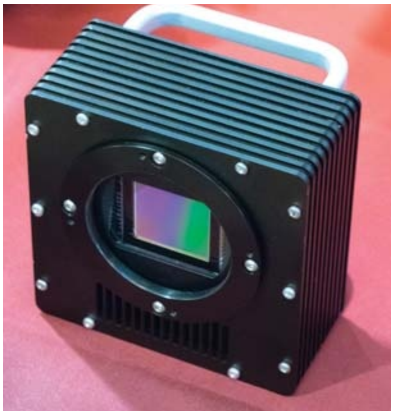
You can use an autoguider in either of two configurations: through the imaging telescope equipped with an off-axis guider, or attached to a separate telescope mounted on the side of your imaging scope. The autoguider checks the position of a single star (the guide star) every few seconds and sends pointing corrections to the mount as needed to keep the guide star centered.

Most camera-control software has autoguiding capabilities, including *TheSkyX*'s camera control add-on (**bisque.com**), *MaxIm DL* (**diffractionlimited.com**), and *PHD2* (**starklabs.com**, reviewed in *S&T:* Dec. 2017, p. 64). Lots of good documentation can be found online explaining how to use autoguiding software and how to troubleshoot any issues.

One common problem encountered when autoguiding through a guidescope is known as *differential flexure*. This generally occurs when the guidescope isn't attached securely enough to prevent slight differences in movement between the guidescope and imaging scope. A device called an off-axis guider, or OAG, can mitigate this problem by eliminating the guidescope entirely. Placed between the telescope and main camera, an OAG contains a small pick-off prism that directs light from the telescope to the guide camera's sensor. When correctly positioned, this prism protrudes only far enough into the light path to capture star images for guiding and should not cast a shadow on the main camera's sensor. The small field provided by the prism should contain an adequately bright guide star. If not, the position of the telescope can be adjusted slightly to bring a suitable star into the autoguider's field of view.

An OAG takes up some of the physical space between your camera and any field flattener or coma corrector in your optical path, so check that you have adequate room between the two before using one.

While autoguiding can help immensely, it isn't always sufficient to produce round stars. I recommend that you consider autoguiding only after optimizing the mechanical and optical aspects of your setup. If you have an excellent mount, or if you're shooting at short focal lengths or limiting your exposures to only how long your mount can go before PE becomes noticeable, you may not need to autoguide at all.



◀ **SENSOR COLLIMATION** Cameras with large CCD and CMOS detectors are highly sensitive to having the sensor square to the telescope's optical axis. Some (such as the Starlight Xpress camera at left) include a push/pull adjustment plate at the front of the camera that allows users to fine-tune the squareness of the detector.

COLLIMATION: SEAN WALKER / *S&T*

Balance

Another consideration for improving tracking is making sure the weight on your mount is evenly distributed. This minimizes the load that the motors need to bear, reducing wear and tear on one of the most crucial parts of an imaging rig. Having the payload and counterweights balanced well can go a long way toward reducing tracking errors.

To balance equipment on a German equatorial mount, start by balancing the declination axis first. Throughout this process, be sure to hold the equipment steady to prevent sudden rotation due to extreme imbalance. Orient the mount so that the counterweight shaft is horizontal, and the scope with all the gear you intend to use (include any anti-dew straps, and remember to remove any lens caps) is also pointed horizontally. Loosen the clutch on the declination axis and gently nudge the scope up and down. If it moves easily in

▼ **FIELD ROTATION** This photo of the Double Cluster (NGC 869 and NGC 884) suffers from field rotation, where all the stars appear to arc around a point outside the top-left side of the image frame. The cause may be either inaccurate polar alignment or differential flexure between the imaging telescope and guidescope.

◀◀ A MATTER OF BALANCE Ensuring your equipment is balanced properly on your mount will go a long way toward reducing tracking errors. Adjust the weight of the telescope tube first on the declination axis, then check the right ascension by sliding a counterweight on the shaft.

◀ CABLE MANAGEMENT Secure any dangling cables close to the telescope and mount so that they don't snag during an exposure or while slewing to another target.

both directions, your scope is in balance in that axis. If not, then adjust the position of the scope forward or backward in its tube rings or along the dovetail plate to balance it. Tighten everything up and then move to the right ascension (RA) axis. Loosen the RA clutch and simply slide the counterweights on the shaft to balance the scope in RA.

Balancing on a fork mount is similar, though you may need to add counterweights to a rail attached to your telescope tube if there aren't accommodations to shift the position of the tube.

Once you have your payload properly balanced, be sure everything is locked down and then test the mount's performance in a guided image. You should also repeat the test with a target on the opposite side of the meridian.

Some mount manufacturers recommend that you keep the RA axis very slightly unbalanced towards the east side for long exposures. This ensures that the RA worm gear is always engaged as the mount tracks the motion of your target. If you find unbalancing the mount helps, first find perfect balance as described above. Then use a very small weight (just an ounce or two will usually do) that can be attached to the telescope or the counterweight shaft as needed, depending on where your target lies.

Ensure any cables connecting your equipment to the control computer are bundled neatly and secure them to the telescope in a manner that minimizes any stresses that could change as the telescope tracks the sky.

▼ PERFECT EVERY TIME Once you've solved all your guiding issues, you're more likely to produce a steady stream of excellent data ready for processing. The author recorded this colorful image of IC 410 (left) and IC 405 through the same equipment as the photo on pages 64-65.

If You Don't Succeed

The best-laid plans don't always work as expected, so if you still end up with slightly trailed stars in your exposures, you can turn to tools that can repair misshapen stars after the fact.

For example, *PixInsight*'s Deconvolution tool has a Motion Blur PSF mode that can significantly reduce star elongation when you input the length and angle of the trailing in your image. There's also a powerful plug-in script for *Maxim DL* that can repair elongated stars (**https://is.gd/trailfix**). Just be aware that no after-the-fact fix will produce as high a resolution in your image as does preventing the problem from happening in the first place. Remember that if stars are elongated, any non-stellar objects in the image are also smeared, and they can't be repaired as easily as the stars.

You may have heard it said that "Good data never goes bad." You can always reprocess good images as your processing skills improve and your artistic tastes change over time. Unfortunately, the reverse is also true: Bad data never gets better. That's why it's worth spending the time to get your imaging system performing at its best before your next clear, moonless night. There's nothing quite as satisfying as sitting at the computer on a perfect night watching while each subexposure downloads and displays tight, round stars.

■ **RON BRECHER** images the night sky from his backyard observatory in Guelph, Ontario.

Meade's DSI-IV Camera

Could this be the best astronomical camera yet offered by Meade? The answer depends on your imaging interests.

◀ Meade's new DSI-IV camera comes as a complete package with a 2-inch nosepiece, USB 3.0 computer cable, 12-volt adapter and cables (needed only for the camera's cooling system), operating software on a CD-ROM, and rugged, waterproof case. The little, sealed plastic bag at right contains a desiccant module that attaches to the camera to help prevent fogging of the CMOS chamber window. The author never had to use it.

ALL PHOTOS BY THE AUTHOR

Meade DSI-IV Monochrome Camera

U.S. Price: $1,099
(one-shot color version $999)
meade.com

What We Like

Highly versatile astronomical camera

Excellent thermoelectric cooling system

Rugged design and construction

What We Don't Like

Included software has excellent video-capture features, but long-exposure imaging controls could be improved

DIGITAL IMAGING HAS BEEN part of amateur astronomy for more than three decades. It's a sobering thought for those of us who've been there since the beginning. Over the years, Meade has introduced a number of astronomy cameras, but the newest — the DSI-IV — might be the best one yet. It all depends on your imaging interests.

The DSI-IV is a highly versatile camera capable of recording high-resolution video of the Moon and planets as well as quality long exposures of faint deep-sky objects. It's built around a cooled, 16-megapixel Panasonic CMOS detector with 3.8-micron-square pixels in a 4,640-by-3,506-pixel array. The sensor's imaging area measures 17.6 by 13.3 millimeters, making it slightly smaller than the APS chips in today's crop-sensor DSLR cameras.

For this review we borrowed a monochrome version of the DSI-IV from Meade. A one-shot color version is also available for a little less money. The camera is roughly 3½ inches (about 90 mm) in diameter, 4 inches long, and is very well made. It weighs 25 ounces (0.7 kg) and is supplied with a 2-inch nosepiece. It will reach focus on any telescope that has a focal point extending at least 18 millimeters outside of the focuser drawtube. With the proper adapters, it will easily work with focal reducers, tele-extenders, and most field flatteners, leaving enough room for a filter wheel or low-profile off-axis guider.

The DSI-IV's regulated thermoelectric cooling easily dropped the CMOS sensor to the specified maximum 40°C below ambient temperature, with sufficient overhead to maintain accurate temperature regulation — an important feature for deep-sky imaging. There are eight small heating elements bonded to the perimeter of the CMOS chamber window that were effective at keeping the window free from fog. While I never needed to use it, there's also a threaded port on the side of the camera for attaching a supplied desiccant module that offers added fogging protection.

A single USB 3.0 cable between the camera and your computer is all that's needed to connect and power the camera. The 12-volt adapter that comes with the DSI-IV, with its additional cable connection to the camera, is only needed for the cooling system, and is thus really only mandatory for long-

▲ *Left:* The DSI-IV only needs its USB 3.0 (it's backwards compatible for USB 2.0 as well) connection to a computer to capture images. The 12-volt input is just for the thermoelectric cooling system and is really needed only for long-exposure imaging. See the text for details about the two USB 2.0 ports. *Right:* Eight small heating elements bonded to the perimeter of the CMOS chamber window were 100% effective at keeping the window fog-free during all of the author's testing.

exposure imaging. It's worth noting that the supplied USB 3.0 cable is only 5 feet long. I was able to keep my laptop close enough to my telescopes to work with a cable this short, but others may need some form of extension such as an active USB 3.0 cable or the addition of a powered USB hub.

There are two USB 2.0 ports on the DSI-IV for connecting filter wheels, focusers, and guide cameras. But note that although these ports are powered, they still draw their power from the USB 3.0 connection. I successfully tested two small cameras on these ports, but your mileage may vary depending on how much power your auxiliary equipment requires.

Getting Started

Following instructions in the DSI-IV's quick-start guide, it was a breeze installing the camera's supplied operating software (called *Meade SkyCapture*), ASCOM drivers (needed for operating the camera with third-party software), and a copy of the user's manual on my aging laptop with an Intel i7 Core processor running Windows 7. At first blush, the manual I installed from the CD-ROM sent with the camera appeared to be the same as the one that opens from the Help menu in *SkyCapture*, but it was actually an older version that had not been updated for the DSI-IV — stick with the version that's displayed by *SkyCapture*'s Help menu.

Using my own adapters, I attached a conventional camera lens to the DSI-IV and began bench-testing the camera. The ASCOM driver worked fine, allowing me to connect the DSI-IV with the software I typically use, including *MaxIm DL* for long-exposure imaging, and *FireCapture* for recording astronomical video clips. But for the sake of the review I wanted to work with the supplied software.

SkyCapture is a slick-looking program with a user interface that I found relatively easy to navigate. It works with a variety of Meade cameras, and it has a number of features for Meade's one-shot color cameras that I couldn't test with the monochrome DSI-IV. Nevertheless, within minutes I was capturing video clips and snapping still images, although my "long" exposures were limited to only a few seconds because of the bright workshop environment (more about this later). There are always bumps on the road to learning any new software, and I certainly encountered my share, but nothing struck me as being due more to the software than my own inexperience using it. Much of my time was spent learning the video controls. Once comfortable with them it was time to get outside.

Going for the Moon

With the exception of Mars, which at the time was way too small for my imaging setups, all the major planets were in the morning sky, so my video tests were all done shooting the Moon. Mead claims The DSI-IV is capable of video frame rates as high as 23 per second at full resolution, but most users will experience lower rates, especially when running the camera in the preferred 12-bit, rather than 8-bit, mode. The issue is not so much the camera as it is how fast your computer can transfer and save images. The solid-state drive in my laptop isn't as fast as the latest models. You can certainly speed frame rates up by reducing the area of the CMOS that's being recorded (using cropped frames or what *SkyCapture* calls ROI for "region of interest"). This is especially true when imaging planets since there's little advantage to recording the blank sky that typically appears in the frame. Even with the Moon I reduced the size of the recorded frame to isolate lunar features rather than the large sweeps of lunar landscape seen in full-frame videos. Using a small region of interest, I typically captured between 40 and 50 frames per second.

◀ The DSI-IV is an excellent performer when shooting astronomical video clips, even if the author's results were less than stunning because of his winter seeing conditions living in New England under the jet stream. This view of Schröter's Valley was processed from 200 frames selected from a 1,600-frame, 30-second video clip captured last February 16th.

Frame rates aside, what really caught my attention with the DSI-IV is the enormous files generated with even short videos, often exceeding four gigabytes for a 30-second clip made with a small region of interest. The manual does warn about this, but it was still an eye opener to fill more than 50 gigabytes of disk space recording about a dozen video clips my first night out.

These videos were later processed with third-party software including *RegiStax* and the freeware *AutoStakkert!3*.

On to the Deep Sky

Once the Moon was out of the evening sky it was time to try the DSI-IV for deep-sky imaging. It's here where I found room for improvement with *SkyCapture* that I hadn't noticed when shooting still images during my bench testing in a relatively bright environment. For example, when framing faint deep-sky targets, I usually make short exposures of 20 to 60 seconds and stretch them to extremes to see what's in the field. With *SkyCapture*, the image that appears at the end of each exposure can't be stretched on screen as is. You can examine a histogram of the displayed image and make adjustments to set the black and white points for displaying a stretched image, but these settings do not take effect until you make the *next* exposure.

▲ Switching the DSI-IV from shooting astronomical videos to making long exposures of deep-sky objects involves only a few mouse clicks with the camera's included *Meade SkyCapture* software and, for optimum results, connecting the 12-volt power supply for the cooling system. These views of the Cone Nebula and Christmas Tree Cluster in Monoceros (*left*) and Horsehead Nebula in Orion (*right*) were each assembled from fifteen 10-minute exposures through a hydrogen-alpha filter with an 8-inch f/3 telescope.

▼ During his testing, the author exclusively used the *SkyCapture* software supplied with the DSI-IV for his astronomical imaging. As explained in the accompanying text, he feels the software's long-exposure mode could stand some improvement but was still effective for capturing images. The screen grab seen here displays one of the 10-minute exposures used for the image above and was made while the camera was in the process of running the automated exposure sequence.

The best workaround, apart from making multiple exposures or guessing at the correct histogram settings before shooting the first one (something that is possible with experience), is to first save the image and then re-open it with *SkyCapture* and use the Range function in the Process menu to actively stretch the image on screen. It's a bit clumsy, not to mention time-consuming, especially if you're typing file names and the like in the dark with gloves on.

There were also features of the software that I couldn't get to work, including the automatic functions for dark-frame subtraction and flat-field correction. These issues may be unique to the DSI-IV update of the software, since I noticed that the flat-field function isn't even discussed in the older user's manual that I mentioned earlier. Regardless, I don't like using automatic calibration routines during image capture, since I prefer having unmodified raw data that can be processed later with various calibration methods. As such, I simply made standard dark and flat-field exposures with the DSI-IV and processed my light frames with third-party software.

Despite my nit-picks with *SkyCapture,* I did use the software exclusively for all the imaging I did with the DSI-IV, and I'm happy with my results. Indeed, most astronomical cameras come with only the most rudimentary image-capture software (and some don't come with any), so getting a package as decent as *SkyCapture* included with the purchase of the DSI-IV is really a plus.

In the end I found the DSI-IV to be a very versatile camera that can satisfy the needs of many of today's astroimagers. It's a camera that can shoot excellent astronomical video and seamlessly transition to shooting decent long-exposure deep-sky images. It can't quite match the deep-sky performance of a cooled, 16-bit, astronomical CCD camera, but the DSI-IV is still a big step up from the astrophotography that can be done with DSLRs. And it comes with a very attractive price tag, especially given the software that's included.

■ **DENNIS DI CICCO** has been reviewing astronomical equipment in the pages of *Sky & Telescope* for more than 45 years.

A 3D-Printed Binoscope

No workshop? No problem.

WHEN ROBERT ASUMENDI looked through Frank Szczepanski's binocular telescope (*S&T:* Apr. 2019, p. 72), he realized several things at once:

- Binocular vision is vastly more comfortable and pleasurable than monovision. (So much so that Hans Lippershey had to build a binocular before the patent office would even consider his patent application for the telescope in 1608.)
- Binocular vision helps to compensate for Robert's severe astigmatism.
- Despite wanting a binocular scope, he also wanted grab-and-go portability, wide fields, and enough aperture to provide satisfying views of deep-sky objects.

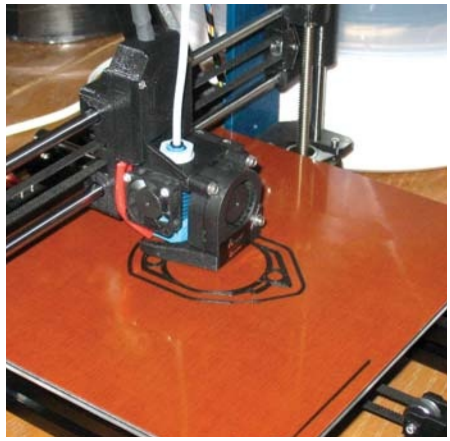
Robert searched for a scope that would satisfy all his requirements but came up empty. "There's no commercial scope that delivers all those things," he reports. "So I made it."

Robert faced two simple challenges: He had never built a telescope before, and he didn't have any shop space. He did, however, have a couple decades of experience with computers. "So my computer became my workshop," he says. "I designed everything in a parametric computer-aided-design (CAD) program."

And because we're now living in the 21st century, 3D-printing the parts became a natural outcome of the design process. That allowed Robert to test aspects of his design without building the entire thing at once. He could examine a real physical object, modify its parameters in the computer, and print another to see how it worked. He didn't have a 3D printer at first, so he jobbed out his designs on 3DHubs (**3dhubs.com**), an online printing service. That worked nicely, but he quickly realized he wanted a 3D printer of his own. Besides eliminating shipping costs, it made unit-testing of small components more practical and allowed him to optimize settings for each part, which made for fantastic, repeatable results.

He started with the focusers. He wanted to use 2-inch eyepieces, but he couldn't find any commercial focusers that would put the drawtubes close enough together for most people's interpupillary distance (the spacing between eyes). He settled on a modified Crayford design that allows the drawtubes to nearly contact each other. And once he'd started designing, he just kept going. Could he 3D-print a filter wheel? Could he 3D-print the secondary mounts? Could he design channels in those secondary mounts to run wires for dew sensors and heaters?

◀ Robert Asumendi's "Drifter" binocular telescope is a marvel of design and execution.



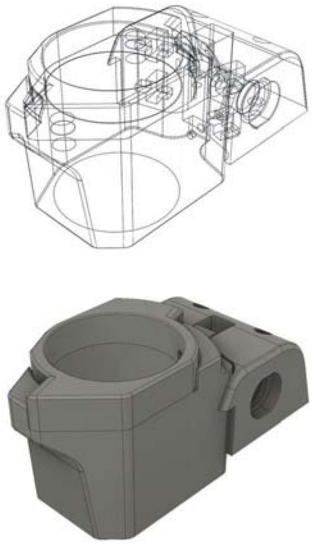
▲ *Top:* The eyepiece adapter fits solidly into the focuser thanks to neodymium magnets embedded in each part. *Bottom:* The 3D printer generates an eyepiece adapter. This piece took about 20 minutes to print and cost about $1.65 in materials.

He could, and did. It was an iterative process, each step building on the previous, both intellectually and physically. Robert says, "The resulting parts would have been extremely difficult, costly, or heavy to machine. The unique honeycomb structure of 3D prints lets you design lightweight, sturdy components that just wouldn't work in other materials. And, of course, with a binoscope you need two of everything, and several of the components are mirrored. With 3D printing, you just use the mirror command and print another one."

ALL IMAGES COURTESY OF THE AUTHOR UNLESS OTHERWISE NOTED

Most of the upper end is 3D-printed. Robert used a carbon-fiber-infused nylon material that's lightweight, durable, and stiff. The interior space of most pieces is honeycombed rather than solid, so they're considerably lighter than wood, and they have almost zero flex. The biggest challenge with binocular scopes — keeping the images merged as you move the scope around the sky — is a non-issue in Robert's scope.

The bottom end is more conventional, with aluminum trusses and plywood mirror box and rocker box. Why didn't he 3D-print all that, too? "Because all that stuff is best realized in other materials using other processes," he explains. "Plus 3D printing is relatively expensive over large volumes." However, the parts of the scope that aren't 3D-printed were CNC-routed or laser-cut, so all the design could still be done in one piece of software.



▲ The focuser design can be displayed as a wire-frame drawing or as a solid object.

Robert bought his mirrors but designed his own cells to support them. And rather than fine-tune the image merging by tilting the primaries, as most binocular scopes do, he chose to do his image merging at the tertiaries, where the adjustment knobs are easy to reach.

Given the stiffness of the carbon-fiber-infused nylon building material and the telescope's overall rigid design, there's very little adjusting necessary. A tweak after setup and the view is often good all night. The scope can move from horizon to zenith without the images separating, and switching eyepieces doesn't affect merging until Robert gets to his highest magnification. Even then, it's a simple matter to re-merge.

One of the biggest bugaboos of binocular scopes is their complexity in setting up. Setting up Robert's scope takes about a minute: Place the scope and base on the ground, slide the top end upward and lock it into place, pop a couple of eyepieces in, fine-tune the merging, and you're ready to go.

The eyepiece holders are another great innovation that neatly solves a common frustration with binocular scopes. Set screws and compression rings tilt the eyepieces, especially when the eyepieces have safety undercuts. In a binoscope, that plays hob with image merging. Robert solved that by printing individual collars for each eyepiece. The collars incorporate neodymium magnets that click them neatly into place — exactly the same place every time, completely eliminating set-screw tilt.

Robert also designed filter cartridges so he can pop various filters in and out of the light path without removing eyepieces. Those, too, are held in place magnetically.

That's the beauty of designing the scope digitally and 3D-printing it: the ability to refine the user experience. Robert says, "With my binoscope, I wanted people to be able to just walk up to it and use it intuitively." He has largely succeeded. I've watched people use it at star parties, and they figure it out within seconds. To adjust the eyepiece separation for their own eyes, they just grab the eyepieces and push them together or pull them apart. The focus knobs are right where you expect them to be. You grab the top end of the scope to move it around the sky.

▲ Robert's computer is his workshop.

▲ The top end of the Drifter is mostly 3D-printed. One side is uncovered to show interior hollows and secondary spider design.

Robert calls his scope the "Drifter" because it's supremely suited to simply scanning the sky in search of beautiful sights. In a wide-field binocular scope, every view is a stunning view, but there's a sense of special delight in sweeping across, say, the Double Cluster or the Dumbbell Nebula without specifically looking for them.

That sense of delight is what it's all about. As Robert says, "I didn't build a telescope because I wanted to try 3D printing. I started 3D printing because I wanted to build a binoscope that never existed before."

We're on the threshold of a new design revolution. I'm convinced that Robert's experience, both the building method and the end result, will get more people into amateur astronomy. And there are still a million unique scopes waiting to be imagined and built.

For more information, contact Robert Asumendi at **robert@analogsky.co**.

■ Contributing Editor JERRY OLTION is a big fan of binocular scopes, 3D-printed or otherwise.

WIRE-FRAME AND SOLID FOCUSER: ROBERT ASUMENDI

▷ DEEP-SKY RISING

Jeff Dai

Several observers watch as Orion rises over the Pamir Mountains in the Xinjiang province of western China. The famous Orion Nebula, M42, is visible above the mountain peak at right, with the equally popular Horsehead Nebula to its left. Even more remarkable for an untracked photograph is the fainter, diffuse hydrogen nebulae visible, including Barnard's Loop appearing as a U-shaped cradle below M42 and the large Angelfish Nebula (Sh2-264) seen at upper left.

DETAILS: *Canon EOS 6D DSLR camera with 35-mm f/1.4 lens. Total exposure: 30 seconds at ISO 10,000 through an Astronomik CLS filter.*

▽ ARC OF SPRING

Sérgio Conceição

The dark rifts of the Milky Way spanning from Lacerta (left) through Scorpius (right) rise in the early morning hours above the glow of the village of Campinho, Portugal.

DETAILS: *Canon EOS 6D DSLR camera with 14-mm f/1.8 lens. Panorama assembled from several frames, each totalling 15 seconds at ISO 6400.*

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BLUE ROSE

Wanda Conde

The Rosette Nebula, NGC 2237, takes on an unusual color palette of blues, yellows, and oranges when imaged through narrowband filters.

DETAILS: *Orion ED80T Triplet Apochromatic refractor with ZWO ASI1600MM CMOS camera. Total exposure: 12 hours through Astronomik Hα, S II, and O III filters.*

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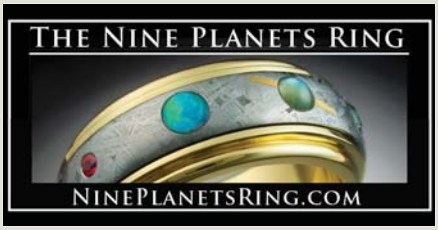

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Blink and You'll See It

The author's serendipitous rediscovery of a Mira variable recalls the decidedly singular way the star was originally found.

▲ Messier 27, aka the Dumbbell Nebula, with the Goldilocks Variable visible in 2016 (left, see arrow) and invisible in 2018 (right)

THE DUMBBELL NEBULA, also known as Messier 27 and NGC 6853, is one of my favorite nebulae, and over the years I've taken many pictures of it. I like to joke to my friends that it's named after me — the dumbbell.

Last October, I invited my freshman seminar astronomy class to my home to show them how to do some astrophotography. Eight students came. We snapped images of stars and other objects before I suggested we take a sequence of pictures of M27. They agreed, and over the next few hours my telescope and camera did just that while my students and I enjoyed tea and brownies inside and talked astronomy.

The resulting photo came out pretty nicely — almost as nicely as one I'd taken two years earlier with the same telescope and camera. Seeing the similarity between the two, I thought it'd be fun to combine the pair, thereby achieving a better picture. So I loaded both photos into a stacking program and set about aligning the images.

As I flipped back and forth between the two photos, I noticed that a fairly prominent star in the 2016 image was entirely missing from the 2018 one. This caught me completely by surprise. I'd never before seen a star totally disappear like that.

I uploaded the earlier photo showing the star to **astrometry.net** to get an astrometrically annotated version of the picture in FITS, the widely used digital file format. I loaded that into my planetarium program and determined the mysterious star's right ascension and declination. Finally, I entered these coordinates into the SIMBAD website. The database revealed that the star is a known Mira-type variable star.

Although a thrill for me, my accidental rediscovery pales in interest next to the unusual manner of the original identification, which occurred as recently as 1990. While creating a map of M27, Czech amateur astronomer Leos Ondra consulted the covers of that year's May issue of *Astronomy* and Autumn issue of *Deep Sky*, both of which, by chance, featured photos of the Dumbbell Nebula. To his astonishment, Ondra noticed a red star on the *Astronomy* cover that was altogether missing from the *Deep Sky* image. After the star was confirmed as a newly identified Mira star, he dubbed it the Goldilocks Variable.

Prior to my own "discovery," I was unfamiliar with Mira stars, though I've long had an interest in RR Lyrae variables and the globular clusters in which they lie. Noticeably blue, RR Lyrae stars have a period that's typically shorter than a day, and they vary in brightness by only a modest amount. Mira variables, on the other hand, are red giants with long periods — on the order of a year — and dramatic dips in brightness.

It is this last property that astonished me the most after my find. It means that, as my two pictures above show, a Mira star can seemingly disappear and then return, phoenix-like, from the sidereal ashes. A few days after my revelation, I blinked the two pictures for my class, and they were as dumbfounded as I'd been.

■ **ROBERT VANDERBEI** is a professor at Princeton University affiliated with several departments, including Astrophysics. He coauthored, with J. Richard Gott, *Sizing Up the Universe: The Cosmos in Perspective* (National Geographic). A mathematician by training, he's interested in variables of all sorts.

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