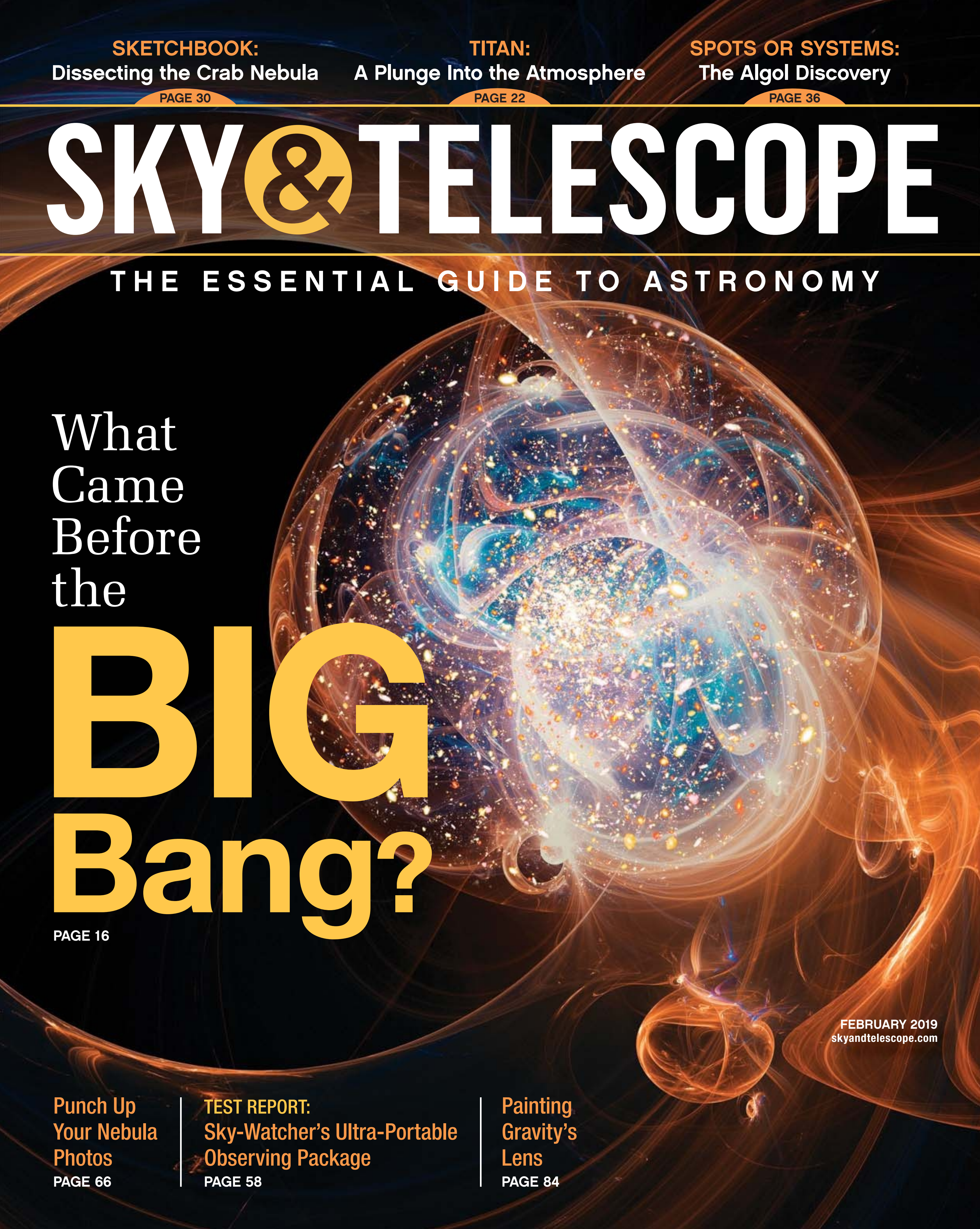

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Wide-field imaging, as depicted above, is possible with ease. The fully mechanical Omegon MiniTrack LX2 mount works just like a clock. No power necessary. No charging. No battery. Simply mount your camera onto the LX2 and wind it up. Easily capture wide-field images of the cosmos on your camera.

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(BBC Sky at Night)

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February 2019 VOL. 137, NO. 2

MARLENA BOCIAN HEWITT

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ON THE COVER

Artist's concept evoking string theory's bubble universes

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The Big Picture

YOU MIGHT WONDER WHY we'd devote our cover story to a question as esoteric as "What came before the Big Bang?" After all, *Sky & Telescope* is all about observing, and even with our most advanced instruments we can't look back that far. And isn't that question unanswerable? That is, don't cosmologists think the Big Bang was the start of everything, even time? And if it's unanswerable, is it science? Theory that isn't empirically testable isn't science.

In short, why should we care?

For good reasons. Theory and experimentation have always gone hand in hand. They feed each other — models inform observation, and vice versa. It's true we can't observe back to the beginning, but we're peering ever closer all the time. That's helping us constrain our view of the earliest periods of our cosmos,

which in turn aids theorists in refining their ideas and simulations of how our universe got jump-started in the first place and grew to its current state.

Moreover, cosmologists are exploring the possibility that the Big Bang *wasn't* the start of everything. Something — whatever it was — might have existed before the Big Bang and given rise to it. They're also entertaining the notion that our universe, however it began, might not be the only one. Universes might burst into existence all the time, like popcorn kernels in a multiverse pot.

Even as cosmologists vigorously debate our universe's dawn, they hope to actually *test* their hypotheses empirically, even at such a great remove. Although it didn't end up providing the evidence it sought, BICEP2 was one such attempt (*S&T:* May 2015, p. 12). Faye Flam describes another in her feature on page 16.

Cosmologists do agree that about 13.8 billion years ago, our universe was inordinately smaller than it is now, possibly no bigger than an infinitesimal dot, as inflation theory has it. "As weird as it sounds," writes Flam about inflation, "a submicroscopic patch of space became our vast observable universe."

You could look at it as somewhat akin to the way a single-celled organism in our planet's distant past went on to become *you* countless generations and several billion years later. Some microscopic cell way back when is your great-to-the-nth-degree grandparent, just as some submicroscopic dot more than 13 billion years ago might have been the progenitor of our 2-trillion-galaxy universe.

As with the history of life, how can we hope to fully appreciate what we see overhead at night without contemplating its origins?

All this is why we're pleased to offer a story about what came before everything. Whatever it was.

Peter

Editor in Chief

PITRIS / ISTOCK / GETTY IMAGES

SKY & TELESCOPE
The Essential Guide to Astronomy

Founded in 1941 by Charles A. Federer, Jr. and Helen Spence Federer

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Subscription Rates: U.S. and possessions: $42.95 per year (12 issues); Canada: $49.95 (including GST); all other countries: $61.95, by expedited delivery. All prices are in U.S. dollars.

Newsstand and Retail Distribution: Curtis Circulation Co., 201-634-7400.

Right-Sizing Aperture

Having used a variety of telescopes at various Northern and Southern Hemisphere sites, I really enjoyed Tom Dobbins's analysis of the optimal telescope aperture for lunar and planetary observing (*S&T:* Nov. 2018, p. 52) and concur with his overall conclusions.

However, a number of other factors also come into play. As with real estate, location really makes a difference. For instance, that elite group of amateur solar system imagers (Christopher Go, Damian Peach, and Leo Aerts, among others) works mainly at low elevation near seas and oceans, far removed from major mountains. Hence, they frequently enjoy atmospheric inversions or smooth laminar flow air currents. Often as well, haze and high humidity prevail at such sites, with diminished transparency but very steady seeing.

The best seeing conditions I've experienced over the years were at Mt. Wilson Observatory, the Atacama Desert, and Mount Pinos in California. While these are arid mountain locations, they border the Pacific Ocean and hence enjoy frequent westerly laminar air flow. In contrast, at my current location east of Flagstaff, where dark, crystal-clear skies and superb transparency dominate, seeing is often rather poor. That's ideal for deep-sky but rarely for lunar and planetary observing.

Still, while 12- to 16-inch-aperture telescopes may be best all-around as Dobbins attests, size still matters. Under comparatively rare superb seeing conditions at Lowell Observatory, the venerable 24-inch Clark telescope outperforms smaller-aperture instruments hands down every time.

Klaus Brasch • Flagstaff, Arizona

▲ It's hard to beat the views with the 24-inch Clark refractor at Lowell Observatory.

I found that Tom Dobbins's article hit the nail on the head. It highlights the term "empty magnification."

This has hit home many times with me. One night, my 10-inch f/4.5 Newtonian apparently outperformed instruments even as large as 60-inch aperture, on the same target, under terrible seeing conditions, taking videos. Computer stacking works well for shifting objects, but not if the seeing prevents details from coming through.

Dave Nakamoto • Azusa, California

Back to Venus?

Shannon Hall's article "Destination: Venus?" (*S&T:* Sept. 2018, p. 14) is a real eye-opener, and I sincerely hope that it helps to turn things around for further exploration of our sister planet by NASA.

An item that was mentioned only in passing intrigues me. The article mainly concerns volcanism, but it also notes "a giant impact crater." It is certainly fascinating that the Venusian surface is otherwise largely smooth or volcanic, indicating relatively recent activity over the entire planet that would erase evidence of other impacts.

But the fact that there is this one big crater seems to me to merit attention. Wouldn't further investigation help us determine how recently the inner solar system has been subjected to significant bombardment? I think that has major implications for planetary defense of our home planet . . . and thus offers yet another practical urgency in favor of returning to Venus.

Joel Marks
Milford, Connecticut

Cosmic Mystery

I've been reading your magazine for over 40 years and have always appreciated the clear, crisp, and accurate science writing. But my appreciation hit a new high with David Nakamoto's article on BL Lacertae objects (*S&T:* Sept. 2018, p. 30). This is one of the best articles I have ever read, combining clarity, accuracy, and good organization with an underlying mystery tale to solve.

Shawn Dilles
Vienna, Virginia

Old-School Astronomy

Jerry Oltion's Big, Bold, Bright, and Beautiful articles (*S&T:* Oct. 2018, p. 28 and May 2018, p. 22) have been much more than nostalgic for me. I purchased my 8-inch Coulter Dobsonian in 1990 and have spent many hours sketching bright and beautiful wonders in the sky. As I've watched observing decrease and astrophotography increase, I've felt like a relic of old-school astronomy. But Oltion's articles have heartily affirmed my love and desire for observational sketching without holding it in opposition to photography. I appreciate all aspects of our hobby and am glad to be fully affirmed in my little corner of it.

Pastor Mark Chapman
Upsala, Minnesota

Guided Tour

Jerry Oltion's "A Tourist's Guide to the Autumn Highlights" (*S&T:* Oct. 2018, p. 28) made me want to set up my telescope and wait for nightfall like nothing else I have read in more than 40 years as an amateur astronomer.

Jaime Tomé
San Juan, Puerto Rico

Diverse Interests

Antonio Peña's article on David Malin's work in color astronomy (*S&T:* Nov. 2018, p. 30) reminded me of my first and only encounter with this ultimate expert in imagery.

While doing a lecture tour in Europe in the 1990s, David visited our local planetarium in Aarhus, Denmark, and I was a bit surprised and also annoyed to learn that he insisted on using his

own lenses for the slide projectors for his lecture. But, of course, he was right! What I had thought of as the best available lens quality from a renowned German supplier fell totally short in comparison, when we changed the light bulbs to fresh ones and compared his images to mine with his totally amazing projecting lenses. On the obligatory city tour the day after, I regained a bit of pride seeing David's reaction to our small cathedral of 1190. Ancient architecture is apparently another of his great interests.

Ole J. Knudsen
Aarhus, Denmark

Spectral Evidence

Some clarification is needed for the discussion of the Hertzsprung-Russell diagram (*S&T:* Dec. 2018, p. 27). The statement "Spectral class indicates the relative abundance of the different elements in stars and correlates with temperature, so *O* and *B* stars are hotter than *K* and *M* stars" is incorrect. Spectral classes are based on the different appearance of absorption lines in a star's spectrum. A *B* star has strong lines of helium and a *K* star has prominent lines of calcium, but this does not mean that a *B* star is mostly helium while a *K* star is primarily calcium. These spectral lines are produced when the atoms in a star's surface absorb certain wavelengths of light, and an atom can only absorb these wavelengths if its electrons are in the right orbits, which depends on surface temperature.

As first demonstrated by Cecelia Payne in 1925, knowing which orbits the electrons are in can be used to calculate the abundances of the elements in a star. In her doctoral thesis, Payne found that all stars are composed of mostly hydrogen and helium, with a smattering of lighter elements.

This must have slipped past your usually knowledgeable editors.

Bradley W. Carroll
Ogden, Utah

Diana Hannikainen replies: *Yes, we goofed in editing and used "abundance" when we were thinking of strength. Thanks for keeping us honest.*

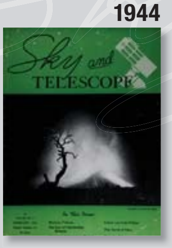
FOR THE RECORD

- In the sidebar "Moon Hides Star" (*S&T:* Nov. 2018, p. 51), the first line should read ". . . occults Chi1 (χ1) Orionis."
- In "New Year's Eve: Celestial Celebration" (*S&T:* Dec. 2018, p. 22), in the table of bright stars, Antares' constellation is Scorpius.
- In "Imbrium's Eyebrow" (*S&T:* Dec. 2018, p. 52), the crater labeled Atlas is actually Hercules. Atlas is the larger crater to the right of Hercules in the image.

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

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

1944



1969

1994

February 1944

Diminishing Returns "When F. C. Brown and I first mounted a selenium cell at the focus of a 12-inch refractor and pointed the telescope at Jupiter there was no detectable response whatever. Since then the faintest object which [A. E.] Whitford and I have measured with a photocell is a star of magnitude 16.1 with the 100-inch reflector. As the probable error of measurement was about 10 per cent, the limit of detection may fairly be called magnitude 18. From Jupiter at magnitude –2 to a star at +18 the change is 20 magnitudes. This advance is perhaps not so much a measure of the excellence of the latest developments as of the crudeness of the first attempts. . . .

"The limit of magnitude 16 was reached six or seven years ago, and the law of diminishing returns is working now. We can predict with confidence that the next 20 magnitudes will be harder to get."

Joel Stebbins (Washburn Observatory) was a leading pioneer in photoelectric photometry. True to his prediction, and despite CCDs, space telescopes, and much greater apertures on the ground, astronomers are still about 5 magnitudes shy of reliably reaching visual magnitude 36.

February 1969

Earth's Tail "Two Polish astronomers, M. Jerzykiewicz and A. Opolski of Wroclaw University Observatory, report an unexpected by-product of a large program of photoelectric photometry carried on at Lowell Observatory. . . . [T]hey found that when a star is within a few degrees of the antisolar point, it appears about 0.01 magnitude fainter than when observed at other times. . . .

"This dimming could be caused by about one thousand dust particles of 10-micron size in a column of one square centimeter cross section extending from star to observer. . . . [The] astronomers believe that their finding is evidence, like the gegenschein, for a dust tail of the earth. But they could not rule out the possibility of an unknown instrumental effect. . . ."

February 1994

Polaris's Pulses "Look on almost any sky atlas and you'll see Polaris shown by the symbol for a variable star. Look in reference catalogs and you'll find it listed as a classical Cepheid with a 4-day period and an amplitude of 0.1 magnitude. . . .

"Now Polaris has almost totally ceased pulsing, according to a report by J. Donald Fernie, Karl W. Kamper, and Sara Seager (University of Toronto). . . . The variation was down to a microscopic 0.010 ± 0.002 magnitude as of mid-1992 when the astronomers made their last measurements. They expect it to become perfectly constant any year now."

Fernie's team retracted its forecast in 1998, noting that Polaris's variations had settled at about 0.03 magnitude.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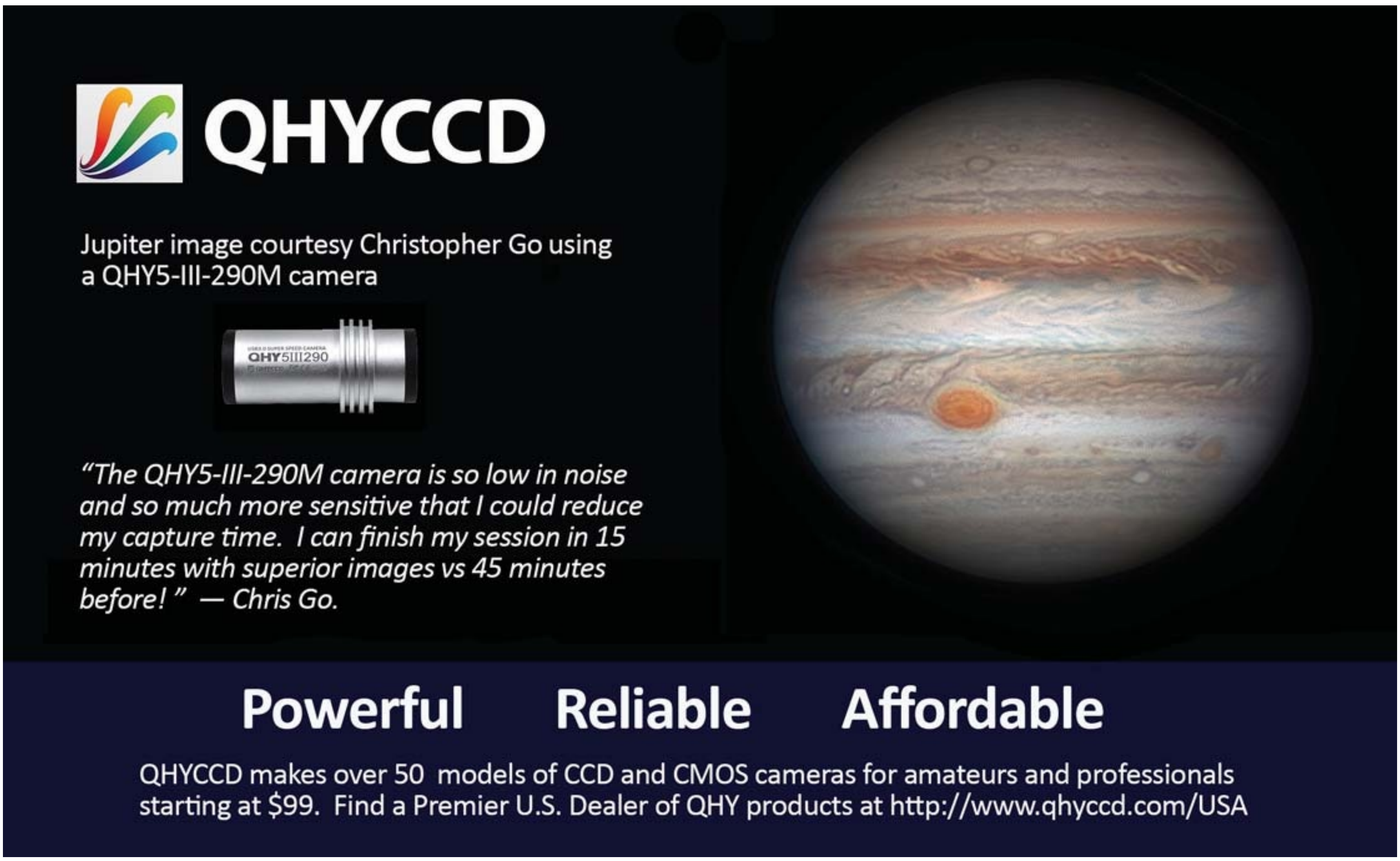
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The BepiColombo mission to Mercury launches from Europe's spaceport in Kourou, French Guiana.

For an infographic of the journey and video of the launch, see https://is.gd/bepilaunch.

S. CORVAJA / ESA

MISSIONS

Mission to Mercury Launches

THE BEPICOLOMBO SPACECRAFT launched October 19th from French Guiana on an Ariane 5 rocket, beginning a seven-year journey to Mercury. The voyage began perfectly, atop towering pillars of flame that lit up the early morning sky and remained visible until the side boosters burned out 2 minutes later, leaving the steady light of the main rocket stage visible as a greenish point in the sky. BepiColombo's journey will return it to Earth, past Venus twice, and take it by Mercury six times before finally settling in to orbit on December 5th, 2025 (*S&T:* Nov. 2018, p. 22).

Getting to Mercury is difficult — so difficult that fewer spacecraft have visited Mercury than have visited Saturn. NASA has previously sent two spacecraft: Mariner 10, which flew by three times in 1974 and 1975, and Messenger, which orbited the planet from 2011 to 2015.

BepiColombo, a combined effort of the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA), will bring flagship-class science to Mercury to answer questions old and new. How can the terrestrial planet with the biggest iron core have so little iron in its crust? How can its crust have so much sulfur when it's so close to the Sun? Why is its magnetic field shifted north of the planet's center?

The mission comprises two science spacecraft (plus a third craft that provides ion propulsion for most of the journey). The Mercury Planetary Orbiter (MPO), built by ESA, will operate in a nearly circular orbit close to the planet. The Mercury Magnetospheric Orbiter (MMO), built by JAXA, will fly in an elliptical orbit far from the planet.

Both probes carry magnetometers, to study how Mercury's magnetic field responds to buffeting from the Sun. Both carry instruments to study the planet's exosphere, the neutral atoms and ions knocked off Mercury's surface by incoming radiation. MMO also has a dust counter, something NASA's Messenger didn't have.

MPO has cameras and spectrometers to take photos and compositional measurements of the surface. From its nearly circular orbit, MPO will get much closer to Mercury's southern hemisphere and obtain much sharper images than Messenger could. The orbiter will try to understand the composition of Mercury's crust, the nature of its volcanic activity, and the timing of the planet's apparent shrinking. Scientists are particularly interested in seeing Mercury's south pole up close for the first time, to confirm whether it has reservoirs of ices and organic-rich materials, as the north pole does.

BepiColombo has a long way to go, but it has accomplished the most dangerous part of its mission — the launch. Orbit insertion in December 2025 should be a piece of cake by comparison. By the time the spacecraft completes its sixth flyby of Mercury in January of that year, it will be traveling slowly enough to be captured naturally, by Mercury's own gravity, the seventh time the planet and spacecraft meet.

■ EMILY LAKDAWALLA

BLACK HOLES

Gas Seen Moving near the Event Horizon

AN INTERNATIONAL TEAM of astronomers has caught the motion of hot, magnetized gas right near the event horizon of our galaxy's central supermassive black hole. This gas is likely part of a puffy disk that the black hole feeds from. The disk provides a flickering light source, its steady glow sometimes spiking in flares that observers see in wavelengths from X-ray to radio.

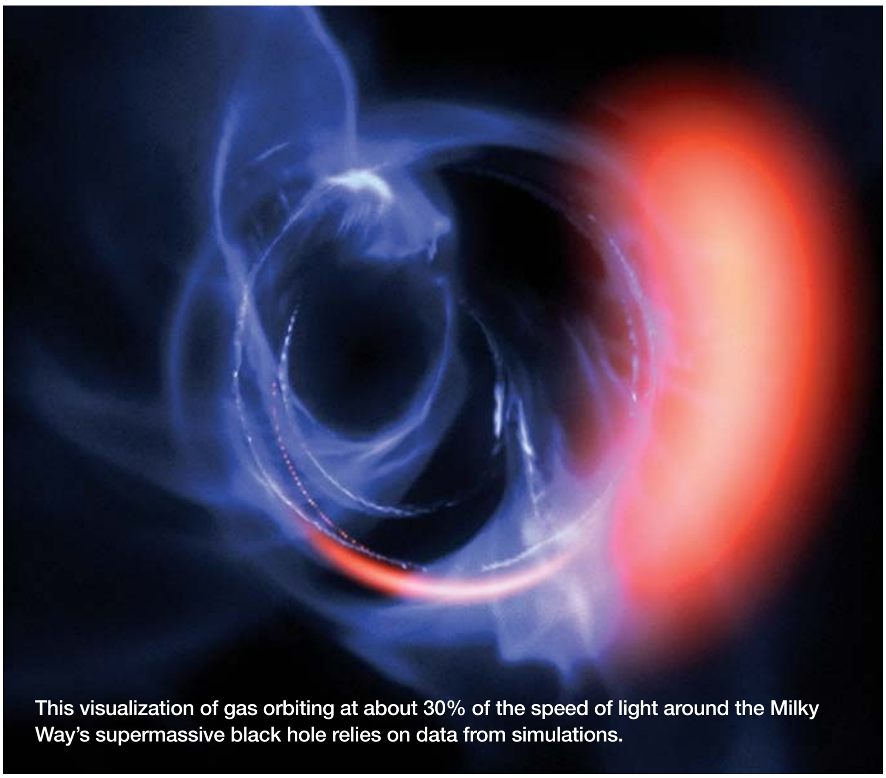
While watching the star S2 whiz by the black hole last summer (*S&T*: Sept. 2018, p. 22), astronomers with the Gravity Collaboration at the Very Large Telescope Interferometer in Chile saw three bright infrared flares from near the black hole. Each flare lasted between 30 and 90 minutes and didn't stay in place. Instead, each appeared to race around the black hole at 30% of the speed of light, tracing out about two-thirds of a clockwise loop that has the black hole at its center. Changing patterns in the light's polarization confirmed the twirling.

As the team reports in the October *Astronomy & Astrophysics*, the data point to hotspots orbiting very close to the black hole's event horizon, completing a pass every 45 minutes or so.

"This is an incredible measurement," says Avery Broderick (University of Waterloo, Canada). If astronomers see more flares behaving the same way, then "this presents an extraordinary opportunity to make precise tests of gravity in its most extreme environments."

Attendees at a galactic center workshop in Germany were excited but cautious. "Everyone believes there is some kind of motion in a flare near the black hole," says Sera Markoff (University of Amsterdam, The Netherlands). Hotspots are the simplest solution, which is why the team went with them. But it's not yet clear if an alternative solution might be better. "Most of us believe that more complicated things are possible, such as motions associated with magnetic flares or jets."

■ CAMILLE M. CARLISLE



This visualization of gas orbiting at about 30% of the speed of light around the Milky Way's supermassive black hole relies on data from simulations.

ESO / GRAVITY CONSORTIUM / L. CALÇADA

IN BRIEF

Weird Stripes on Dione

Saturn's moons are a hodgepodge of misfits. Iapetus looks like the Death Star from *Star Wars*. Tiny Pan resembles a cosmic empanada. And now something appears to be drawing straight lines across the surface of Dione. The bright lines stretch for up to hundreds of kilometers, are less than 5 kilometers wide, run parallel to the equator, and reside only at lower latitudes. They appear to lie atop extant features such as ridges and craters, which means they've been emplaced fairly recently. The most likely culprit is something in the same plane as Dione's orbit that gently rained down on the surface, researchers argue October 15th in *Geophysical Research Letters*. A passing comet, Saturn's rings, or the moons Helene and Polydeuces — which share Dione's orbit — are all suspects.

■ CHRISTOPHER CROCKETT

Hubble Takes a Nap

The Hubble Space Telescope has fully recovered from a three-week hiatus. The nearly 29-year-old observatory put itself into safe mode on October 6th after noting anomalous behavior from one of its gyroscopes, which are vital for ensuring that the telescope stays on target. Support crews suspected that the backup gyro might have developed an air bubble or stiff power wire after sitting inactive for years. To clear out the blockage, the team commanded Hubble to go through a series of turns, hoping to reset the gyro — and it worked. The venerable observatory got back to work on October 27th by turning its gaze toward a remote star-forming galaxy.

■ CHRISTOPHER CROCKETT

Colossal Supercluster Lurks in Early Universe

Researchers have identified what may be a gargantuan predecessor to modern superclusters, complex webs of galaxies spanning hundreds of millions of light-years. The light from this proto-supercluster has taken about 11 billion years to reach Earth. Seven galaxy clusters appear linked together by filaments of galaxies across roughly 20 million billion billion (2×10^{25}) cubic light-years of space. The entire ensemble is about as massive as 4.6 quadrillion Suns. While not the first galaxy cluster seen in the early universe, none are as massive or as sprawling as this one. Olga Cucciati (National Institute for Astrophysics, Italy) and colleagues reported the discovery in the November *Astronomy & Astrophysics*.

■ CHRISTOPHER CROCKETT

MISSIONS

The Kepler Space Telescope Comes to an End

AFTER A NINE-YEAR historic mission, the Kepler space telescope has finished its job. Exhausted of fuel and hobbled with inoperative reaction wheels, Kepler's exoplanet hunting days are over.

"As NASA's first planet-hunting mission, Kepler has wildly exceeded all our expectations and paved the way for our exploration and search for life in the solar system and beyond," said Thomas Zurbuchen (NASA) in an October 30th press release.

Launched on March 6, 2009, Kepler took up station in an Earth-trailing heliocentric orbit. The telescope's initial mission was to stare at a patch of sky overlapping the constellations Lyra, Draco, and Cygnus, looking for rhythmic dips in starlight that betray the presence of transiting planets as they passed in front of their suns. To this end, Kepler monitored about 150,000 stars during its 3.5-year primary mission (upping to nearly half a million stars during its entire career) and ultimately turned up 2,899 exoplanet candidates and 2,681 confirmed worlds — more than two-thirds of all planets known in the galaxy.

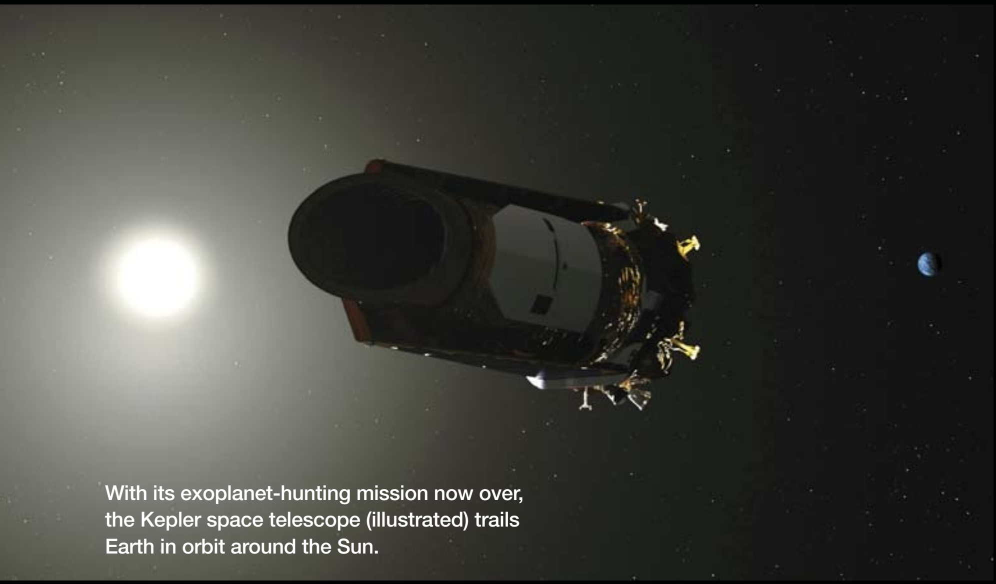
The slew of Kepler's discoveries suggests that 20% to 50% of stars in the Milky Way have small, rocky, Earth-sized planets that could maintain liquid water on their surfaces. Kepler also showed us that the most common sort of world is one not seen in our solar system — super-Earths bigger than Earth but smaller than Neptune (*S&T:* Mar. 2017, p. 22). Just what these worlds are like remains to be seen.

Kepler also revealed miniature solar systems, such as the eight planets in the Kepler-90 system orbiting a Sun-like star or the six worlds whipping around the Kepler-42 system, both of which fit all their worlds in a much smaller space than our system does and make our own look sparse in comparison.

The exoplanet-hunting task is now passed to the Transiting Exoplanet Survey Satellite (TESS). Launched in early 2018, TESS will cover most of the sky during its initial two-year survey and is expected to add thousands more worlds to our catalog of known exoplanets (*S&T:* Mar. 2018, p. 22).

Less than three decades ago, no exoplanets were known. Kepler will now follow Earth in its orbit around the Sun, a testament to the pioneering effort to uncover worlds beyond our solar system.

■ DAVID DICKINSON



With its exoplanet-hunting mission now over, the Kepler space telescope (illustrated) trails Earth in orbit around the Sun.

NASA

MISSIONS

Sunset for Dawn

SHORT ON FUEL, the end has come for NASA's Dawn spacecraft, the first and only mission to visit the dwarf planet Ceres and the asteroid Vesta. It was the first mission to orbit more than one body beyond Earth and the Moon. It was NASA's first deep-space mission to use ion propulsion. And Dawn was also the first spacecraft to visit a dwarf planet, beating the New Horizons flyby of Pluto by just a few months.

Launched in 2007, Dawn eventually arrived at asteroid 4 Vesta on July 16th, 2011. Dawn revealed the misshapen world in dramatic detail, mapping it from pole to pole while probing it from core to surface (*S&T:* Nov. 2011, p. 32). One key finding was that Vesta seems to be a remnant of the rocky planetesimals from the early days of the solar system. But it turned out that the exploration of Vesta was just a prelude for the excitement to come.

Dawn fired up its ion engines and departed Vesta on September 5, 2012, for a 30-month transit to Ceres, arriving March 6, 2015. On approach to Ceres — the largest body in the asteroid belt — Dawn spotted several bright patches on the world's surface. These proved to be briny salt deposits of hydrated magnesium sulfate and ammonia-rich clays, remnants of water-ice eruptions from the world's interior. Dawn gave us key insights into the cryovolcanic activity erupting on the surface of Ceres and a look at an active dwarf planet (*S&T:* Dec. 2016, p. 16).

The 11-year mission came to an end when the spacecraft missed two scheduled communications on October 31st and November 1st, leading mission scientists to conclude that the spacecraft had finally run out of fuel. Without steering, Dawn can no longer aim its main communications antenna back at Earth. The probe will now remain in orbit around Ceres, in line with planetary protection protocols guaranteeing Dawn won't crash into the dwarf planet for the next few decades.

■ DAVID DICKINSON

MILKY WAY

Ancient Merger Wreckage in the Milky Way

WE LIVE IN A BIG disk galaxy, a whirligig pancake that's enshrouded in a halo of old stars. And increasingly, astronomers suspect that very early in our cosmic pancake's history, a collision messed up the serene stellar disk and donated the detritus that makes up much of the halo.

Reporting in the November 1st *Nature*, Amina Helmi (University of Groningen, The Netherlands) and colleagues confirm that a previously noted horde of nearby stars in the halo is quite unusual. These stars rotate around the galactic center in the opposite, or *retrograde*, direction as the disk does. They also have different chemical compositions than those in the disk. The strange characteristics suggest that the stars aren't indigenous to the Milky Way — rather, they're probably crumbs from when our galaxy ate a galactic snack very early in its history.

Helmi and colleagues took a closer look at the retrograde stars' motions and compositions and noted three characteristics. First, the stars move together as a big unit. Second, their heavy-element levels suggest these stars didn't all form in a single burst but over an extended period. Third, the stars have a range of ages.

Taken together, these quirks set the stars apart from those born in the Milky Way, implying that they came from a cannibalized galaxy roughly 600 million times as massive as the Sun — about the same mass as the Small Magellanic Cloud. Simulations also confirm that a merger with such a galaxy roughly 10 billion years ago could explain the stars' properties.

So many are the retrograde stars (about 30,000), that they form a huge swarm around the disk for at least thousands of light-years around the Sun. Helmi's team estimates that roughly 80% of our galaxy's halo could be from this single collision. The merger would have also puffed up the galactic disk that existed at that time, creating the relatively thick disk we have today.

■ CAMILLE M. CARLISLE

● **For a video simulation of the merger, see https://is.gd/mwmerger.**

▲ A computer simulation illustrates the positions and motions (yellow arrows) of stars after a putative merger between the Milky Way and another smaller galaxy.

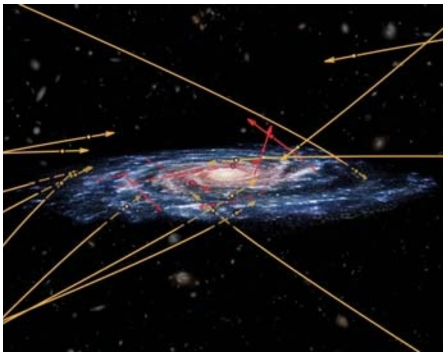
MILKY WAY

Some Stars May Be Visiting From Elsewhere

SOME HIGH-SPEED STARS in the Milky Way might actually be escapees from another galaxy.

Speedy stars are useful indicators of extreme interactions with supernovae and black holes, as well as for probing the gravitational field of the galaxy. Combing through data from the European Gaia satellite, which is mapping the positions and speeds of over a billion stars in and around the Milky Way, Tomasso Marchetti (Leiden Observatory, The Netherlands) and colleagues recently identified 20 stars that are moving so fast, they are more than 80% likely to break the gravitational bonds of our galaxy.

To determine where these 20 stars originated, the researchers used the current orbits to follow their trajectories backwards for up to 5 billion years.



▲ Position and trajectories of 20 high-speed stars are shown in this illustration. Seven stars (red) are leaving our galaxy while the rest (orange) are coming toward the Milky Way, possibly from another galaxy.

Seven of the 20 stars can be traced back to the disk of our galaxy. However, the other 13 seem not to have originated in the Milky Way at all. The team reports its results in an upcoming *Monthly Notices of the Royal Astronomical Society*.

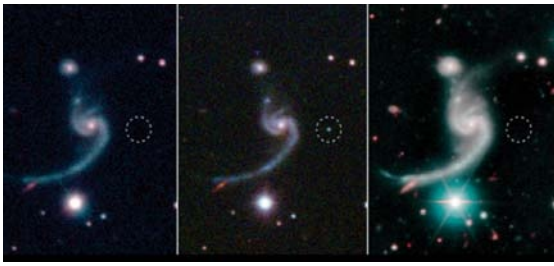
It's impossible to say where these stars came from with any certainty. One possible source is one of our galactic neighbors, the Large Magellanic Cloud. If the stars came from there, their existence could tell us more about the presence of black holes or the history of supernovae in that tiny galaxy. Alternatively, the stars could belong to the outer reaches of our own galactic halo, thrown inward by gravitational interactions with smaller galaxies eaten by the Milky Way long ago. Additional spectral data for these stars could help narrow down their likely origins by determining their ages and chemical compositions.

Marchetti and colleagues plan to follow up with ground-based observations in the near future, but they are also continuing to explore Gaia's data for additional ways of identifying high-velocity stars. They hope to apply their methods on the complete set of 150 million stars with full 3D-velocity data expected in 2020.

■ SUMMER ASH

SUPERNOVAE

Low-key Blast Marks Possible Birth of Neutron Star Duo



▲ The moments before (left), during (middle), and after (right) Supernova iPTF14gqr appeared in the outskirts of a spiral galaxy.

LAST YEAR, A TSUNAMI of gravitational waves washed over Earth, heralding the collision of two neutron stars in a far-off galaxy. Such collisions appear to be the birthplace of many of the heaviest elements such as gold, platinum, and uranium (*S&T:* Feb. 2018, p. 32). Now an unusual, rapidly brightening supernova might help researchers understand how such neutron star duos arise in the first place.

The supernova, designated iPTF-14gqr, went off in the outskirts of a galaxy some 900 million light-years away. Detected in October 2014, this supernova seemed odd right away. Most supernovae take a few weeks to hit their peak brightness. This one did so in less than 7 days, suggesting it had only a relative paucity of debris to clear out of the way.

Kishalay De (Caltech) and colleagues estimate that SN iPTF14gqr released only one-fifth of the mass of the Sun — most supernovae expel several Suns' worth of gas. What's more, the team deduced that the star was about 1.5 times as massive as the Sun shortly before the explosion. But for a star to go boom, its original mass needs to be at least eight times as massive as the Sun. Something must have stripped the star of most of its mass before it died. The most likely candidate, the team argues in the October 12th *Science*, is a companion neutron star.

Here's how the team thinks the story played out: Two massive stars once orbited each other. One of them exploded, leaving its core behind as a neutron star. This neutron star then stripped its buddy of most of its gas. By the time the second star exploded — and became known as SN iPTF14gqr — there wasn't much gas left. The explosion would also have produced a neutron star, leaving two neutron stars in a tight orbit.

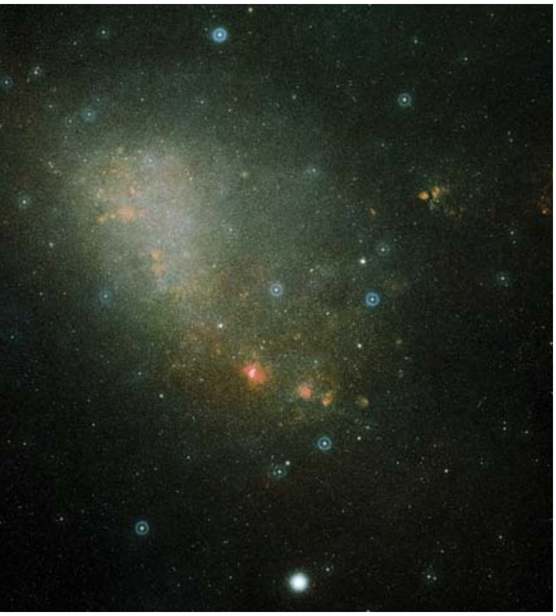
"This is the first example of a supernova that produced a compact binary system that is tight enough to eventually merge and produce gravitational waves," De says. Unfortunately, at nearly 1 billion light-years away, the high-energy light from any putative neutron stars is much too faint to detect.

■ CHRISTOPHER CROCKETT

MAGELLANIC CLOUDS

Evidence Mounts for Magellanic Collision

THE PAST DECADE HAS seen astronomers' understanding of the Magellanic Clouds — two dwarf galaxies near the Milky Way — completely overthrown, resulting in new revelations about the violent and ongoing formation of our own galaxy. Now, a team led by Sally Oey (University of Michigan) has made a discovery that bears out predictions that these two galaxies once collided: A big chunk of the Small Magellanic Cloud (SMC) is moving toward the Large Magellanic Cloud (LMC) and the Magellanic Bridge of gas and stars that joins them.



◀ This picture of the Small Magellanic Cloud is composed of two images from the Digitized Sky Survey 2.

Astronomical wisdom once held that the LMC and SMC had been orbiting the Milky Way for billions of years, but a landmark study in 2007 showed that the dwarf galaxies are likely falling toward the Milky Way for the first time (*S&T:* Oct. 2012, p. 28). That realization introduced a new puzzle: If the Magellanic Bridge wasn't stripped from the LMC and SMC by the powerful gravity of the Milky Way, as previously suspected, how did it get there?

In 2012, researchers offered an answer. The Magellanic Clouds must have had a close encounter with each other in the recent past — perhaps even a direct collision — to pull the bridge's stars and gas away so strongly.

In the November 1st *Astrophysical Journal Letters*, Oey and her collaborators present support for this hypothesis based on stellar position and velocity data from the Gaia satellite. They discovered that many of the stars in the eastward "wing" of the SMC are moving in concert, a result that can only be explained by the LMC's gravitational force acting on the galaxy globally.

With further study, astronomers might be able to use the observed bulk motion to understand the direct collision in even more detail: how long ago it occurred, at what speed, and at what angle. The better astronomers understand the past trajectories of these galaxies, the more precisely they can predict their future fates, which will likely see them accumulated into the Milky Way.

■ EMILY SANDFORD

SUPERNOVA: SDSS / CALTECH / KECK; MAGELLANIC CLOUD: DAVIDE DE MARTIN (ESA / HUBBLE) / DSS2

What Came Before the BIG B

ANG?

Cosmologists are tackling a once-verboten question with out-of-the-box thinking.

PITRIS / ISTOCK / GETTY IMAGES

It's natural to want to know what happened before the Big Bang. For years, cosmologists answered that it was unknown, unknowable, or that there was nothing before the Big Bang, not even time. As you extrapolate our expanding universe backwards, you eventually reach a point of infinite density where the known laws of physics break down. The Big Bang theory doesn't rule out the possibility that there was some pre-existing universe from which ours sprang, but if such a thing existed, it was beyond the reach of science.

But then something changed. Now, serious cosmological theories posit that the Big Bang happened within a pre-existing space, universe, or network of universes. Of course, nothing could have happened in our observable universe before it existed, but scientists today are able to conceive of events "before" the Big Bang by widening their perspective. And for some, the push to uncover our deepest cosmic origins is tied up with another grand quest — to understand the nature of time, and why it keeps propelling us so relentlessly into the future.

At first, there was a general agreement that the Big Bang happened first, and then a tiny fraction of a second later, inflation began. But now many cosmologists refer to inflation as something that happened before the Big Bang.

I noticed the change of heart more than a year ago, when, after a lecture, I asked pioneer cosmologist Alan Guth (Massachusetts Institute of Technology) what happened before the Big Bang. He didn't dismiss the question. Instead, he said that he's working on it.

Guth reiterated something I'd heard him say in previous lectures — that the Big Bang theory doesn't tell us "what banged, why it banged, or what happened before it banged." He also suggested I speak with physicist Sean Carroll (California Institute of Technology). Carroll said the idea that the Big Bang was the beginning of time is a plausible hypothesis, but not the one he thinks best fits with the universe as we observe it.

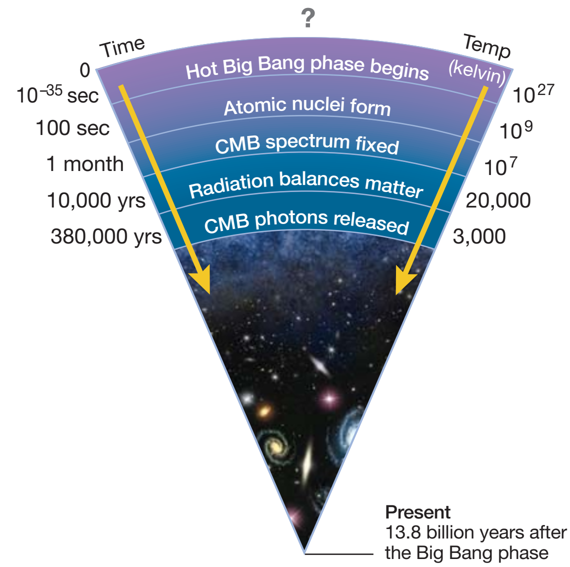
So what *did* come before? There are almost as many theories as there are theorists, but they fall into a few broad categories. Some postulate a sea of rapidly expanding space that gives rise to new universes like bubbles in a pot of boiling water. Others favor a bland expanse of empty space that occasionally gives birth to baby universes full of energy and matter. In one scenario, the Big Bang was more of a Big Bounce, the comeback of a contracting universe. And although these cosmic visions might sound more psychedelic than scientific, the faint imprints of what came before might not be as unobservable as we once thought.

Redefining the Big Bang

What we do know from observation is that on large scales, the galaxies sprinkled through the visible universe are charging away from one another. The universe is expanding, and if you extrapolate back in time, it looks like everything was once a dense, trillion-degree soup of disembodied particles. That's the part of the Big Bang theory that remains well-established. When it was first devised, the theory made several sharp predictions, among them that the universe would contain a specific ratio of hydrogen, helium, and lithium and that radiation from the Big Bang would be detectable today in the form of a pervasive *cosmic microwave background*. Both of those were spectacularly confirmed.

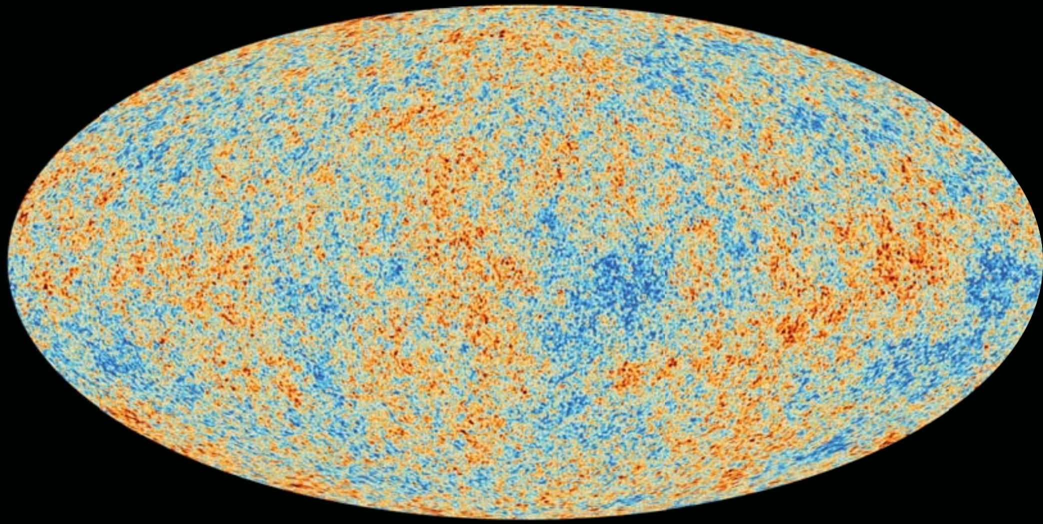
But by the 1970s, problems appeared that made it clear the theory had to be modified. For one thing, the Big Bang failed to explain the relative homogeneity of the universe. On very large scales, galaxies are distributed through the sky the same way in all directions, as if they'd been stirred through the heavens. But under the original Big Bang theory, it's physically impossible for them to have mixed together within the finite age of the universe. There hasn't been enough time.

In 1981, Guth hit on an adjustment to the Big Bang that appeared to take care of the problem — a quick burst of extremely fast expansion that would precede the normal, more leisurely expansion of the universe. (Alexei Starobinsky in the Soviet Union came up with a similar idea independently.) Guth dubbed his idea *inflation*, but unlike what was happening to the currency at the time, cosmological inflation wouldn't have diluted the cosmos. As other theorists building on Guth's suggestion soon proposed, a peculiar kind of



▲ **BIG BANG COSMOLOGY** Cosmologists agree that the modern observable universe arose from an extremely hot, dense state. As things expanded and cooled, protons, neutrons, and then atomic nuclei formed. Eventually, the nuclei joined with electrons to make atoms, and the universe became transparent, freeing the photons that we now detect as the cosmic microwave background. But what came *before* this hot, dense Big Bang state is debated.

LEAH TISCIONE / *S&T*



COSMIC MICROWAVE BACKGROUND The Planck spacecraft mapped the relict radiation from the Big Bang phase with an angular resolution of 5 arcminutes, or ⅟₁₂°. The small changes in temperature correspond to density variations that became the seeds of cosmic structure.

energy that creates a repulsive force drove this exponential expansion. Instead of thinning out, the density of this energy remained the same. And so as space grew, the total amount of this energy swelled to enormous proportions and was converted, eventually, to ordinary matter and radiation. As weird as it sounds, a sub-microscopic patch of space became our vast observable universe.

Inflation seems to defy the law of conservation of energy — Guth himself famously quipped that it's the ultimate free lunch — but it's all perfectly compatible with the rules laid out in Einstein's general relativity. Energy can be positive or negative. The gravitational energy that fills space is considered negative, while the repulsive force driving inflation is considered positive. So you can start out with zero energy and get a whole lot of both positive and negative energy, says cosmologist Anthony Aguirre (University of California, Santa Cruz). Because these two add up to zero, the conservation law isn't violated (*S&T:* Nov. 2006, p. 36).

At first, there was general agreement that the Big Bang happened first, and then a tiny fraction of a second later, inflation began. Another fraction of a second later inflation ended, starting the hot, dense phase of the universe that expanded into our universe of space, stars, and upwards of 2 trillion galaxies.

But now many cosmologists refer to inflation as something that happened *before* the Big Bang. "If we take inflation seriously, then we need to start correcting people claiming that inflation happened shortly *after* our Big Bang, because it happened before it, creating it," wrote MIT physicist Max Tegmark in his 2014 book, *Our Mathematical Universe: My Quest for the Ultimate Nature of Reality*.

At issue is what we mean by "Big Bang." There is some disagreement over what, exactly, the term refers to these days, says Matthew Johnson (York University and the Perimeter Institute for Theoretical Physics, Canada). Many agree with Tegmark that "Big Bang" should refer only to the hot, dense state of matter that expanded and cooled into our observable universe, and not to any notion of an absolute beginning. This terminology can help separate the part of cosmology that's backed with strong evidence — the hot Big Bang and what came afterwards — from the more speculative notion of inflation. And inflation wasn't much of a bang. Tegmark describes it as a cold little swoosh.

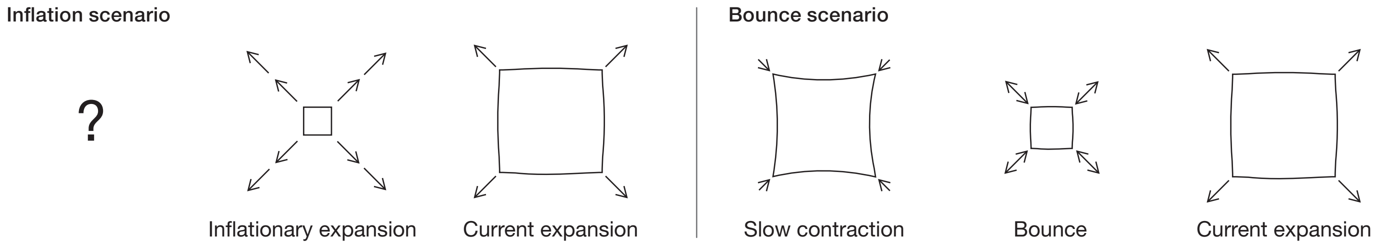
Another problem with the old scenario, fitting inflation in after the Big Bang, is that it was hard to explain how this inflationary phase could come to a neat and tidy end. "There's this side effect that once you get it going, it's very hard to stop everywhere at once," says Aguirre. If you want to avoid making any assumptions about a conspiracy to stop inflation, you end up with the prospect that it would end in some places, but it would keep going in others. Since inflation is an ultra-fast expansion of space itself, the still-inflating parts would grow huge, dwarfing what we thought was the universe. And that monstrously large, still-inflating part would continue to spawn new, independent universes like bubbles in a foam (*S&T:* Dec. 2012, p. 20).

From a perspective outside of our bubble, or "pocket universe" as some call it, this inflating space was busy giving rise to other bubble universes long before ours came into being in an ever growing *multiverse*. You just have to consider time in a broader frame, says Aguirre. "To see the mixture of inflating and non-inflating regions at a given time, one must use a different definition of time that includes both events inside the pocket and outside the pocket at the same time," he says.

But how did inflation begin? Cosmologist Andrei Linde (Stanford University), one of the first people to recognize the possibility of a multiverse, has proposed that inflation happens naturally in a wide range of situations — it's a surpris-

The laws of physics are symmetrical forwards and backwards, and yet, we can stir cream into coffee and scramble eggs, but can't un-stir or unscramble them.

ESA / PLANCK COLLABORATION



▲ **INFLATION OR BOUNCE?** To explain why the observable universe is geometrically flat and its contents well mixed, astronomers think it began almost infinitely compact, then grew in a brief, exponential spurt called inflation before continuing to expand more slowly. However, it's unclear what came before inflation. One alternative idea is that instead of inflating, the universe existed earlier in a contracting state, then bounced.

LEAH TISCIONE / S&T

ingly common outcome of elementary particle theories. In Linde's theory of *chaotic inflation*, patches of inflating space can emerge from an existing universe — one that's much less orderly than our universe, a sort of hodgepodge of regions dense and sparse.

Bouncing Universes to Baby Universes

Despite such radical variations on the theme, inflation remains the mainstream view in cosmology. It fits with new observational evidence, much of it from that same leftover radiation that helped confirm the original Big Bang theory. Over recent decades, scientists have studied this cosmic microwave background in ever-finer detail from ground-based detectors and from the perch of a series of increasingly complex satellites.

According to the theory, if inflation happened, then tiny density bumps in the early universe — inevitable thanks to the laws of quantum mechanics — would have grown large during the growth spurt and left an imprint of hot and cold spots in the cosmic microwave background. That imprint would survive as inflation ended and the hot Big Bang started, with the denser regions seeding the formation of galaxies. So far, observations show a pattern of hot and cold spots that matches those predictions.

Still, other theorists found that they could explain these same observations with a very different scenario — a series of "bouncing" phases of contraction and expansion. Back in 2001, a collaboration of physicists and cosmologists proposed such a scenario in which the Big Bang was really a collision of two existing universes floating in a higher-dimensional space. The idea took the notion of higher dimensions from string theory, which predicts the existence of 11 dimensions — seven spatial ones beyond our familiar three of space and one of time. While string theory posits that the extra dimensions are curled up in a way that makes them impossible to observe, some physicists have proposed that one or more of these dimensions stretch out, so that our universe might float within a higher-dimensional space the way a sheet of paper might float through a three-dimensional room.

One of the inventors of this scenario, Paul Steinhardt (Princeton University), says that in the past decade he and his collaborators have streamlined the bouncing universe idea so that they no longer need the collision or the extra dimensions. All that's required is an existing universe, which contracts slowly until it "bounces" and starts expanding. This, he says, could happen once or in cycles.

The contraction of an existing universe can solve all the puzzles that inflation fixes, Steinhardt argues. It smooths out variations and gives rise to the same large-scale uniformity and cosmic structure, all without requiring any more assumptions than inflation does. The cause of the contraction isn't well understood, but neither is the cause of inflation. And the bouncing scenario has the advantage of not predicting an infinite number of universes, he adds.

Caltech's Sean Carroll favors another possible prequel to the Big Bang. He came to thinking about the origin of the universe while trying to answer a question about everyday life: Why do we have an apparent arrow of time? The laws of physics are symmetrical forwards and backwards, and yet, we can stir cream into coffee and scramble eggs, but can't un-stir or unscramble them. Time streams along indifferently into the future, toward disorder, death, and decay.

As Carroll explains in his 2010 book, *From Eternity to Here*, scientists of the 1800s finally made some serious headway on this ancient problem when they discovered the second law of thermodynamics. A property called entropy, which is something like disorder, increases relentlessly and

ENTROPY

We usually shorthand the concept of entropy to "disorder" or "randomness." More specifically, it's related to the number of microscopic ways that a macroscopic system can be in a particular state – the higher the number, the greater the entropy. For example, a shiny new car has a relatively small number of ways that its molecules can be arranged such that the car still qualifies as shiny and new. But there's a far greater number of ways that the car can look old – myriad possibilities for dents, rust spots, and so forth. The "old" state thus has a higher entropy than the "new" state.

irreversibly, even if temporary pockets of order can crop up here and there.

If entropy has been increasing for all time, then it must have been very low at the origin of the universe. Things don't naturally acquire low entropy, Carroll says. He realized that neither the Big Bang nor inflation offered an explanation. So he had to consider what came even earlier.

Since the natural state of things is high entropy, he wondered if a universe could be born from the highest-entropy-possible state of things. While it might seem counterintuitive, theories of quantum gravity point to empty space (with its formless *vacuum energy*) as the ultimate and final equilibrium state of a once lively universe. That's because empty space has more ways to be disorderly than a universe with structure, or even one filled with a dense, soup-like matter (see "Entropy," facing page). Such a place would be very boring, most of the time. But the uncertainty principle of quantum mechanics allows interesting things to happen.

Just as radioactive elements emit particles in a random way, Carroll says, there's a probability that this empty space can give birth to the occasional baby universe. Such a newborn universe can pinch off to form a new and separate region of space and time. This doesn't violate the second law, he says. "The entropy of the baby universe is small, but it's a new addition to the entropy of the universe as a whole, which is therefore still increasing."

Others conjecture different mechanisms for generating an arrow of time — increasing complexity, for example, or gravity. These ideas assume that time is what's called an *emergent property* — existing only under certain conditions, just as temperature and pressure as we experience them don't exist independent of matter. But some, like physicist Lee Smolin (Perimeter Institute for Theoretical Physics, Canada), argue that time is a fundamental facet of reality that transcends the laws of physics.

Looking for Fingerprints

Inventing interesting, plausible theories, however, has become a lot easier than testing them with observations. The abundance of untested ideas has led to accusations that cosmology has left the path of empirical science. But cosmologists aver that they didn't set out to transgress the bounds of experiment — the paradoxes of the Big Bang as originally formulated forced them to enter seemingly unobservable realms.

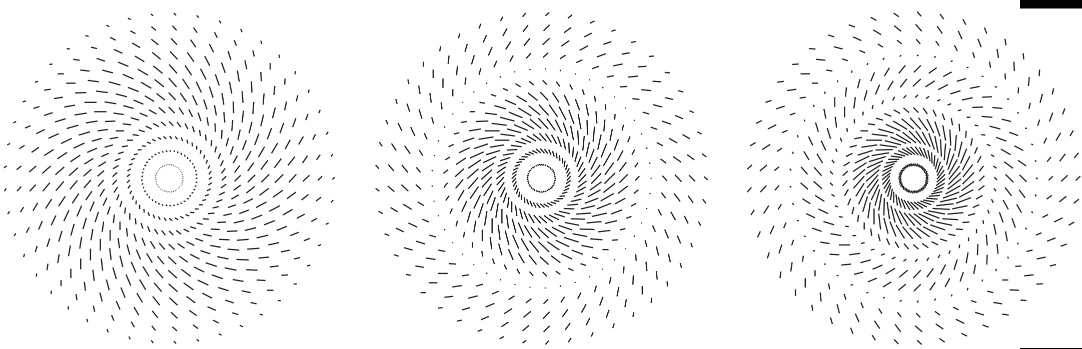
New hope for empiricism came in 2014, when it appeared that a telescope called BICEP2, located at the South Pole, had picked up a polarization pattern in the cosmic microwaves. This pattern would have ruled out the collision theory and favored some versions of inflation over others. But it turned out the observers had misinterpreted their signal — what they saw had originated from mundane dust in our own galaxy (*S&T:* May 2015, p. 12).

Then, in early September 2018, Xingang Chen, Avi Loeb, and Zhong-Zhi Xianyu (Harvard), announced another possible test: a faint signal that could rule out either all the inflation-based scenarios or the contraction-then-bounce one.

The test rests on the premise that there was a fraction of a second during which the space that would become our universe existed before it became a hot, dense soup of particles — the so-called hot Big Bang phase. At this stage, space was permeated by high-energy fields that oscillated at regular time intervals. The oscillations should have left different patterns in the density variations that gave rise to cosmic structure, depending on whether space was expanding exponentially, as in inflation, or contracting. And this, Chen says, might be observed in the hot and cold regions of the microwave background, or in the distribution of galaxies across the sky. He and his colleagues posted the idea on arXiv.org, a site where not-yet-published scientific papers go up for public review.

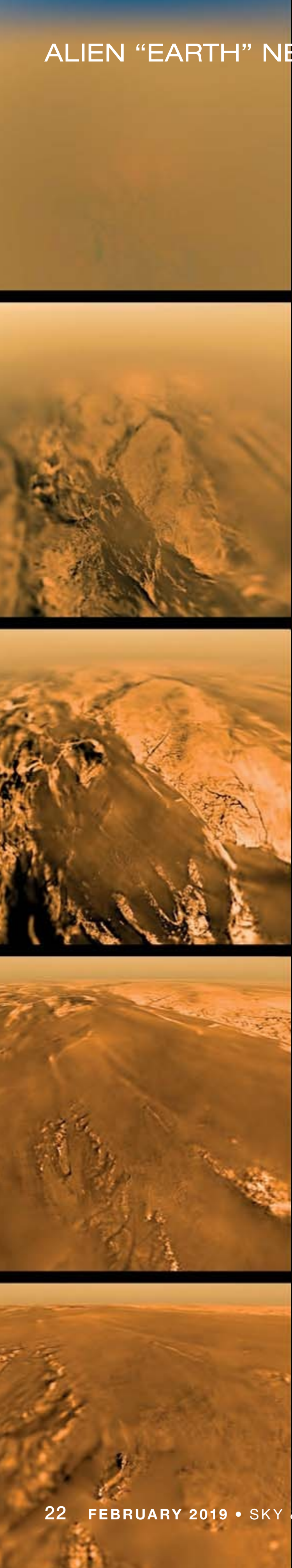
If cosmologists can determine whether in this instant space was contracting or expanding, the result will point to vastly different pictures of a much larger, or even infinite, pre-existing physical reality. Thus, although these cosmological theories might seem fanciful and far removed from observations, many scientists are not content to let them stay that way. As long as people keep thinking of tests that might work, these scenarios remain tethered to the great expansion of scientific knowledge.

B MODES If inflation happened, then the resulting ripples in spacetime should have left polarization patterns called B modes (three examples shown) in the cosmic microwave background. Conversely, a contraction and bounce would not leave such patterns.



ANTONY LEWIS

FAYE FLAM is a columnist for *Bloomberg Opinion*. She writes on science, medicine, and the environment. Find more about her work at **fayeflamwriter.com**.



Titan's Veil

Saturn's largest moon has a remarkably complex atmosphere, with all the chemical ingredients for life as we know it.

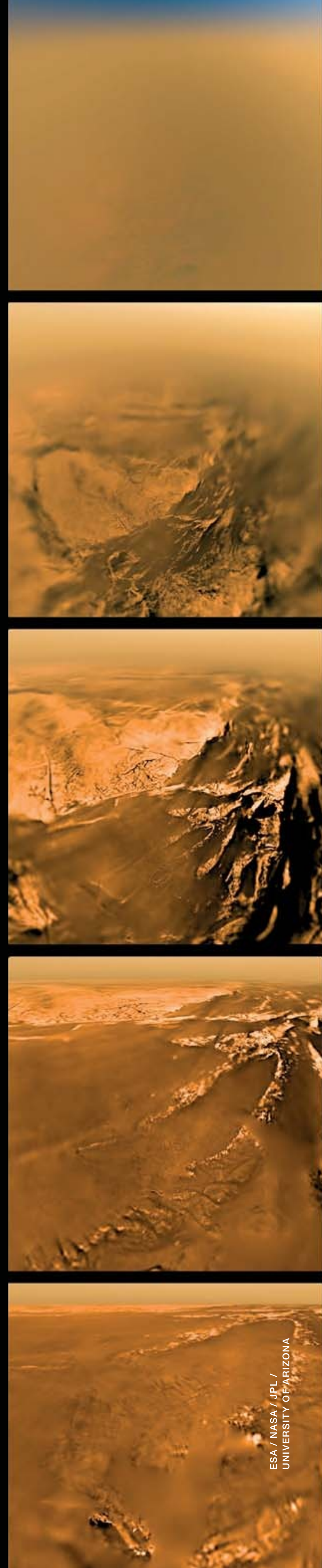
Titan is often described as Earth-like. Besides our home planet, it's the only world in the solar system to possess a dense molecular nitrogen (N_2) atmosphere and an active hydrologic cycle — though Titan's cycle doesn't involve water. The atmospheric surface pressure on Titan is about 1½ times that at sea level on Earth, and its surface temperature is 94K (–179°C, –290°F), conditions in which water is rock-hard ice.

Instead, Titan's environment is very near the *triple point* of methane (CH_4), which means that methane can exist as a solid, liquid, or gas depending on local conditions. (Earth's surface is similarly near the triple point of water.) The result is a marvelous world of lakes and seas, rivers carving channels into water-ice bedrock, and intense rainstorms of large droplets that occasionally punctuate the relative calm of extensive sand-dune fields — all made of methane and related compounds.

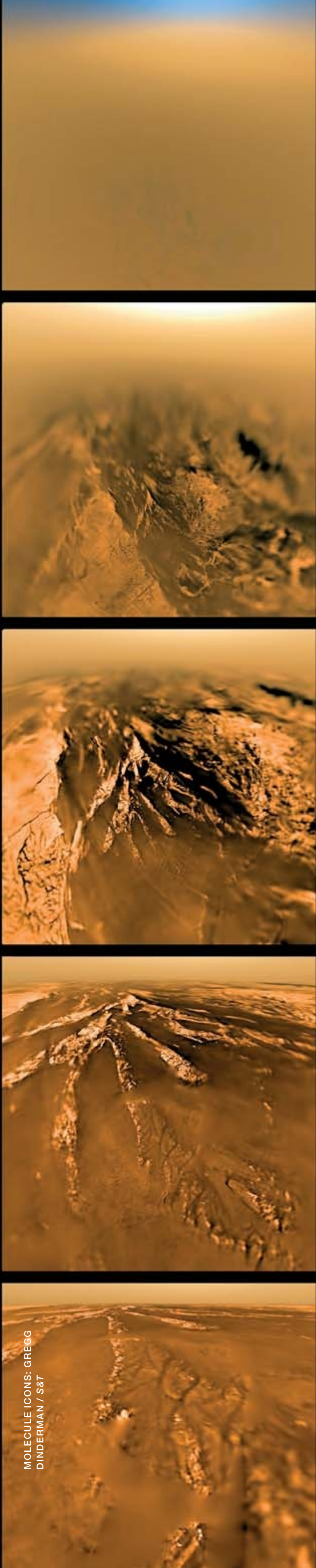
Much of our understanding of this landscape comes from 13 years of intensive study with the Cassini-Huygens mission, undertaken jointly by NASA and ESA (*S&T:* Sept. 2017, p. 16). Before that, Titan's thick atmosphere and characteristic orange haze largely obscured our view of the surface.

Although we often look at Venus and Mars to teach us about our world, Titan's atmosphere is the best solar system analog we have for the early Earth environment

◀▶ **HUYGENS' DESCENT** These images were taken by the Huygens probe during its descent to Titan's surface on January 14, 2005. Each row shows the four cardinal directions, and each column has views taken at five different altitudes. Altitudes from top row and moving down: 150 km (93 mi), 30 km (19 mi), 8 km (5 mi), 1.5 km (0.9 mi), 300 m (1,000 ft).



ESA / NASA / JPL / UNIVERSITY OF ARIZONA



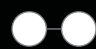
and an important place to study the chemistry that might have occurred in our planet's atmosphere before life as we know it produced the large amount of molecular oxygen (O_2) we now breathe. It might even give us the tools to recognize habitable planets around other stars.

A Hydrocarbon Laboratory

After molecular nitrogen, methane is the most abundant gas in Titan's atmosphere (2% to nitrogen's 98%). Ultraviolet photons from the Sun break N_2 and CH_4 molecules into pieces that react with each other to produce heavier byproducts, which eventually form Titan's thick organic haze. This photochemistry is similar to the way that sunlight spurs the formation of smog here on Earth.

Some of the molecules formed by Titan's photochemistry are very familiar to us — molecules like propane (C_3H_8) or hydrogen cyanide (HCN) — and they fall into broad categories of chemical compounds called *hydrocarbons* (molecules with hydrogen atoms attached to carbon atoms) and *nitriles* (molecules with a carbon atom triple-bonded to a nitrogen atom). More broadly, we refer to the compounds in Titan's atmosphere (and, eventually, on its surface) as *organic*, which simply means the molecules contain hydrogen atoms bonded to carbon atoms.

Prior to the arrival of the Cassini-Huygens spacecraft, the heaviest molecule that scientists had ever detected in Titan's atmosphere was benzene (C_6H_6), discovered using data from ESA's Infrared Space Observatory in the late 1990s. Benzene is a pretty complicated molecule to result from atmospheric chemistry, although we do also see it at Jupiter's poles, where it is made via energetic-particle chemistry in the aurorae. Thus we knew that the organic chemistry in Titan's atmosphere was very complicated even before Cassini-Huygens. Indeed this is one of the reasons why we have been interested in Titan since the Voyager encounters first revealed that complex organic reactions are happening in its atmosphere.

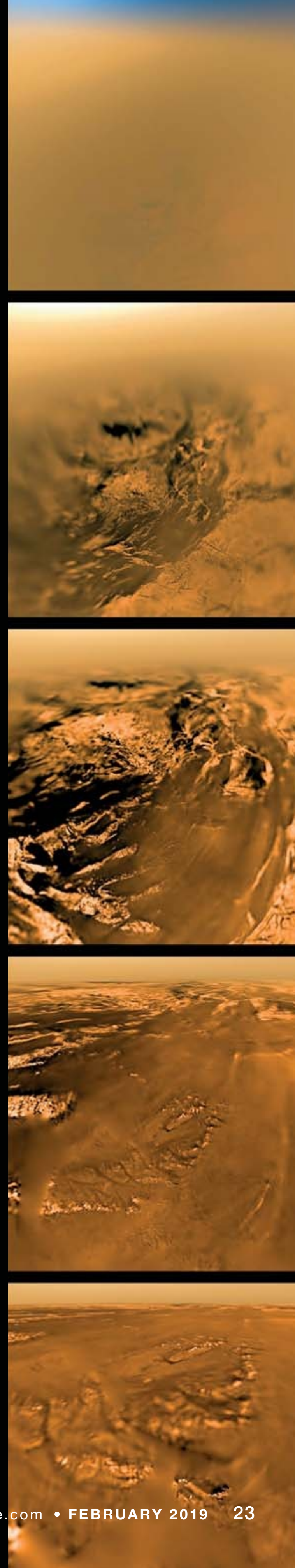


#1
Hydrogen

▲ **TOP 10** Here and on the following pages are the 10 most abundant photochemically made molecules in the stratosphere above Titan's equatorial regions. White is hydrogen, black is carbon, red is oxygen, and blue is nitrogen.

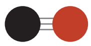
ORGANICS

An *organic* compound is any molecule that contains carbon bonded to hydrogen. The molecule can contain other elements, too. Hydrocarbons are a type of organic compound and consist of *only* hydrogen and carbon. Most carbon-bearing molecules are organic.



MOLECULE ICONS: GREGG DINDERMAN / S&T

Why do we care how complex the atmospheric chemistry is? One of the big questions we are interested in answering is how far organic chemistry can proceed in the absence of life. We know from analyzing meteorites that compounds like amino acids (the building blocks of proteins) can be produced by abiotic processes. With Titan, we can begin to understand how far abiotic organic chemistry can proceed in an atmosphere.



#2 Carbon monoxide

This is important for two reasons. First, we need to know what kinds of molecules are made *only* by life so that we can use them to detect life both within the solar system and elsewhere in the universe. Many of the molecules used by life on Earth, like amino acids and nucleobases (the building blocks of DNA and RNA), are not unique to biotic processes: They’re also produced without life’s involvement and are found in meteorites and comets. But their relative amounts in these environments are different than what we find when they’re created by life on Earth. So we need to study abiotically produced organic molecules in order to be able to tell the difference between abiotic sources and biotic ones when looking at other planets.

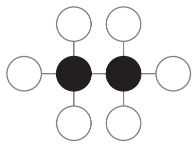
We need to know what kinds of molecules are made *only* by life so that we can use them to detect life both in the solar system and elsewhere.

Second, we want to understand the role that planetary atmospheres play in the origin and evolution of life. One potential role is to provide material (like organic molecules) to help life get started and/or to evolve. Since we realized, even before the arrival of Cassini-Huygens, that the organic chemistry occurring in Titan’s atmosphere was complex, we knew we needed to study Titan’s atmosphere further to investigate these questions.

To explore what the Cassini orbiter and Huygens probe have taught us about chemistry on Titan, let’s take a trip into the atmosphere, starting at the top and working our way down.

Ionosphere: Surprise Super-Molecules

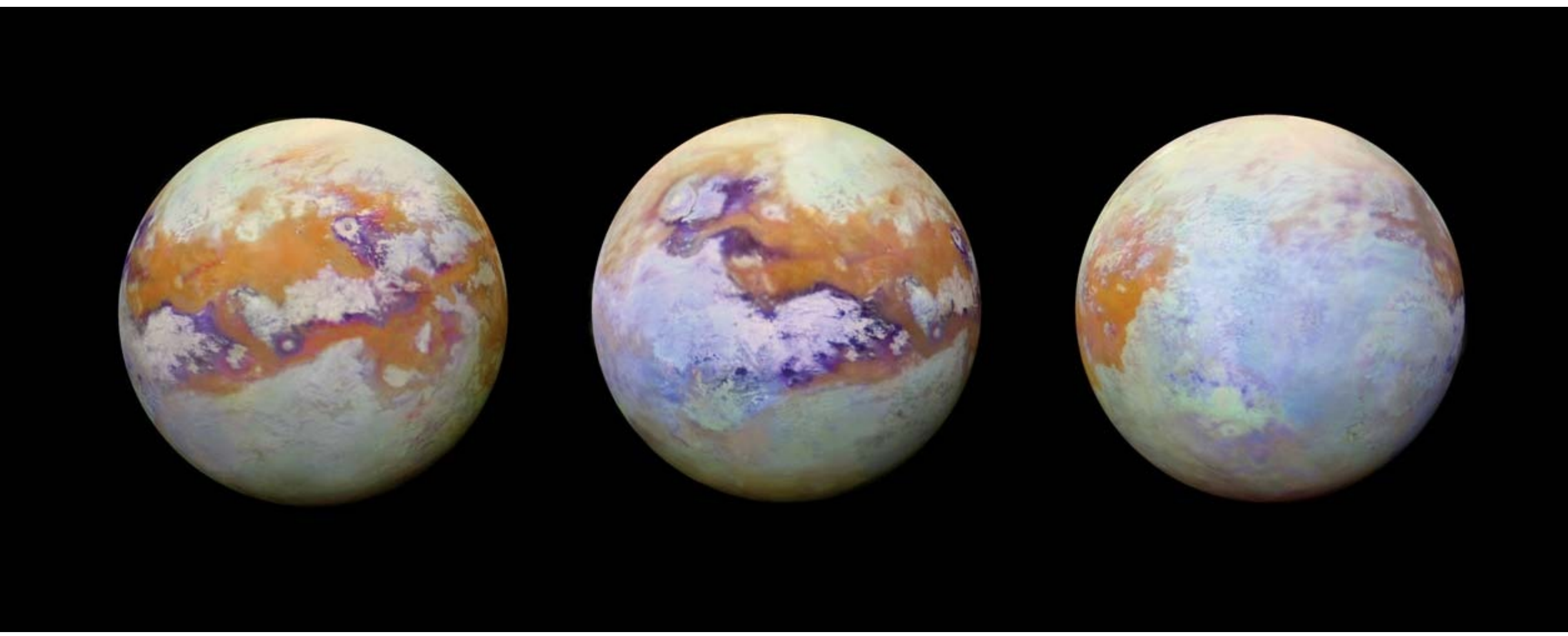
The Ion and Neutral Mass Spectrometer (INMS) was the primary instrument designed to measure the composition of Titan’s ionosphere as Cassini repeatedly flew through it during the spacecraft’s mission. INMS measured the composition of the atmosphere by measuring the masses of the molecules it ingested. The team had designed the instrument to cover a mass range of 1 to 99 atomic mass units, which roughly covers atomic hydrogen (1) to molecules with approximately six to seven “heavy atoms” like carbon, nitrogen, or oxygen. This mass range easily included the heaviest molecule known to exist in Titan’s atmosphere when it was designed (C_2N_2, with an atomic mass of 52) and the



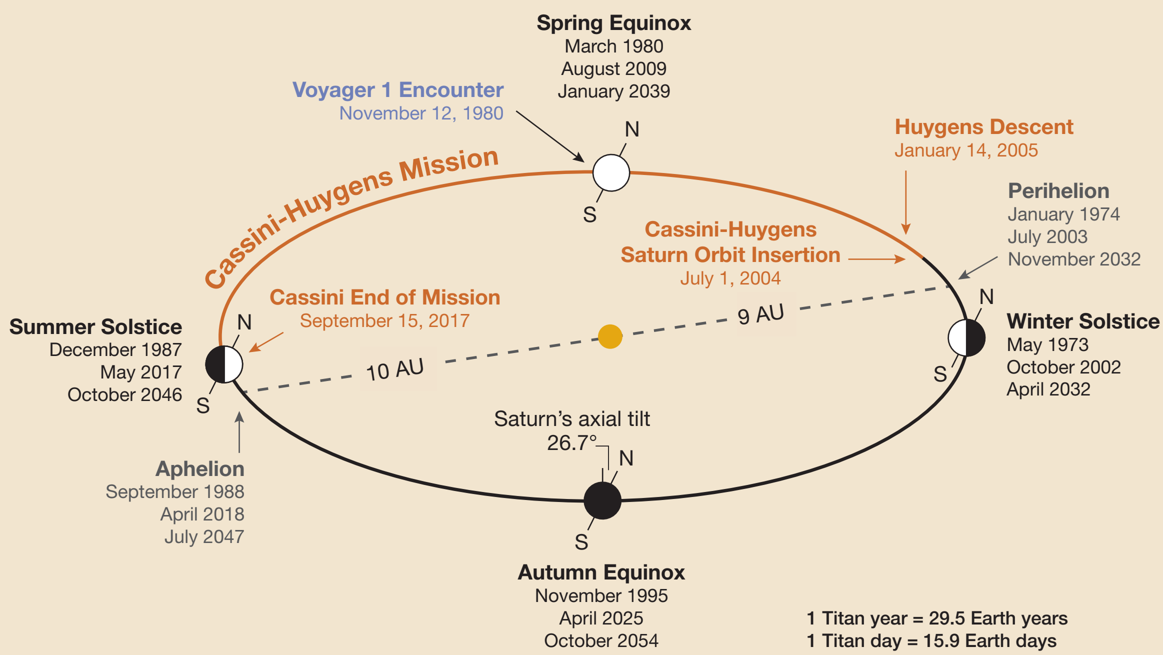
#3 Ethane

▼ **TITAN’S SURFACE** These infrared images combine 13 years of Cassini’s visible and near-infrared imagery into smooth mosaics of the surface that hides beneath Titan’s thick atmosphere. Reddish brown marks the moon’s equatorial dune fields, while the bluish and purplish regions might be enriched in water ice. The central longitudes of each view are (from left to right) approximately 30°, 60°, 120°, 210°, 300°, and 330° west.

NASA / JPL-CALTECH / ASI / USGS



▶ LONG VISIT Cassini-Huygens reached Saturn just after the planet's perihelion. After sending Huygens to Titan's surface in 2005, Cassini surveyed the moon 127 times at various distances.

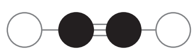


S. M. HÖRST / *JOURNAL OF GEOPHYSICAL RESEARCH: PLANETS* 2017

heaviest molecule discovered before Cassini arrived in the Saturn system (C_6H_6, mass of 78). Scientists thought that would be good enough.

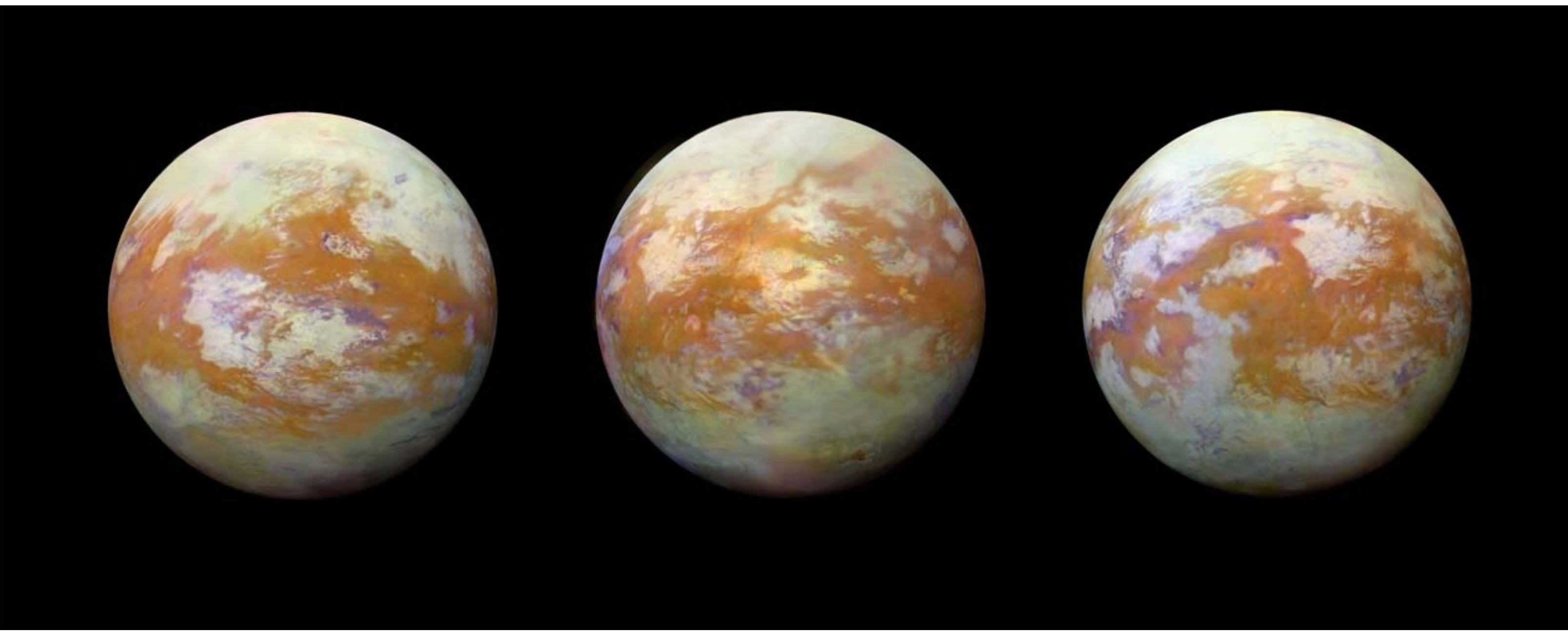
It wasn't. INMS found molecules all the way up to its upper mass limit. That was frustrating: It meant we wouldn't be able to use INMS to tell what the heaviest species are in Titan's atmosphere.

Luckily, the orbiter had a variety of instruments. Another one, called the Cassini Plasma Spectrometer (CAPS), was designed to analyze light ions in the Saturn system and characterize the plasma environment. CAPS was capable of measuring a much larger range of ions than INMS, but it only had sufficient mass resolution to identify the composition of the light ions it was designed to study.



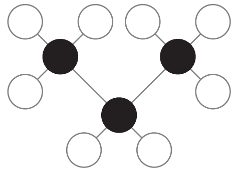
#4 Acetylene

However, when CAPS starting making measurements of Titan's atmosphere during close flybys, it found something startling: negatively charged ions with a mass-to-charge ratio of up to 10,000 atomic mass units. That means that, instead of recording ionized mol-



ecules consisting of six or seven heavy atoms in this region of Titan’s atmosphere, CAPS instead found ions made of 600 or 700 heavy atoms stuck together, the mass of small proteins on Earth!

Unfortunately, CAPS was not designed to identify such heavy ions. So although we know they’re present high above Titan, we’ll need another mission to be able to identify them.



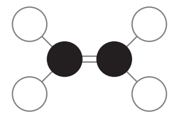
#5
Propane

CHON: Life’s Four Building Blocks

The discovery of these very large ions is incredibly important, because it has changed our understanding of the chemistry occurring in Titan’s atmosphere and of how its hydrocarbon hazes form. In doing so, it has also altered our ideas about how planetary atmospheres work in general.

We did not know that atmospheres were capable of producing such large molecules, especially so high in an atmosphere, where the pressure is very low and molecular collisions (which build larger compounds) are rare. If these molecules are made of the same atoms required for the small set of molecules that life as we know it here on Earth uses — carbon, hydrogen, oxygen, and nitrogen (collectively dubbed “CHON”) — then these ions may be important for understanding the origin and evolution of life on Earth. If life exists on Titan, then they could be important for understanding its rise there, too.

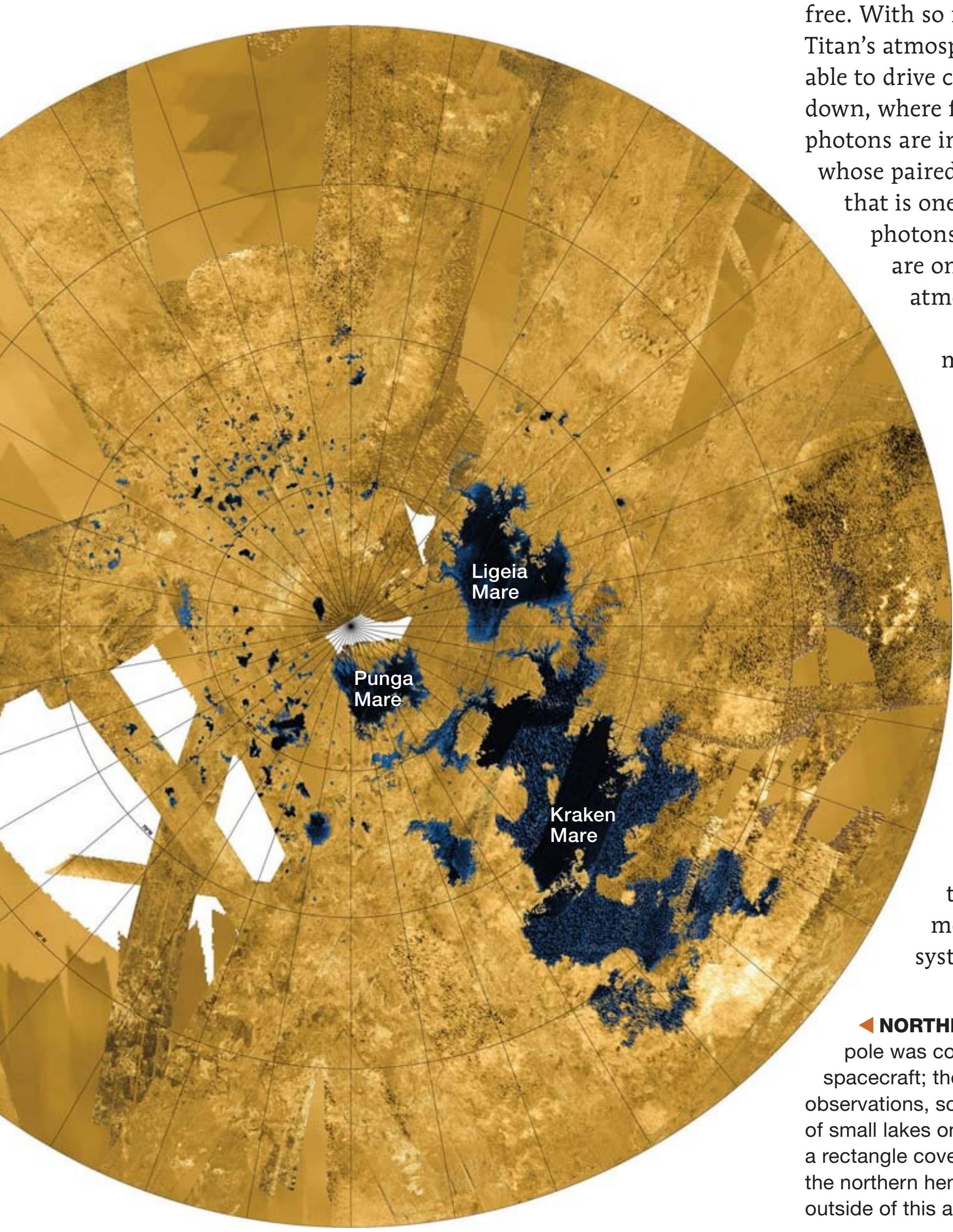
Chemistry requires energy. The ionosphere is largely created by very high-energy photons from the Sun impinging upon the atmosphere’s molecules and knocking electrons free. With so many photons flooding into it, this region of Titan’s atmosphere has more energy available to drive chemistry than regions deeper down, where few photons penetrate. These photons are important for breaking up N_2, whose paired atoms share a triple bond that is one of the hardest to break; the photons capable of breaking this bond are only available very high up in the atmosphere.



#6
Ethylene

The amount of energy available matters for many of the questions we are asking, because it means the difference between nitrogen participating in the chemistry or not. We knew before Cassini that Titan’s atmospheric chemistry included substantial amounts of carbon and hydrogen, but INMS measurements have shown us that the ions in Titan’s ionosphere also contain much more nitrogen than we expected to find there. If nitrogen is involved in the chemistry, then three of the four elements necessary for life are accounted for.

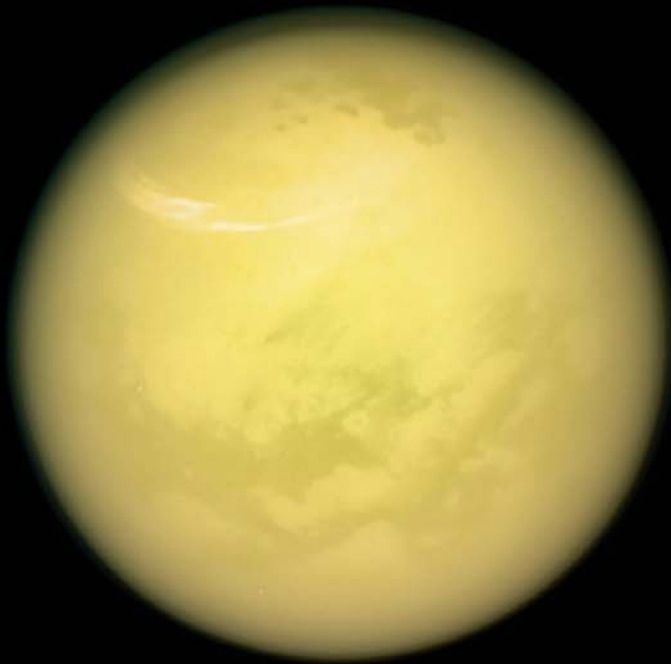
One additional discovery made by CAPS shows that the final element, oxygen, might be playing a role, too. Scientists didn’t know about the salty-water plumes of Enceladus until spotting them in data from Cassini. It turns out that the water shooting out of that moon’s south pole spreads throughout the Saturn system, including to the top of Titan’s atmosphere.



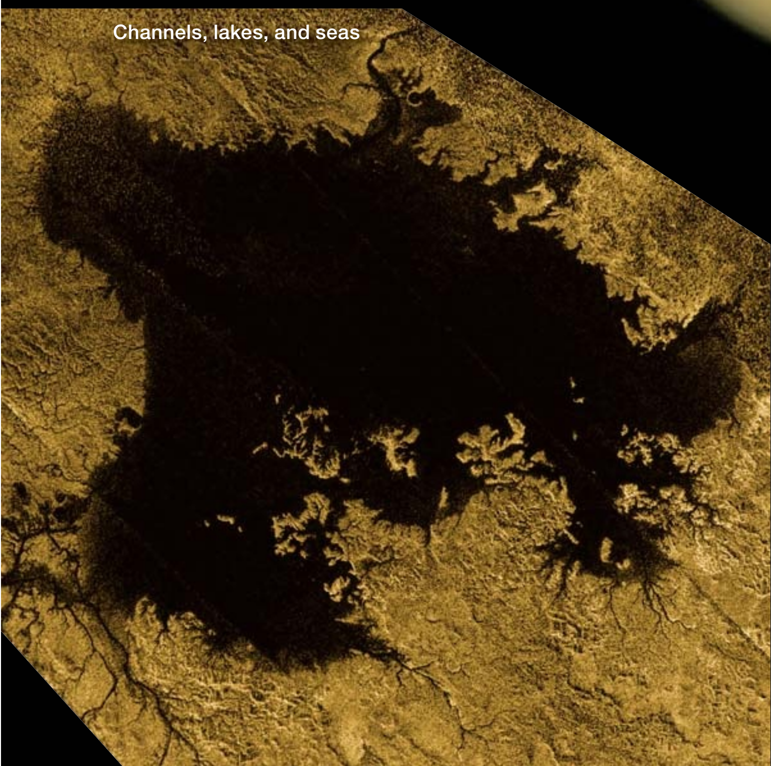
◀ **NORTHERN LAKES** This colorized mosaic of the moon’s north pole was constructed using radar-mapping data from the Cassini spacecraft; the edges extend down to 50°N latitude. Using Cassini’s observations, scientists discovered three seas (labeled) and hundreds of small lakes on Titan. Nearly all the lakes and seas are confined to a rectangle covering about 900 km by 1,800 km (600 by 1,100 mi) in the northern hemisphere; only 3% of the liquid detected on Titan falls outside of this area. The lakes might be seasonal features.

LAKES: NASA / JPL-CALTECH / ASI / USGS; SURFACE FEATURES: SURFACE: NASA /JPL / ESA / UNIVERSITY OF ARIZONA; CRYOVOLCANO: NASA / JPL / USGS / UNIV. OF ARIZONA; DUNES: NASA / JPL-CALTECH / ASI; MARE: NASA / JPL-CALTECH / ASI / CORNELL; HEMISPHERE: NASA / JPL-CALTECH / SPACE SCIENCE INSTITUTE

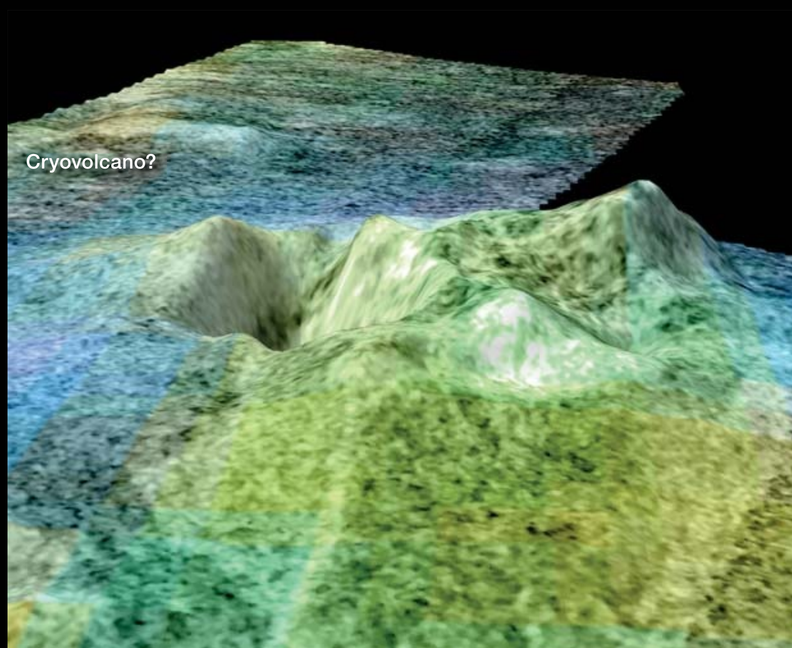
SURFACE FEATURES GALORE
Titan has an active surface with dunes, lakes, and even (potentially) cryovolcanoes. Shown clockwise from top right are a colorized version of the pebbled surface Huygens landed on; a 3D radar map of Doom Mons (tallest peak) and its nearby pit Sotra Patera (vertical height exaggerated by a factor of 10); a slice of the dunes of Shangri-la; Ligeia Mare and its channel systems in false color; and a global image combining infrared and visible-light data to reveal the surface: Dark areas at the north pole are seas and lakes, whereas dark regions at the equator are dunes.



View from the surface



Channels, lakes, and seas



Cryovolcano?

Dunes

The atmosphere is dense enough in the mesosphere that a spacecraft can’t orbit there — but tenuous enough that it’s difficult to study with common techniques. This region is therefore often called the “ignorosphere.”

As the water molecules drift along, solar photons break them up, producing ionized oxygen atoms (O^+). Calculations indicate that those ions are deposited in the same region of the atmosphere where the heavy ions exist. That means that oxygen may also be participating in the ionospheric chemistry, resulting in the formation of very heavy ions that contain CHON.

#7 Hydrogen cyanide

Indeed, laboratory experiments that try to simulate the processes at work in the upper atmosphere show that some amino acids and nucleobases may be present. Therefore, there’s every indication that complex molecules of prebiotic interest form in Titan’s upper atmosphere.

The incredibly heavy ions that CAPS detects are at the very beginning of their journey on Titan, not the end. They will still undergo a number of processes that may alter their composition and physical properties as they descend through the atmosphere and precipitate onto the surface.

Mesosphere: Changing Haze

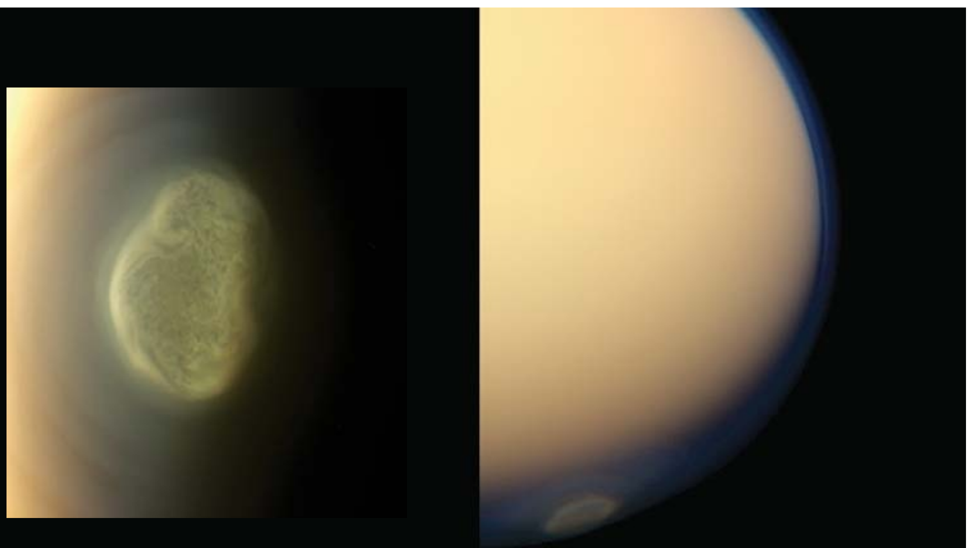
Deeper down in the atmosphere, Cassini revealed other secrets. The region below the ionosphere, the *mesosphere*, tends to be difficult to measure: The atmosphere is dense enough that a spacecraft can’t orbit there — but tenuous enough that it’s difficult to study the region with common techniques. Likewise, Earth’s mesosphere is at too high an altitude to study with balloons and too low to study directly with spacecraft. This region is therefore often called the “ignorosphere.”

Nevertheless, Cassini’s Ultraviolet Imaging Spectrograph was particularly well suited to studying Titan’s mesosphere. It finally provided us with our first detailed measurements of this layer’s composition and density, furnishing important inputs and tests for models of Titan’s atmosphere.

At the bottom of the mesosphere is something called the *detached haze layer*, first discovered by the Voyager 1 spacecraft. When Cassini arrived in the Saturn system, the detached haze layer was at a much different altitude than where we’d left it during Voyager’s 1979 flyby, which was very confusing to Titan scientists. Luckily, the length of Cassini’s mission allowed us to find out that the haze changes altitude with season (a year in the Saturn system lasts nearly 30 Earth years). When we returned to the same part of Titan’s year that Voyager had explored, the layer returned to the same location where it had been observed before.

#8 Carbon dioxide

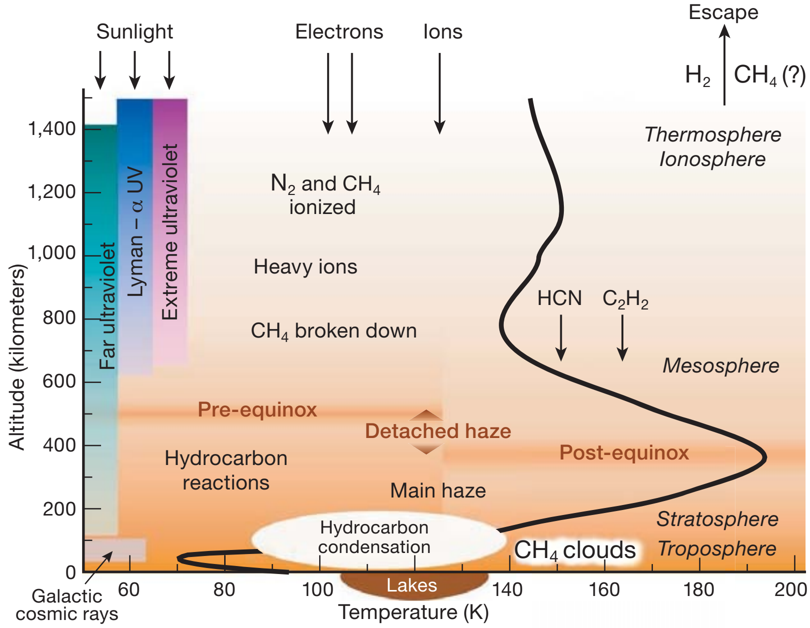
We still don’t know exactly why the detached haze layer changes altitude or very much about its composition, but we do know that both chemistry and motion in the atmosphere, as well as the feedback between them, play important roles. For example, haze particles affect how energy moves through the atmosphere. Energy’s movement in turn affects atmo-



POLAR BEAUTY MARK
Far right: This large vortex, shown here in a natural-color composite, formed at Titan’s south pole as the hemisphere approached winter. The cloud system sticks above the surrounding cloudtops. *Near right:* A close-up reveals what might be open-cell convection, during which air sinks in the center of the cell and rises at the edge, forming clouds at cell edges.

NASA / JPL-CALTECH / SPACE SCIENCE INSTITUTE (2)

▶ ATMOSPHERE IN PROFILE Shown is a representative temperature profile for Titan's atmosphere (black line), along with some of the major chemical processes. Shorter (more energetic) ultraviolet wavelengths reach shallower depths in the atmosphere. Relativistic particles called galactic cosmic rays might reach all the way down into the troposphere.



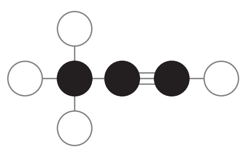
GREGG DINDERMAN / S&T, SOURCE: S. M. HÖRST / JOURNAL OF GEOPHYSICAL RESEARCH: PLANETS 2017

spheric dynamics, which can then affect where the haze particles are located. So by studying the haze, we'll have a better idea of what's going on energy-wise in the atmosphere.

Stratosphere and Troposphere: Abundant Methane

Lower down, in Titan's stratosphere, additional chemistry is driven by sunlight's less-energetic ultraviolet photons, which break up some of the larger molecules originally formed higher in the atmosphere that have sunk to this level. Those molecular fragments then react with the widespread CH_4, destroying more of it. The major net chemical reaction in Titan's atmosphere is the conversion of CH_4 into H_2, which escapes to space because of Titan's low gravity, and C_2H_6 (ethane), which condenses into droplets that fall onto the surface, where the liquid stays because it cannot evaporate in Titan's surface conditions.

This is a crucial reaction sequence: It means that CH_4 is irreversibly destroyed in Titan's atmosphere. Computer models indicate that all the existing methane in Titan's atmosphere should be used up in 10 to 100 million years. Scientists generally assume this means that CH_4 is somehow resupplied, perhaps from outgassing of methane trapped in cage-like surface compounds called clathrates, and not that it is merely what is left of a much larger original abundance of methane in the atmosphere that is in the act of disappearing.



#9
Methylacetylene

The less-energetic photons may also drive photochemistry within ices that have condensed out of the atmosphere. One of the most striking examples of condensation in Titan's atmosphere occurred as the south pole moved into winter: A polar vortex formed and a giant ice cloud, later identified as HCN ice, appeared. This is one of many examples of the seasonal changes that were observed by Cassini, a benefit of having such a long-lived mission, which provided data for almost half of a Saturn year.

As we descend into the troposphere, more condensation can occur. Here CH_4 clouds and storms appear seasonally and change latitude as they chase the sunlight that drives their formation. Titan's dense atmosphere and low gravity result in raindrops that fall slowly and grow to larger sizes than on Earth. Rain appears to be relatively infrequent on Titan — but when it does rain, it pours, resulting in flash floods that carve streams and rivers into the organic-coated, water-ice bedrock.

The Huygens probe descended through all these regions of the atmosphere, finally landing near the equator in a relatively dry wash, similar in appearance to those in the deserts of the U.S. Southwest. As the Huygens probe sat on the surface, it measured methane evaporating from beneath it due to the heat of the probe. This indicates that liquid methane (and likely other liquids as well) had ponded just below the surface, perhaps the memory of the last rainstorm.

All of the liquid and solid organic compounds produced in the atmosphere eventually end up on the surface, where they are either further modified by chemical processes or instead modify the surface themselves, or both. In this way, Titan's surface and atmosphere are uniquely connected. To fully understand what's going on in the atmosphere — and what it could tell us about both our planet and others beyond the solar system — we'll need more information about Titan's surface, especially the composition. Several teams are working on mission concepts for returning us to Titan to explore these questions.

#10
Diacetylene

In the meantime, scientists will dig deeper into the wealth of data returned by Cassini-Huygens, point powerful telescopes at Titan to search for new molecules, and run laboratory experiments to better understand how organic materials behave at cryogenic temperatures. With hard work we will crack the enigma of Titan.

■ When not dreaming of parasailing through Titan's atmosphere, Johns Hopkins planetary scientist **SARAH HÖRST** investigates organic chemistry throughout the solar system.

COSMIC EXPLOSION The Crab Nebula as it appears today at visual wavelengths as seen with the 32-inch Schulman Telescope. But it didn't always look this way. North is up in all images and sketches unless otherwise noted.

Above the Southern H

orn of Taurus

The Crab Nebula is amazing no matter how you look at it.

The dying star had about 10 times the mass of our Sun and had just lost its ability to fuse elements in its core. Without the outward pressure of fusion to hold back its own crushing gravity, the inner core collapsed within seconds into a 20-kilometer-wide sphere of neutrons. The outer core of the star immediately crashed onto this abruptly smaller and superdense core at 23% the speed of light. A titanic shock wave explosively rebounded off the star's neutron core, completely disrupting its outer layers in a star-shattering Type II supernova. The intensely sudden and cataclysmic death of the star was briefly brighter than the entire Milky Way galaxy.

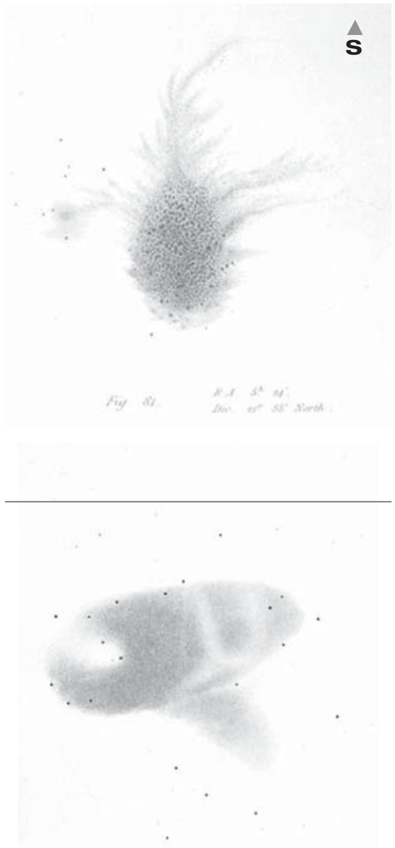
Around 6,500 years later Chinese astronomers saw a brilliant "guest star" in the pre-dawn sky near Zeta (ζ) Tauri on July 4, 1054. For 23 days it was visible in broad daylight and at night it had a reddish-white color. It took more than a year and a half for it to gradually fade from sight.

Some 700 years after that, the still-expanding debris nebula of the supernova inspired Charles Messier to start his catalog of things that looked like comets but didn't move relative to the stars. Discovered 27 years earlier by John Bevis, Messier independently found the nebula while searching for Comet De la Nux (C/1758 K1). By 1781 Messier's list included 102 more objects, which was extended to 110 by various modern authors based on notes he and his collaborator, Pierre Méchain, left behind.

The nebula was then given a nickname that didn't fit its actual appearance, and was used as a damning example of all that was wrong with 19th-century nebular astronomy. In the 20th century, scientists gradually pieced together its incredible nature, a process that continues today. Now I'm here to convey why the remains of that shattered star are so important, and to show what's possible to see of it with a large amateur telescope in the early 21st century.

The Nickname

In 1844 Lord Rosse made a sketch of **Messier 1** that inspired its nickname, the *Crab Nebula*. The sketch looks more like a pineapple — or a tadpole — than a crab, and has the additional charm of looking nothing like the actual object. Lord Rosse even repudiated this sketch, but the Crab Nebula name stuck anyway.



EARLY SKETCHES (*Top*) Lord Rosse's 1836 disavowed sketch of the Crab Nebula as seen through his 36-inch scope. This sketch inspired the Crab Nebula nickname. As per Lord Rosse's notes in the original publication, south is up. (*Bottom*) R. J. Mitchell's 1855 sketch of the Crab Nebula using Lord Rosse's 72-inch telescope.

The definitive view of M1 through Lord Rosse's 72-inch telescope was sketched by R. J. Mitchell in 1855. Although it no longer looks like a pineapple, it still looks different than the object we see today. But that may be more a matter of style; except for the fin, the overall shape is pretty close to an unfiltered view in a large amateur telescope today. On the other hand, a somewhat wispier fin can be seen in the title image on page 30.

It's also possible the fin is just less noticeable today. After all, the Crab has had 163 years to expand since this sketch — nearly 17% of its existence. Or perhaps a 72-inch speculum metal mirror just produces a different view than aluminized glass mirrors and CCD cameras.

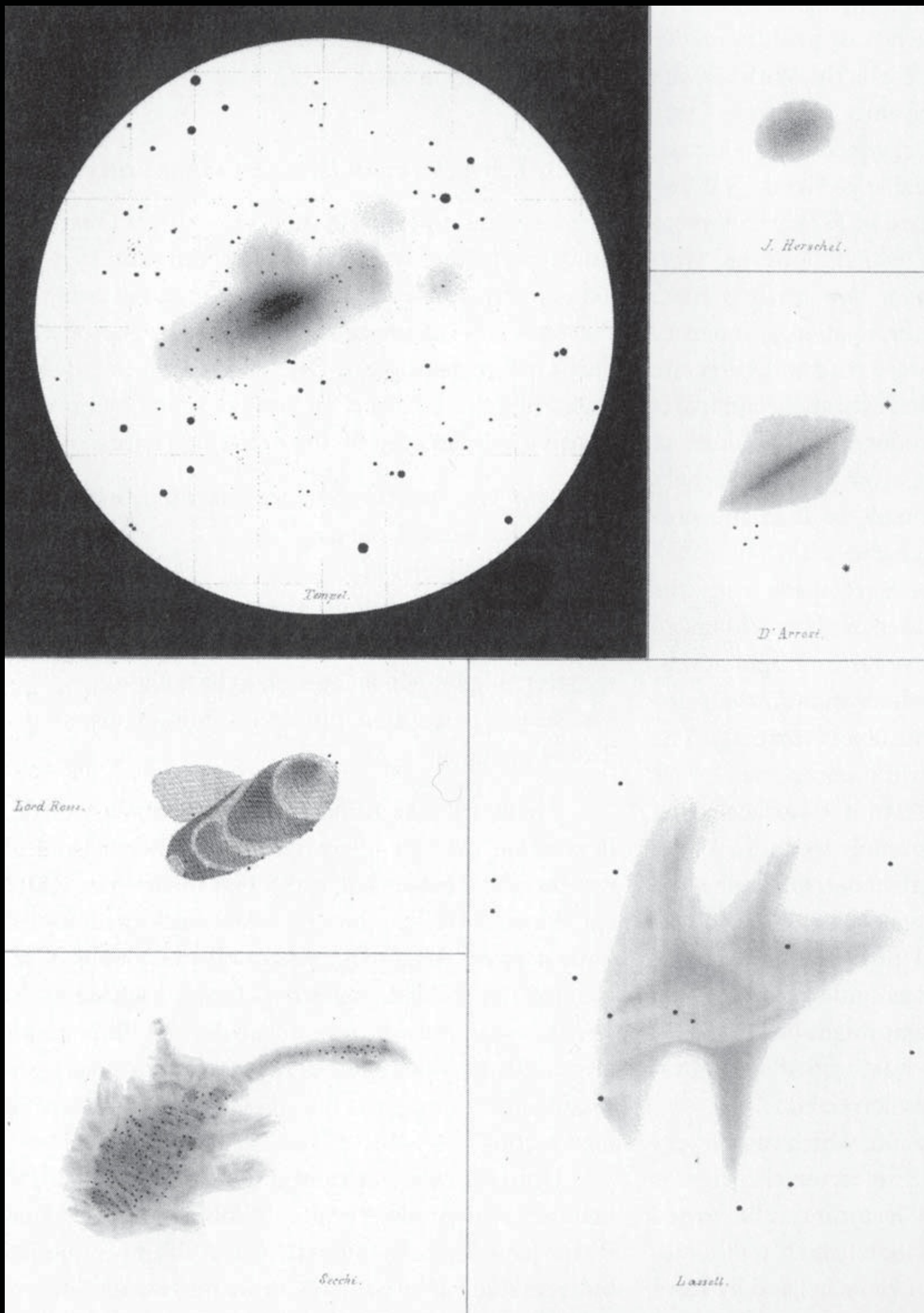
Subjective Science

In 1876 the German astronomer Wilhelm Tempel used a collection of Crab Nebula drawings made by some of the most well-regarded astronomers of the day — including himself — to show how useless these drawings were scientifically. It was a point well made, because each sketch looked like it was of a different object.

Tempel was emphasizing the need for a standardized method of sketching deep-sky objects, but also showing the futility of using subjective visual observations; they weren't accurate enough for scientific use.

There was no hope of being able to quantify objects like the Crab Nebula with visual observations, because even the best-trained astronomers of the 19th century were still

CRAB NEBULA: ADAM BLOCK / MOUNT LEMMON SKYCENTER / UNIVERSITY OF ARIZONA; ROSSE'S SKETCH: *PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY OF LONDON* (1844) / PUBLIC DOMAIN; MITCHELL'S SKETCH: INSTITUTE OF ASTRONOMY LIBRARY / UNIVERSITY OF CAMBRIDGE / CC BY 4.0



OBSERVING IS SUBJECTIVE Wilhelm Tempel's Crab Nebula sketch comparison between six prominent 19th-century astronomers. Clockwise from top right, the sketches were made by J. Herschel, D'Arrest, Lassell, Secchi, Lord Rosse, and Tempel.

WILHELM TEMPEL / *KÖNIGLICHE BÖMISCHE GESELLSCHAFT DER WISSENSCHAFTEN* subjective human beings. It's ironic though, because the Crab is the only object on Messier's list where changes might have been detected over several decades if these sketches had only been more accurate.

However, photography and spectroscopy were just a few years away from being sensitive enough to begin unravelling the Crab Nebula's secrets.

Deciphering the Crab

During 1913–1915 Vesto Slipher was the first to examine the Crab's spectrum and thus lay the groundwork for later studies that showed the nebula to be expanding. Some years later, in 1921, Carl Lampland discovered changes within the Crab Nebula by examining photographs taken with the Lowell Observatory 40-inch reflector, which he studied with a blink comparator.

At the same time, it was suggested that the Crab was related to the 1054 Chinese guest star, and in 1928 Edwin Hubble proposed that the expansion rate of the Crab Nebula and its location supported the idea that it was the debris of the 1054 supernova. Jan Oort analyzed the Chinese astronomical records in 1942 and came to the same conclusion.

That same year Walter Baade noted that the Crab's expansion rate was accelerating and that the stellar remains of the supernova must be responsible. This supported the idea he and Fritz Zwicky had put forth eight years earlier:

"With all reserve we advance the notion that supernovae represent the transitions from ordinary stars to neutron stars which in their final stages consist of extremely closely packed neutrons."

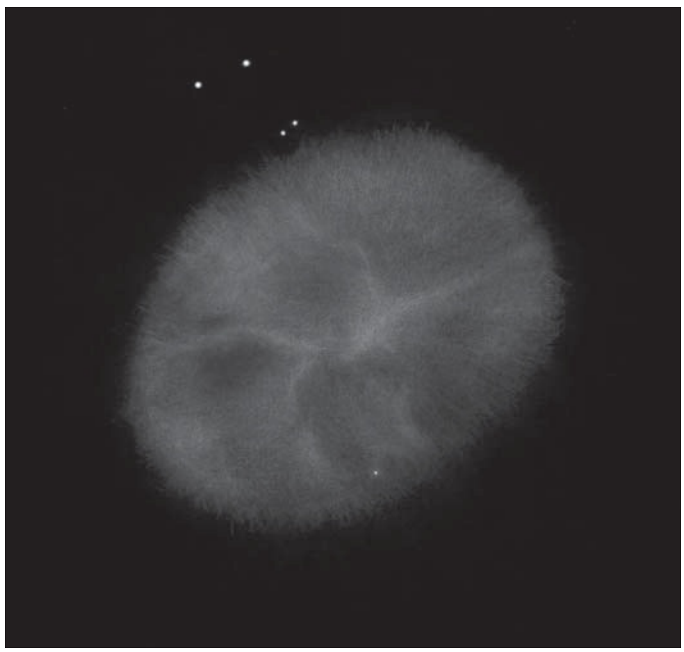
The Crab's radio emission was discovered in 1949, which was the first detection of these frequencies in an optical object other than the Sun. From this point theoretical studies and observations went hand in hand until 1967, when Franco Pacini proposed that a strongly magnetized, rapidly spinning neutron star was possibly energizing the Crab Nebula.

Jocelyn Bell Burnell, while still a graduate student at the University of Cambridge, famously discovered the first pulsar a year later, and then shortly thereafter the Crab's pulsar (PSR B0531+21) was identified and confirmed to be the central engine powering the Crab Nebula. It became the first pulsar associated with a supernova remnant, and it remains an object of active research today.

In a Nutshell

The Crab Nebula is the youngest, brightest, and closest supernova remnant, and its neutron-star pulsar is the collapsed core of the supernova's progenitor star. Approximately 20 kilometers in diameter, it's a sphere of tightly packed neutrons that rotates 30 times per second, with a collimated beam of light blasting out from each of its magnetic poles. The pulsar produces a relativistic outflow of synchrotron radiation that helps accelerate the expansion of the Crab Nebula.

▼ **UNFILTERED AND FILTERED VIEW** (*Top*) The sketch shows the unfiltered view through the author's 28-inch scope. Except for the fin, this view looks similar to the overall shape of R. J. Mitchell's 1855 drawing. Magnifications from 253× to 408× were used for both sketches, but depending on how steady the seeing is, more than 1000× can be used on the Crab. The only difference between these two sketches is the use of an O III filter for the second sketch. (*Bottom*) This shows the view through the 28-inch using an O III filter. The filter radically changes the apparent shape of the Crab Nebula by bringing out its overall oval outline as well as a few of the brighter filaments. The O III filter also dims many of the stars seen in the unfiltered view. Note that this sketch has been left with many pencil marks around the perimeter of the nebula to suggest the sense of detail that was just out of reach. The scale and orientation are the same in both sketches.



HOWARD BANICH (2)

The Crab is approximately 6,500 light-years away, stretches 13 light-years along its major axis, and is expanding at a rate of 1,500 kilometers per second. In other words, it's an absolutely fantastic object.

The Visual Crab

As the only supernova remnant in the Messier list, the Crab seems like it should be an amazing telescopic sight. For instance, its fairly substantial size of 6′ × 4′ makes the 8.4-magnitude Crab Nebula bright and large enough to be an obvious fuzz ball even in my 80-mm finderscope. I first saw the Crab in 1982 through my 12.5-inch telescope, and it was bright enough that it was easy to see with direct vision from my light-polluted backyard. It seemed that perhaps with a little averted vison I might observe some details.

No such luck! It didn't take long to realize that none of the famous filaments could be resolved. It didn't look like the few telescopic comets I'd already seen either — they had tails — but I took it on faith that that's how they often looked to Messier.

But in the 1990s with a 20-inch scope I was able to detect the Crab as a chubby, fuzzy S. No internal details, just an amorphous nebula with a funny shape that was dimmer on the ends than in the middle. It stood out quite well on the best nights, and I was able to see the neutron star along with the slightly brighter field star that appears right next to it. Both of these stars are rather faint at approximately 16th magnitude, so it took steady seeing conditions, high magnification, and averted vision to see them well.

And that is so incredibly cool! After all, how many pulsars can you see in an amateur scope? Only one, the Crab Pulsar — PSR B0531+21.

The Crab and the O III Filter

An O III filter is even more essential to seeing filaments in the Crab than the hydrogen-beta filter is to seeing the Horsehead Nebula (*S&T:* Jan. 2019, p. 58). When using an O III filter with my 20- and 28-inch scopes, the Crab's brightest filaments become visible, and the overall shape of the nebula becomes oval. I get excited each time I see this transformation, and my sketches illustrate the difference as seen through my 28-inch scope.

You'll also notice I've seen only suggestions of the fainter filaments and hints of a ragged perimeter. The filaments are low-contrast, difficult-to-see features under even the best observing conditions with a large amateur telescope. I've tried many times to see more, but the O III sketch shows my best effort with my own scopes.

However, I once saw considerably more filaments in Jimi Lowrey's 48-inch scope but didn't have time to make a representative sketch. You can imagine how awesome the Crab Nebula looked, though.

A Dead-Solid Awesome Sight

Even better — way better in fact — in April of 2010 I was part of a group of ten observers that rented the 90-inch Bok telescope on Kitt Peak for one night of visual observations. The Crab was our second object of the night, and although filaments were everywhere, they were surprisingly subtle.

Okay, now I don't feel so bad about seeing only a few filaments in my own scopes, and even though they were still a spectacular sight I had hoped for a brighter view. We used a 41-mm Panoptic eyepiece, which gave a magnification of 502×, along with a Lumicon O III filter. From my notes:

"I can't sketch all the filaments that jump out with the O III filter — a unique sight! I'd need a good hour to sketch all the detail, and that would cause a riot."

However, seeing filaments was of secondary importance because our primary aim was to blink the Crab pulsar.

Dan Gray of Sidereal Technology was one of the observers, and he'd made a programmable rotating shutter, which he called a "chopper," to specifically use on the Crab pulsar. It was designed to fit on the eyepiece end of the 90-inch Bok scope and was set to rotate a little more slowly (29.431 rotations/second) than the frequency of the pulsar (30.23 rotations/second).

Dan removed the 41-mm eyepiece with the O III filter and quickly installed the shutter, much to our excitement. We used a 17-mm Nagler eyepiece with the shutter, producing a magnification of 1210×, which narrowed the field of view to just the central portion of the Crab.

The pulsar and the nearby field star were the two most obvious things in the eyepiece and were set against a background of bright nebulosity.

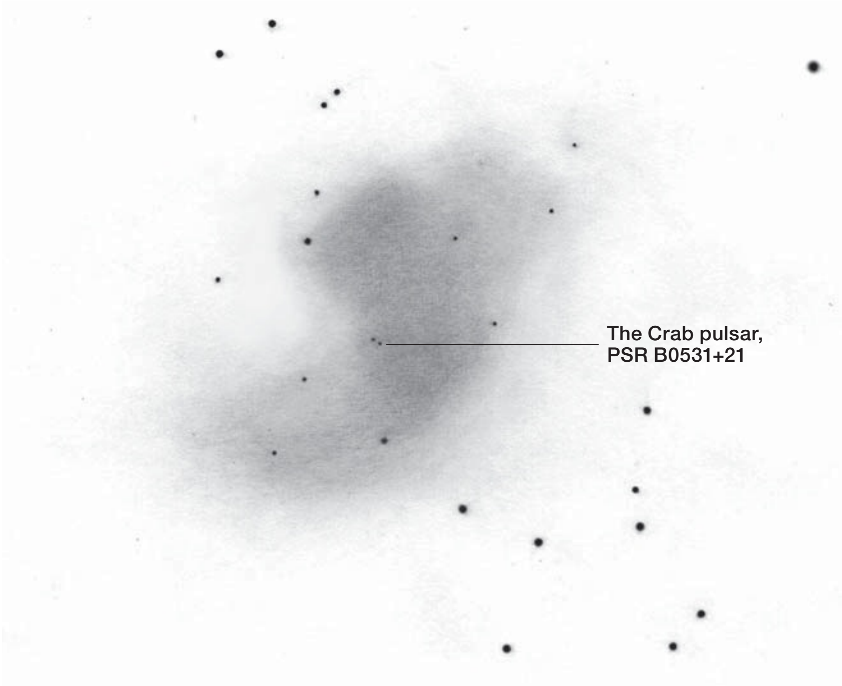
Everyone was eager for a look, but I was first in line. Man was I excited! But would it work? Would the pulsar blink?

Oh my goodness . . . ***OH MY GOODNESS***! Even though we had hoped to see

▲ **TELESCOPE AND CHOPPER** The image at top shows the 90-inch Bok telescope at Kitt Peak in Arizona. Below, Dan Gray's rotating shutter — which he called a "chopper" — and the eyepiece were attached to the bottom end of the telescope.

TELESCOPE: HOWARD BANICH; CHOPPER: DAN GRAY

Holy cow, there it is — and blinking with Dan Gray's chopper — WOOHOO!!!



▲ **LOCATION OF THE PULSAR** *Left:* The 16th-magnitude pulsar, PSR B0531+21, and the very slightly brighter field star that appears next to it, are exaggerated in brightness in this sketch so they're easily visible. *Right:* The author's sketch from the night of April 12, 2010, shows how the amplitude of the Crab Pulsar's brightness changed using Dan Gray's "chopper." The minimum to maximum frequency was about 2 seconds as seen using 1210× on the 90-inch Bok telescope at Kitt Peak. The pulsar is the star on the right.

changes in the pulsar's brightness, the precise rate Dan had chosen for the shutter made the pulsar *smoothly* change in brightness, from maximum to invisibility and back again over approximately 2 seconds.

It was like a lighthouse beacon on a foggy night:

"Holy cow, there it is — and blinking with Dan Gray's chopper — WOOHOO!!! It was best seen with averted vision and was quite obvious once I caught the beat of the 2-ish second amplitude. Once I got the beat I watched for about 10 beats before Dan pushed me away from the eyepiece for his turn. This is a dead-solid awesome sight!"

This observation will always be one of the most exciting things I've seen through a telescope. My exclamations at the eyepiece immediately brought all the other observers rushing to the observing platform as Dan was good-naturedly, but firmly, pushing me aside for his turn.

I can't say we saw a difference between the primary and slightly fainter interpulse, but that wasn't the point — we saw the Crab pulsar's brightness change with our own eyes.

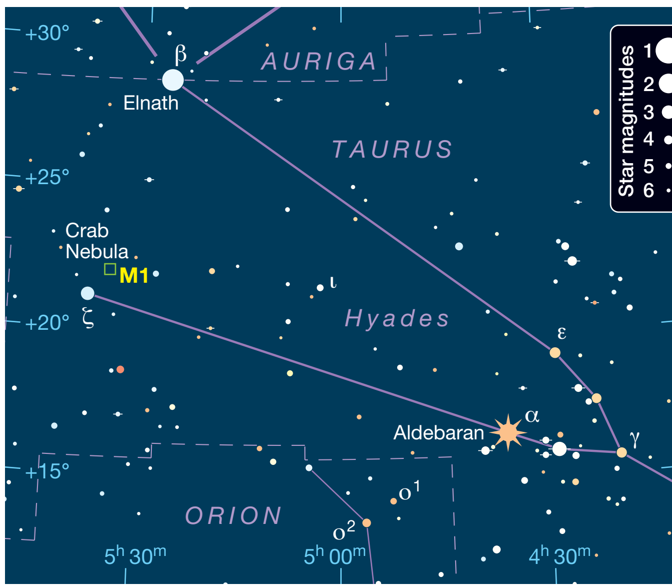
Cool animations

1. To get an idea of what we saw, check out: **https://is.gd/crabmovie1**
2. See the Crab Nebula expansion over 10 years at: **https://is.gd/crabmovie2**
   This is a short animation made by Detleff Hartmann using images he took with his homemade 17.5-inch telescope.

HOWARD BANICH (2)

We understood the special nature of this observation, so everyone took several turns at the eyepiece. We may or may not be the only ten people to have ever seen the Crab pulsar change in brightness visually, but we count ourselves exceptionally fortunate to have done so. It's one thing to know that it rotates at 30 times per second, but it's an utterly breathtaking experience to see that it actually does.

■ Nearly nine years later Contributing Editor **HOWARD BANICH** is still enthralled by this observation — he sincerely thanks his good friend Dan Gray for making the "chopper." Howard can be reached at **hbanich@gmail.com**.



Explaining A

HEAD OF THE GORGON The name Algol comes from the Arabic phrase *ra's al-ghūl*, which translates to "head of the demon," but the star has been associated with Medusa, the Gorgon of Greek mythology, at least since Ptolemaic times.

lgol

How John Goodricke and Edward Pigott discovered and interpreted a new variable star.

AN ASTRONOMER'S POSE Born in the Netherlands, John Goodricke spent most of his life in the United Kingdom. This portrait, composed in pastels by James Scouler the year Goodricke turned 21, originally hung in the astronomer's own home in Lendal, York.

On November 12, 1782, 18-year-old John Goodricke of York, England, compared the brightness of the star Algol (Beta Persei) to neighboring stars in Perseus and Andromeda. Astonished at what he'd seen, he wrote in his journal:

This night I looked at Beta Persei and was much surprized [sic] *to find its brightness altered — It now appears of about the 4th magnitude. I observed it diligently for about an hour — I hardly believed that it changed its brightness because I never heard of any star varying so quickly in its brightness. I thought it might perhaps be owing to an optical illusion, a defect in my eyes, or bad air, but the sequel will show that its change is true and that I was not mistaken.*

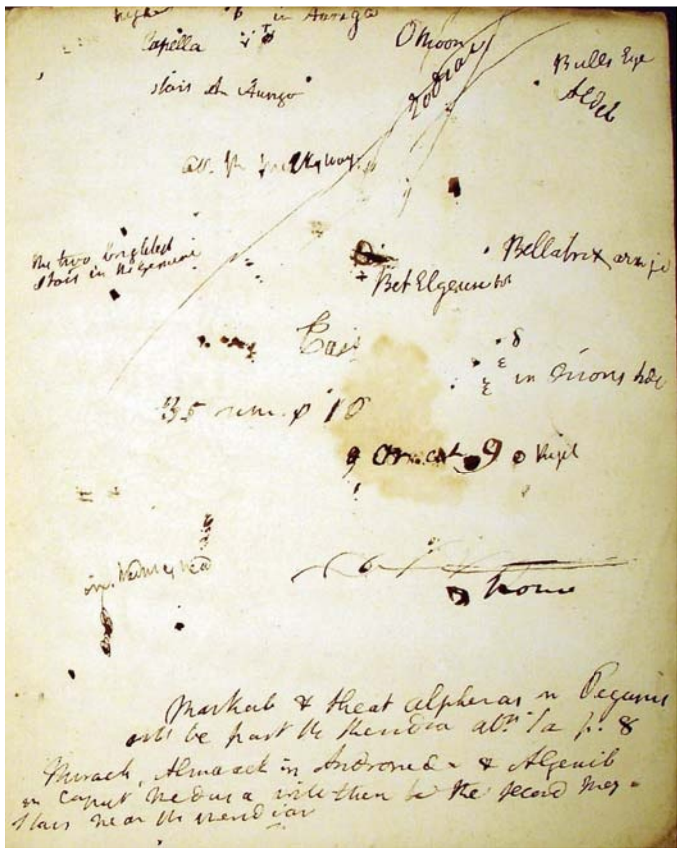
The next night, Goodricke returned for another look at Algol and wrote, "Beta Persei is now much changed. It now appears of the second magnitude. . . . very unexampled change!"

Goodricke didn't observe Algol's dimming by chance. He and Edward Pigott, his mentor and friend, were searching for stars whose light varied. At that time the best-studied variable star, with a period of about 11 months, was Mira (Omicron Ceti). Hence, Goodricke expected any change in brightness to take weeks, not hours. Although earlier astronomers remarked that the light of Algol (imagined since ancient times to represent the winking eye of the Gorgon, Medusa, in the constellation of Perseus) didn't seem constant, no one had systematically observed the star. Over the next three years, the two young Englishmen would characterize the variation of Algol, another eclipsing binary system (Beta Lyrae), and the first two known Cepheid variables.

Goodricke and Pigott

John Goodricke (1764–1786) was born in Groningen, the Dutch Republic (present-day Netherlands), where his father Henry was a diplomat. An early illness (perhaps scarlet fever) left John completely deaf — a significant handicap in those times when the deaf were still subject to prejudice. Fortunately, the Goodricke family had the resources and the insight to help a child with special needs. Had he lived a longer life, John Goodricke would have eventually become a baronet and inherited a large estate.

Goodricke attended Braidwood Academy, the first school for the deaf in the British Isles, and then the Warrington Academy. The Warrington mathematics curriculum included a significant amount of astronomy, and John's mathematics notebook includes a sketch of the sky. From the position of the Moon and the times indicated in the text, it's clear that



WRITTEN RECORD This sketch of the Moon (top center) and stars comes from the inside back cover of John Goodricke's mathematics notebook from Warrington Academy for the year 1779–1780. The position of the Moon and the descriptive note about the star positions (bottom) make it possible to determine that Goodricke drew the sketch in November 1779.

BACKGROUND TEXTURE: PABLOHART / E+ / GETTY IMAGES; ALGOL: HERITAGE IMAGES / CONTRIBUTOR / HULTON ARCHIVE / GETTY IMAGES; GOODRICKE: ROYAL ASTRONOMICAL SOCIETY; SKETCH: EXPLORE YORK ARCHIVES

he was observing in late November 1779. A total eclipse of the Moon occurred on November 23, 1779. Was Goodricke checking his homework or merely planning to observe an astronomical event? We don't know, but we do know that he was interested in observing before meeting Edward Pigott. In 1781 Goodricke completed his studies at Warrington and rejoined his family in York.

That same year, Edward Pigott (1753–1825) also moved to York with his parents. Edward's father Nathaniel used astronomical observations for determining latitude and longitude, and Edward learned the art of observing from him. In York, Nathaniel constructed a two-story stone observatory. The instruments — telescopes, a quadrant, and a theodolite — came from London's finest instrument makers. Nathaniel was a member of the Royal Society of London, and both Pigotts kept abreast of current astronomical developments through correspondence with astronomers such as William Herschel and Charles Messier.

Edward Pigott's astronomical interests ranged further than his father's, however. He frequently compared the apparent stellar magnitudes reported by Flamsteed with those of earlier observers such as Tycho and Ptolemy. One of Edward's early journals contains a list of publications entitled "Authors on Variable Stars." When Goodricke joined him, Pigott suggested that they systematically observe suspected variables.

After Goodricke first saw Algol's "very unexampled change," in which the star's brightness dropped from an estimated third magnitude to somewhere between fourth and fifth magnitude, both men observed the star every clear night. Neither saw another dimming event until both witnessed one on December 28, 1782. They found the brightness remained approximately constant except for a seven-hour dip every 2 days, 20 hours, and 45 seconds. The two realized that the cause of such a pattern might be one body passing in front of another, and each speculated in his observing journal. Goodricke wrote:

[Algol's variation] can't be accounted for in any other manner than supposing it to have suffered an Eclipse . . . by the interposition of a Planet revolving around it. . . .

Edward Pigott elaborated, writing:

Having, on further consideration stronger reasons to believe that what I wrote to Mr. J. Goodricke on the 29th of December 1782 may possibly happen induces me to make the following memorandum of it — the opinion I suggested was that the alteration of Algol's brightness was maybe occasioned by a Planet of about half his size, revolving around him, and therefore does sometimes eclipse him partially. . . .

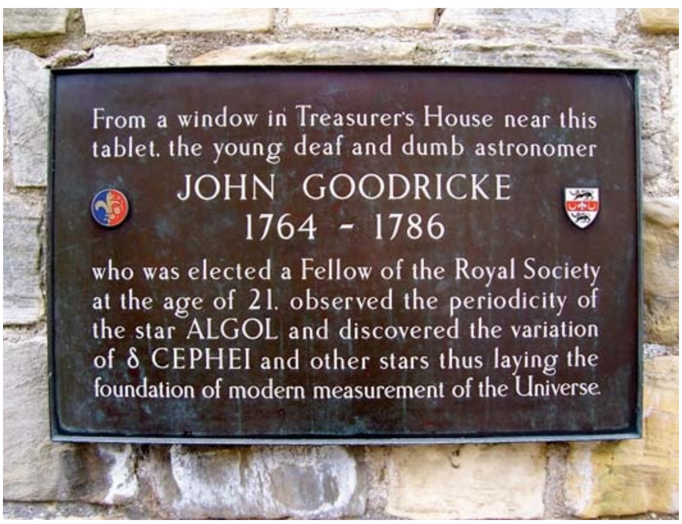
In May 1783, William Herschel confirmed the discovery of Algol's variability, and Goodricke sent his report to the Royal Society. In the report's conclusion, Goodricke wrote that he

. . . should imagine [Algol's variation] could hardly be accounted for otherwise than either by the interposition of a large body revolving round Algol, or some kind of motion of its own, whereby part of its body, covered with spots or such like matter, is periodically turned towards the earth.

Covered with Spots

The starspot hypothesis may seem strange to modern minds. How could a large and apparently permanent spot cause the brightness to drop for seven hours during a period of almost three days? Yet at the time there was considerable support for

▼ **WORKING FROM HOME** In 1782, John Goodricke lived and observed near the close of York Minster. In 1949 Sidney Melmore used dates, times, and notes written in Goodricke's observing logs to argue that Goodricke observed from the north window on the top floor of the southeast wing (at right, behind the tree branch) of the Treasurer's House, looking south toward the cathedral. However, records show that the Goodricke family rented rooms from Edward Topham, who owned the northwest wing of the house (left).



LINDA FRENCH (2)

this idea. No less a figure than Isaac Newton had written, in Book III of *Principia* (1687):

As to those fixed stars that appear and disappear by turns, and increase slowly and by degrees, and scarcely even exceed the stars of the third magnitude, they seem to be of another kind, which revolve about their axes, and, having a light and a dark side, shew those two different sides by turns.

Modern observers will recognize the particular pattern of brightness variation shown by Algol — nearly constant brightness except for a sharp decrease for a few hours — as characteristic of a detached eclipsing binary system. While astronomers of Goodricke's time realized that binary stars were theoretically possible and quite likely, no systems had yet been shown to be true binaries. Sunspots, however, were a known phenomenon, and established astronomers favored the starspot explanation.

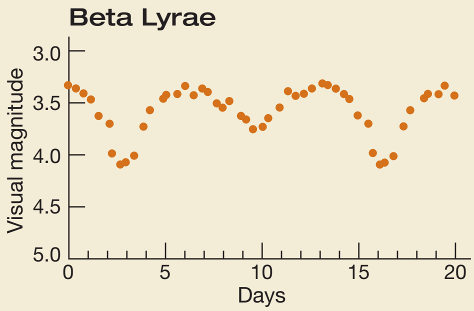
In August 1783 the Royal Society awarded the Copley Medal, its highest honor, to John Goodricke "for his discovery of the Period of the Variation of Light in the Star Algol." Today this work and later discoveries are recognized as a collaborative effort between Goodricke and Pigott.

The two observers were especially productive in the autumn of 1784, when they discovered three new variable stars. In September, Goodricke noted that Beta Lyrae, now recognized as a contact binary, appeared to vary in brightness. On the same night, Pigott saw a change in the star known today as Eta Aquilae, later classified a Cepheid variable. Goodricke noted the variability of the namesake Cepheid, Delta Cephei, in mid-October. In Pigott's paper on the variability of Eta Aquilae, he addressed possible causes for the variation:

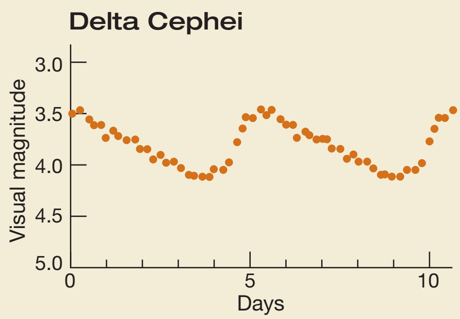
Hitherto the opinion of astronomers concerning the changes of Algol's light seem to be very unsettled . . . though various are the hypotheses to account for it; such, as supposing the star of some other than a spherical form, or a large body revolving round it, or with several dark spots or small bright ones on its surface, also giving an inclinations to its axis etc.; though most of these conjectures with regard to Algol be attended with difficulties, some of them combined do, I think account for the variation of Eta [Aquilae].

John Goodricke visited London in 1785, where he met the Astronomer Royal, Nevil Maskelyne. In July of that year, Maskelyne wrote Goodricke, asking, "Did you ever doubt whether some hemispheres of our Sun (exclusive of the variable spots) may not be brighter than others?" Although the phrasing is odd, it is clear that Maskelyne was attempting to persuade his young colleague to accept the starspot hypothesis.

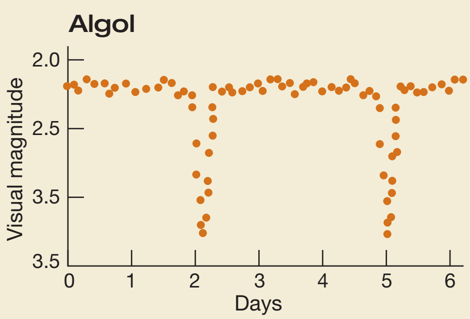
One more observational detail nudged Goodricke toward the spot hypothesis and away from eclipses. In his paper describing the variation of Delta Cephei, Goodricke wrote that "Even Algol does not seem to be always obscured in the same degree, being perceived to be sometimes a little brighter than Rho Persei, and sometimes less than it." Rho, a nearby star in Medusa's head, is a convenient comparison star for a naked-eye observer as its average visual magnitude is 3.4, the same as Algol's in eclipse. But here Goodricke apparently fell prey to an error well known to modern photometrists:

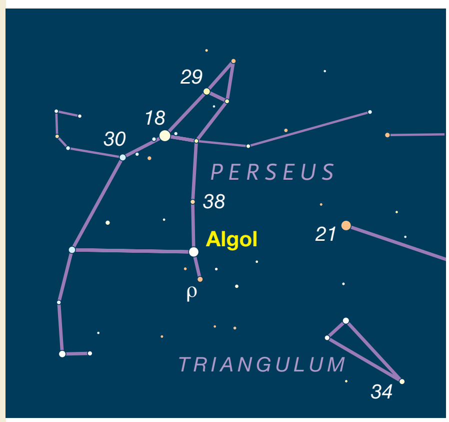


▲ **A NEW VARIABLE** Goodricke detected Beta Lyrae's variability in September 1784. The light cycle of Beta is never constant because the star is a contact, or semi-detached, binary where material transfers at a rapid pace from the gaseous envelope of a massive star onto a lower mass star. Beta's apparent visual magnitude peaks around 3.2. The light curve shows minima at different depths, with the dimmest as low as 4.4.



▲ **DISCOVERING DELTA** Goodricke noted the variability of Delta Cephei in October 1784. Delta's brightness cycles from 3.5 to 4.4 and back up again over the course of 5.4 days.





▲▶ **THE GORGON'S EYE** Algol (Beta Persei) dips from magnitude 2.1 to 3.4 and back every 2.7 days. Use this chart to estimate its brightness with respect to the comparison stars of magnitude 2.1 (Gamma Andromedae) and 3.4 (Alpha Trianguli). Rho Persei is also a variable star.

LIGHT CURVES: GREGG DINDERMAN / S&T

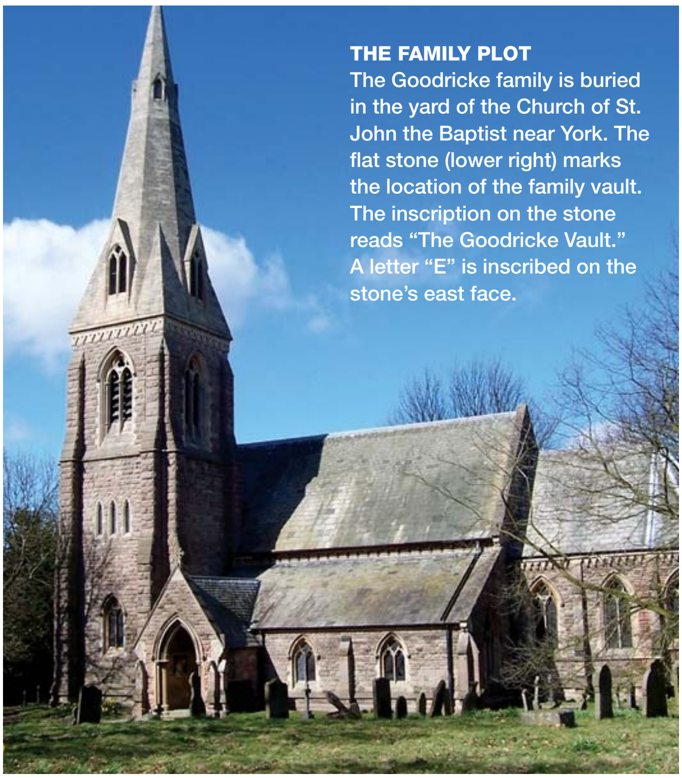
Rho is a semiregular variable whose brightness ranges from 3.3 to 4.0! The eclipse hypothesis depended upon Algol's brightness staying constant between eclipses and dipping equal amounts during each eclipse. Since the brightness seemed to vary during some "eclipses," Goodricke and Pigott both eventually accepted the variations they had discovered as being due to starspots.

Goodricke had little time left to live. On April 6, 1786, he was elected to membership in the Royal Society; on April 20th of that year he died, aged 21. Later that year, Edward Pigott published the work he and Goodricke had done to determine the latitude and longitude of York. Pigott noted his young colleague's passing thus:

> *This worthy young man exists no more; he is not only regretted by many friends, but will prove a loss to astronomy, as the discoveries he so rapidly made sufficiently evince: also his quickness in the study of mathematics was well known to several persons eminent in that line.*

Edward Pigott went on to discover the variable stars R Scuti and R Coronae Borealis.

Proving the binary nature of Algol was impossible for nearly a century until the advent of astronomical spectroscopy. It's easy to look back and say, "They had the right answer! Why did they let themselves be talked out of it?" But no physical binary stars (and certainly no exoplanets!) were known at the time, while sunspots had been observed for more than a century. It's remarkable that the first explanation that occurred to Pigott and Goodricke led to the very technique astronomers use today to detect exoplanets. Their observations and theorizing were decades ahead of their time.



THE FAMILY PLOT
The Goodricke family is buried in the yard of the Church of St. John the Baptist near York. The flat stone (lower right) marks the location of the family vault. The inscription on the stone reads "The Goodricke Vault." A letter "E" is inscribed on the stone's east face.

Epilogue: Searching for John Goodricke

How did a young man with such a serious handicap achieve so much in such a short lifetime? Bits of Goodricke's story have been woven into a mostly false narrative. He is frequently referred to as "deaf and dumb" or a "deaf mute." A plaque describing Goodricke in this manner is mounted on a wall outside Treasurer's House, the family's home in York. However, in his journals, Goodricke describes conversations with a clockmaker. He writes, "I remonstrated with Mr Hartley . . ." Although he was deaf, he read lips and attempted to speak (learning to lip-read was part of the curriculum of Braidwood Academy).

The Czech-British astrophysicist Zdeněk Kopal visited the graveyard where Goodricke is buried and concluded that he was not interred with his family because they were ashamed of him, "a blot on the family's escutcheon" because of his deafness. Kopal apparently reached this conclusion after seeing a stone in the graveyard marked simply, "The Goodricke Vault." But there's a less sinister explanation. The Goodricke vault was located under the floor of an earlier church on the site. As their estate passed into other hands, the new owners wanted to build their own church. None of the Goodricke family was buried in the new church. County records show that John Goodricke rests with his grandparents, his parents, his brother, and his nephew.

In preparation for a Semester Abroad course in England with my Illinois Wesleyan University students, I looked into Goodricke's life. I realized that the stories I had learned could not be true. Cold, unloving parents would not have provided their deaf child the education he needed. John Goodricke thrived through their support, an excellent education, and the generous mentorship of Edward Pigott.

■ **LINDA FRENCH** is an astronomer and Professor of Physics at Illinois Wesleyan University. She studies small solar system bodies in her "regular" astronomical research. John Goodricke's story piqued her interest due to her long teaching career and doing research with undergraduates.

LINDA FRENCH (2)

OBSERVING
February 2019

1 MORNING: Antares, Jupiter, Venus, the waning crescent Moon, and Saturn form a graceful arc 35° long stretching from the southeast to the south-southeast in the brightening twilight. Notice how the ever-thinning Moon has popped over to the other side of Saturn the following morning.

3 EVENING: Algol shines at minimum brightness for roughly two hours centered at 11:55 p.m. EST (8:55 p.m. PST); see page 50.

6 EVENING: Algol shines at minimum brightness for roughly two hours centered at 8:45 p.m. EST.

10 EVENING: After sunset, look halfway up in the south-southwest to see the waxing crescent Moon hanging some 6° lower left of Mars.

12 DUSK: Mercury reemerges from its superior conjunction with the Sun — look toward the west-southwest after sunset to see the tiny world. Binoculars help.

13 EVENING: The Moon, one day past first quarter, is in the Hyades, 2° from Aldebaran.

17–19 MORNING: Venus has been creeping up on Saturn all month and has now caught up with the ringed planet. Look toward the southeast before sunrise to see the brilliant Morning Star glide over Saturn, with only about 1° separating the two planets on the morning of the 18th.

17 EVENING: The waxing gibbous Moon is in Cancer, nestled up against M44, the Beehive Cluster.

21 EVENING: The soft glow of the zodiacal light is visible at mid-northern latitudes from dark sites during the next two weeks. Look toward the west after sunset for a hazy pyramid of light stretching up through Taurus to Gemini, tilted slightly to the left.

23–24 NIGHT: Algol shines at minimum brightness for roughly two hours centered at 10:41 p.m. PST (1:41 a.m. EST).

26 EVENING: Algol shines at minimum brightness for roughly two hours centered at 10:30 p.m. EST.

27–28 DAWN: Antares, Jupiter, Saturn, and Venus form a long arc stretching from the south to the east-southeast horizon. The waning crescent Moon is 2° upper right of Jupiter on the 27th, and halfway between Jupiter and Saturn on the last day of the month.

— DIANA HANNIKAINEN

▲ Algol, the brighter star lower right of center, shines — and dims — in Perseus; see page 36 for more on the history of this object. Clockwise from the left are: Capella, Auriga's lucida; the Double Cluster (NGC 869 and NGC 884); and the Pleiades in Taurus. Alpha Persei is near the center.

AKIRA FUJII

FEBRUARY 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		

NEW MOON
February 4
21:04 UT

FIRST QUARTER
February 12
22:26 UT

FULL MOON
February 19
15:54 UT

LAST QUARTER
February 26
11:28 UT

DISTANCES

Apogee	February 5, 09^h UT
406,555 km	Diameter 29′ 23″
Perigee	February 19, 09^h UT
356,761 km	Diameter 33′ 29″

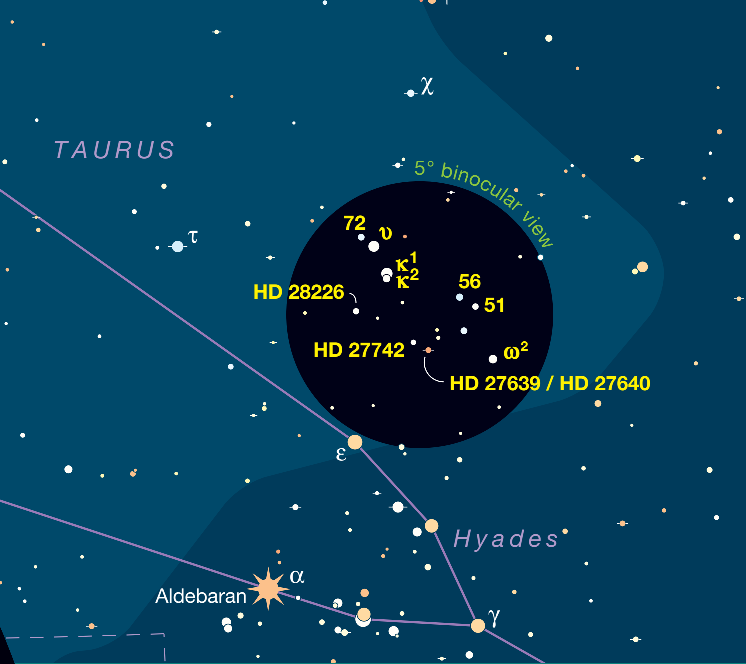
FAVORABLE LIBRATIONS

• Pingre Crater	February 19
• Neumayer Crater	February 20
• Helmholtz Crater	February 21

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

Between the Clusters

I assume that like most binocular observers, you've probably looked at the Pleiades and Hyades many times in recent months. I often zip between the two nearby clusters to compare them. In doing so, for a long time I passed over a rich and beautiful star field that lies between them.

About 5° north of the Hyades, a scattering of 4th- to 6th-magnitude stars is spread southwest to northeast over about 4°. Many of the stars fall into pairs that are coincidentally aligned southwest to northeast as well. Collectively they make an elongated dagger shape, like a swordfish or a vintage rocket ship. **Omega^2 (ω) Tauri** forms the nose, **51** and **56 Tauri** constitute the northern border, and **HD 27639** and **HD 27742** form the southern edge. From HD 27742, a nice chain of faint stars runs north to **Kappa^1 (κ)** and **Kappa^2 Tauri**. With a separation of about 345″, Kappa Tauri makes a fine binocular double. From Kappa, look for a tall shark tail formed by **Upsilon (υ) Tauri** and **72 Tauri** to the north, and **HD 28226** to the south.

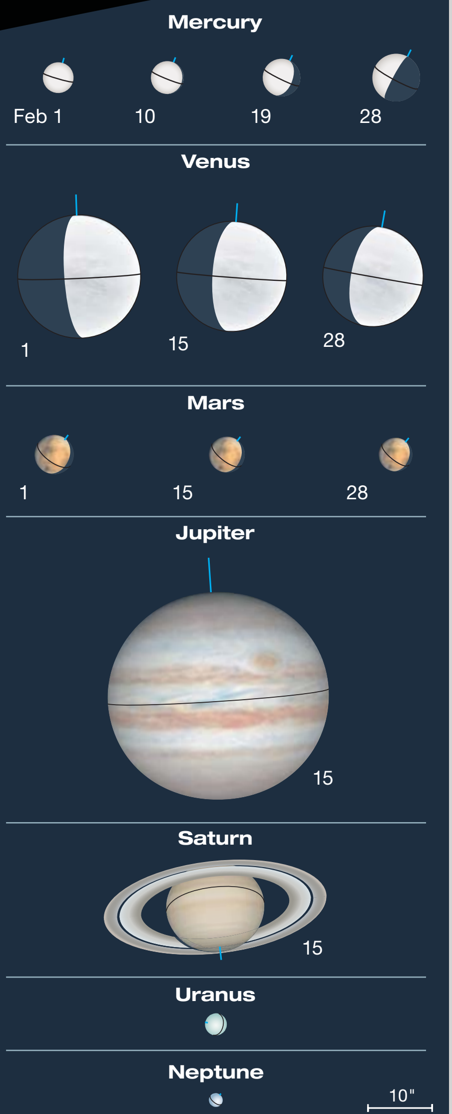
Most of these are main sequence and subgiant stars that lie between 100 and 500 light-years away. Like the members of the Hyades and Pleiades, they're our neighbors in the Orion Spur of the Milky Way. The exception is HD 27639, an *M*-class red giant that lies 2,300 light-years away. HD 27639 forms a tight binary with **HD 27640**. Their separation is only 1.9″, tighter than either component of Epsilon (ε) Lyrae, which makes them a challenge even for telescopes. If you revisit this area with a scope, have a close look at that star chain between HD 27742 and Kappa Tauri, and see if you can spot the 11th-magnitude star that sits exactly halfway between Kappa^1 and Kappa^2 Tauri.

■ MATT WEDEL wonders what else he's missed in the neighborhoods near his favorite objects.

WHEN TO USE THE MAP

Late Dec	11 p.m.
Early Jan	10 p.m.
Late Jan	9 p.m.
Early Feb	8 p.m.
Late Feb	Dusk

These are standard times.



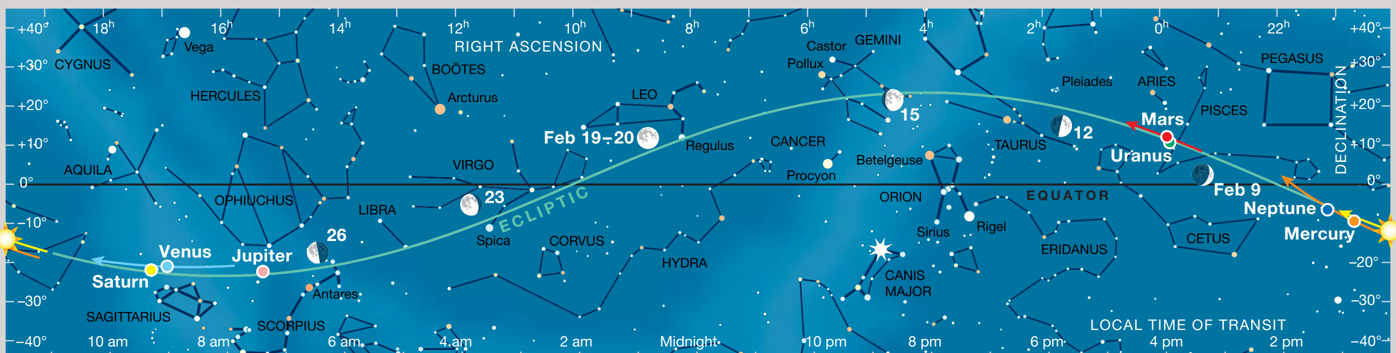
PLANET DISKS have south up, to match the view in many telescopes. Blue ticks indicate the pole currently tilted toward Earth.

PLANET VISIBILITY **Mercury:** visible at dusk after the 12th • **Venus:** visible at dawn all month • **Mars:** visible at dusk, sets before midnight • **Jupiter:** visible at dawn all month • **Saturn:** visible at dawn all month

February Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	$20^h 56.1^m$	–17° 19′	—	–26.8	32′ 28″	—	0.985
	28	$22^h 41.8^m$	–8° 15′	—	–26.8	32′ 18″	—	0.990
Mercury	1	$21^h 03.9^m$	–18° 56′	2° Ev	–1.5	4.8″	100%	1.397
	10	$22^h 06.6^m$	–13° 22′	8° Ev	–1.3	5.1″	96%	1.312
	19	$23^h 04.7^m$	–6° 17′	15° Ev	–1.1	5.9″	80%	1.144
	28	$23^h 45.7^m$	+0° 20′	18° Ev	–0.4	7.4″	44%	0.903
Venus	1	$17^h 44.6^m$	–20° 49′	45° Mo	–4.3	19.2″	62%	0.869
	10	$18^h 28.7^m$	–21° 13′	44° Mo	–4.2	17.8″	66%	0.935
	19	$19^h 13.5^m$	–20° 52′	43° Mo	–4.2	16.7″	69%	1.000
	28	$19^h 58.5^m$	–19° 44′	41° Mo	–4.1	15.7″	72%	1.063
Mars	1	$1^h 15.8^m$	+8° 20′	69° Ev	+0.9	6.1″	89%	1.527
	15	$1^h 51.4^m$	+11° 58′	64° Ev	+1.0	5.7″	90%	1.647
	28	$2^h 25.1^m$	+15° 04′	60° Ev	+1.2	5.3″	91%	1.758
Jupiter	1	$17^h 06.0^m$	–22° 14′	54° Mo	–1.9	33.6″	99%	5.859
	28	$17^h 23.1^m$	–22° 32′	77° Mo	–2.0	36.1″	99%	5.461
Saturn	1	$19^h 03.6^m$	–22° 11′	27° Mo	+0.6	15.2″	100%	10.928
	28	$19^h 15.2^m$	–21° 53′	51° Mo	+0.6	15.6″	100%	10.645
Uranus	15	$1^h 48.5^m$	+10° 38′	63° Ev	+5.8	3.5″	100%	20.282
Neptune	15	$23^h 06.8^m$	–6° 44′	19° Ev	+8.0	2.2″	100%	30.867

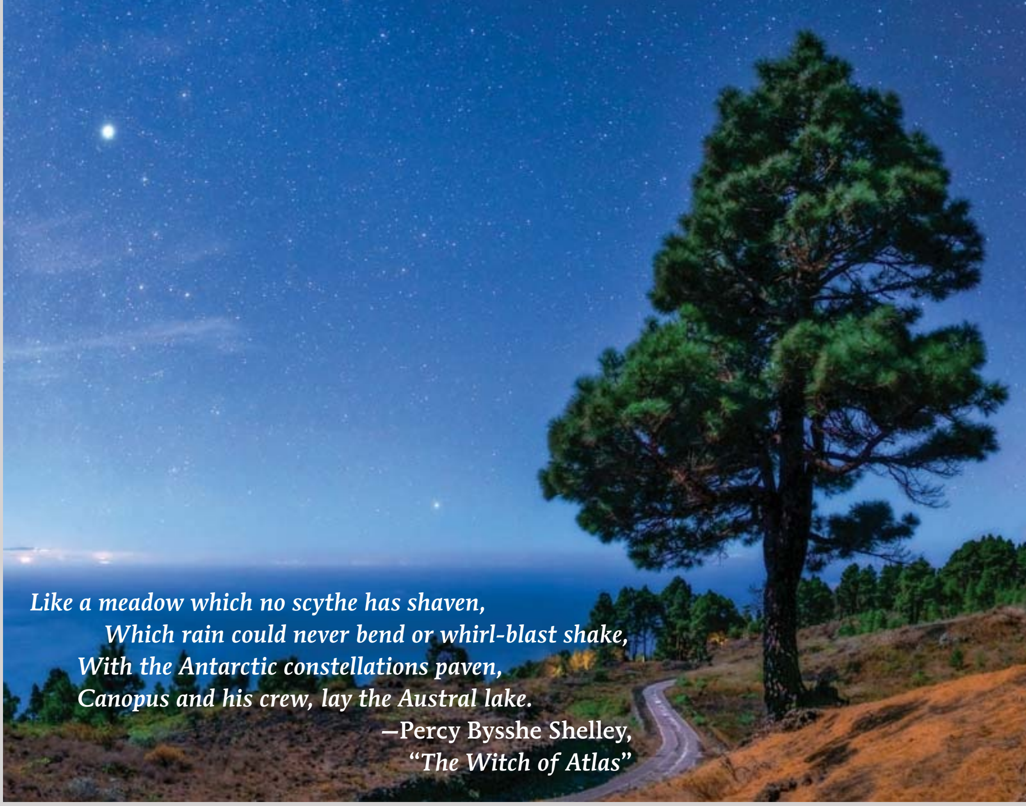
The table above gives each object's right ascension and declination (equinox 2000.0) at 0^h Universal Time on selected dates, and its elongation from the Sun in the morning (Mo) or evening (Ev) sky. Next are the visual magnitude and equatorial diameter. (Saturn's ring extent is 2.27 times its equatorial 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-February; 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.

The Second Star

You may not have (yet) seen the second brightest star in our heavens, but read on to learn more about this intriguing object.



▲ **ON THE HORIZON** From La Palma, in the Canary Islands, Canopus hangs very low on the southern horizon, while Sirius shines higher up.

BABAK TAFRESHI

This month's topic is a star that shines more than half a magnitude brighter than Arcturus. It's even well within a magnitude of matching the peerlessly bright Sirius.

But that only scratches the surface of what's unusual and even unique about this particular object. We're talking about potentially the closest supergiant to us; the only very bright star named after a possibly historic figure; the only object beyond our solar system that our classic interplanetary spacecraft used for navigational guidance; and the only star we know that has *four* separate runs (three in our distant past, one in our distant future) as the brightest star in Earth's night sky.

The star I'm talking about is Canopus.

The second star. In the United States, Chicago is fondly known as "the Second City," and I'm told that Lyon is bestowed (by many) the same title in France. In the heavens, perhaps Canopus should be called "the Second Star."

I say this, of course, because Canopus is second only to Sirius in apparent brightness. This is quite noticeable in some parts of the world because the two stars are fairly close together in the heavens. It's true that Canopus is a full 36° farther south than Sirius, but it's only 5¼° farther west. Canopus comes to its midnight culmination (arrival on the sky's central meridian) on December 27th and its 9 p.m. culmination on February 10th. Both figures are just five days ahead of those for Sirius. Interestingly, from around the rather populous 35°S line of latitude on Earth (which passes near the cities of Sydney, Buenos Aires, and Cape Town) Sirius shines about 20° north of the zenith and Canopus about 20° south of the zenith in February. What a wonderful opportunity for comparison.

How far north is Canopus visible? Of course, in reality, observers at mid-northern latitudes can't make the direct comparison between Sirius and Canopus because the latter is either forever below their southern horizon or low in their southern sky where atmospheric extinction is great. From places like southern Florida and southernmost Texas, Canopus climbs no higher than about 10° or 12° — where even on a very clear night it's dimmed by about a magnitude and therefore looks only about as bright as Procyon.

But how far north is Canopus visible at all? The limit without refraction in our atmosphere should be about 37°N. I know observers in South Carolina who see Canopus. But have any of you observing in the mountains of North Carolina seen it, at least with optical aid?

The nature of Canopus. Canopus is believed to lie about 310 light-years from Earth and shines with an absolute magnitude of –5.7 and a luminosity of 15,000 times that of the Sun. It's probably a rare *F*-type supergiant (the spectrum is usually given as *F*0Ib; but note that some sources classify it as *F*0II and *A*9II, placing it in the bright giant category). Based on its luminosity, its mass is estimated to be 8 to 10 times that of the Sun, which is borderline for it to go supernova. Its ultimate fate may be to end up like Sirius B: a more massive-than-average — and possibly even a rare neon-oxygen — white dwarf.

Next month — Canopus continued. It's only fitting that the "Second Star" gets a second column. So next month we'll discuss the color of Canopus, the origin of its name, the reason for it being the unique navigational star for interplanetary spacecraft — and more. We'll also discuss the remnants of Canopus's original constellation, Argo — including the parts that can be seen well from mid-northern latitudes.

■ Contributing Editor **FRED SCHAAF** first learned about phenomena of atmospheric optics from the Dover Publications edition of Marcel Minnaert's classic *The Nature of Light and Color in the Open Air*.

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

Dawn Triplet

A trio of bright planets adorns the dawn skies in February, while Mercury joins Mars mid-month to grace the evening skies.

This February, the only bright planet visible in the evening sky all month long is Mars, which doesn't set until the midnight hour is approaching. However, for the second half of February, tiny Mercury can be observed low in the west during evening twilight. Meanwhile, all month at dawn, a string of three prominent planets — Jupiter, Venus, and Saturn — decorates the sky in the southeast. Majestic Jupiter is highest to the upper right in the line all month. Venus starts the month as the middle planet of the three. But the brilliant world closes the gap between itself and Saturn until a close conjunction between the two on February 18th, after which Venus is increasingly farther to the lower left of the ringed planet.

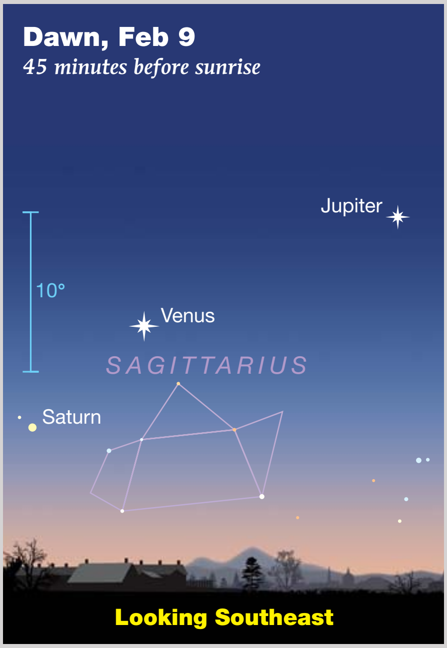
DUSK

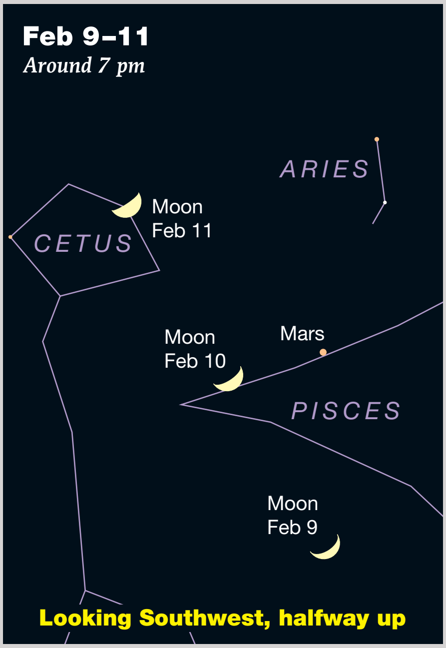
Mercury was at superior conjunction with the Sun on the night of January 29–30. Though bright, it doesn't get high enough to see in evening twilight until about February 12th. Look for the speedy planet low in the west; it appears a little bit farther above the horizon at each dusk. Although Mercury's magnitude dims from around –1.2 to –0.2 during the second half of February, the lapse between sunset and Mercury-set grows to about 1½ hours. Mercury reaches a greatest eastern elongation of 18° from the Sun on the American evening of February 26th. Around that date, Mercury stands about 8° or 9° above the horizon 45 minutes after sunset, and its 7″ wide disk is about half-lit.

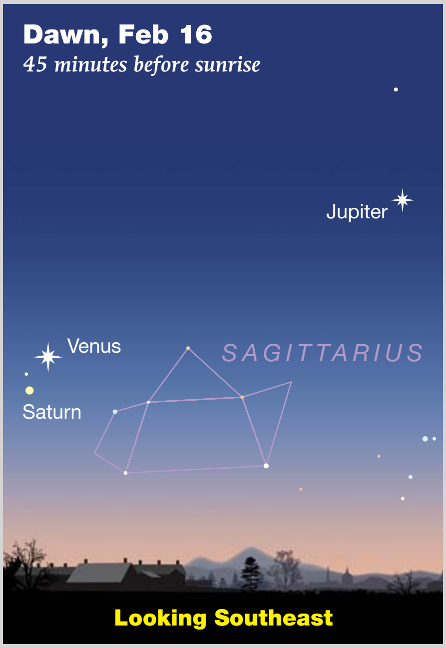
Neptune starts setting too soon after the Sun to observe by mid-month.

EVENING

Mars shines fairly high in the southwest after dusk has faded out and sets around 11 p.m. Since its glorious close approach to Earth last July, Mars has dimmed by almost four magnitudes, and its disk has shrunk to only one-quarter of its maximum width. The magnitude of Mars this month lessens from +0.9 to +1.2, while its apparent diameter decreases from more than 6″ to less than 5½″. This is too small to show any surface features in most amateur telescopes, though you might notice the planet's shadowed edge make it look slightly out-of-round this month. Mars crosses the boundary line from

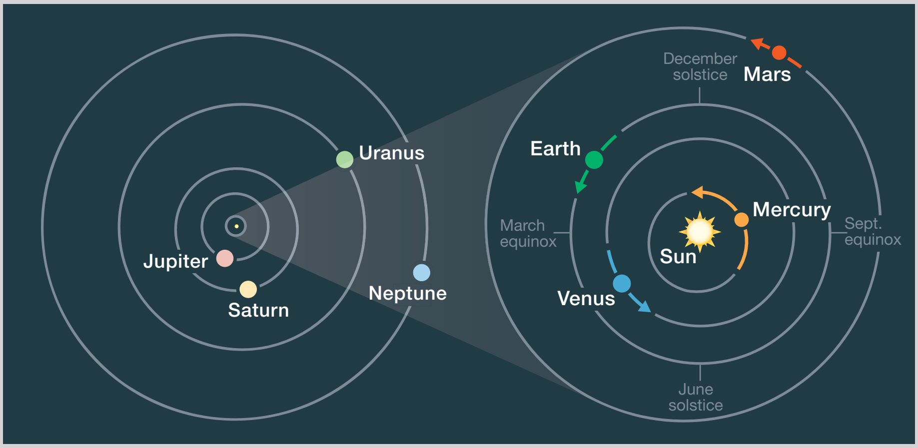






Pisces into Aries at mid-month and has a close conjunction with Uranus.

On February 12th, look for **Uranus** a little more than 1° south of Mars. Compare the disks of the two in your telescope. Magnitude-5.8 Uranus is only about 3½″ wide, and its low-surface-brightness globe of blue or green contrasts greatly with the more intensely lighted and bigger-looking orange globe of Mars.



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

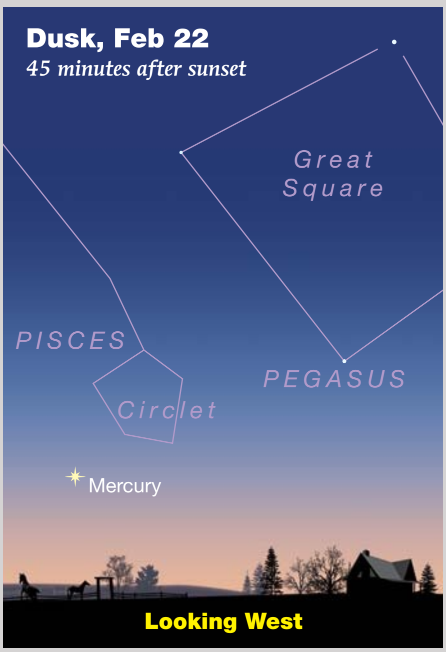
PRE-DAWN AND DAWN

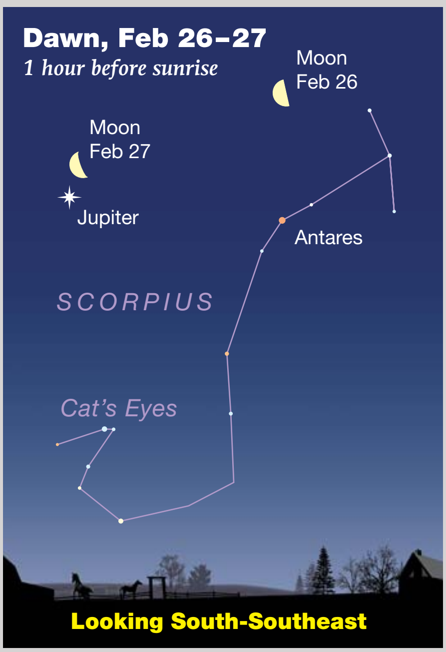
Jupiter comes up in the southeast after 3:30 a.m. as February begins but almost as early as 2 a.m. by month's end. Jupiter's rising breaks the drought of several hours of having no planets above the horizon. The king of the planets burns in Ophiuchus near Scorpius. Its magnitude improves from –1.9 to –2.0 this month, and telescopes show its globe grow from 33½″ to 36″ wide.

Venus rises more than 30 minutes after Jupiter at the start of February but is starting to fall back towards our line of sight with the Sun, while Jupiter's elongation from the Sun keeps increasing. By month's end Venus comes up about 2½ hours after Jupiter. Venus dims from magnitude –4.3 to –4.1 this month as it races across Sagittarius. Its disk shrinks from 19″ to 16″ in February, and its phase increases from 62% to 72%.

Saturn has a close conjunction with Venus — with just 1° separating the two — on the American morning of February 18th. Thus Saturn switches places with Venus in the line with Jupiter. At the start of February Saturn rises 1½ hours before the Sun and about 85 minutes after Venus. But at month's end Saturn precedes the Sun by more than 2½ hours and Venus by about 40 minutes. Saturn remains at magnitude +0.6 all month and grows the slightest in apparent diameter, but its globe is still less than 16″ wide, similar in size to the lit part of Venus when they are in conjunction this month. The glorious rings now span 35″ wide and are tilted a generous 24° from horizontal.

▼ 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.





MOON PASSAGES

The Moon shines as a slender waning crescent halfway between Venus and Saturn at dawn on February 1st and is 3° lower left of Saturn the next day. A thick waning lunar crescent is 6° lower left of Mars on the evening of February 10th. The Moon is at perigee (closest to Earth in space) on the American morning of February 19th, only about 7 hours before the moment of the full Moon. The Moon is exactly at last quarter when 8° due north of Antares at the American dawn of February 26th. The Moon glows 2½° above Jupiter on February 27th and almost halfway between Jupiter and Saturn the next morning.

■ Contributing Editor **FRED SCHAAF** is the author of *The 50 Best Sights in Astronomy and How to See Them*, published by John Wiley & Sons in 2007.

Echoes from a Variable Star

RS Puppis continues to delight astronomers more than 120 years after its true nature was discovered.

The thick cloak of nebulosity that surrounds RS Puppis makes the star unique among Cepheid variables. These dust clouds reveal "light echoes" of the star's pulsations. The echoes have to travel farther, so they arrive at Earth later than does the starlight.

On these midwinter nights, the constellation Puppis wheels slowly across the southern horizon. Divorced from the larger constellation Argo Navis by the pen of Nicolas-Louis de Lacaille during his voyage of 1750–1754, Puppis represents the ship's stern, floating aft of Canis Major. Puppis remains somewhat unfamiliar to many northern skywatchers: Our scopes seem to stop at Canis Major, possibly because the brightest stars in Puppis — Zeta (ζ), Rho (ρ), and Pi (π) — are no match for Sirius. But Puppis does hold some intriguing stellar sights, namely, the variable star **RS Puppis**.

RS Puppis is easy to find and remains relatively bright throughout its period of variability. A line extended from Delta (δ) CMa through the tip of the Big Dog's tail, Eta (η) CMa, across Puppis leads to the star's general location. Begin your star-hop from Zeta Pup, moving 3° north-northeast from the star to the open cluster NGC 2546. From this scattering of stars continue about 2° north-northeast to find a delicate stellar arc that curves northward to RS Pup.

RS Pup's variability was detected in 1897 by Ms. Reitsma, an observatory assistant at the University of Groningen, during her examination of Cape Photographic Durchmusterung (CPD) plates from 1888 and 1890. The star's variability was confirmed visually in 1897–1898 by Alexander W. Roberts, observing from Lovedale Observatory, South Africa, and R. T. A. Innes, observing from the Royal Observatory, Cape of Good Hope. From this, David Gill, His Majesty's Astronomer at the Cape of Good Hope, concluded that the star's brightness varied from 6.8 to 7.9. His numbers are very close to today's estimations: Over a period of 41.3 days, RS Puppis dims gradually to magnitude 7.67 before rapidly rising to magnitude 6.52.

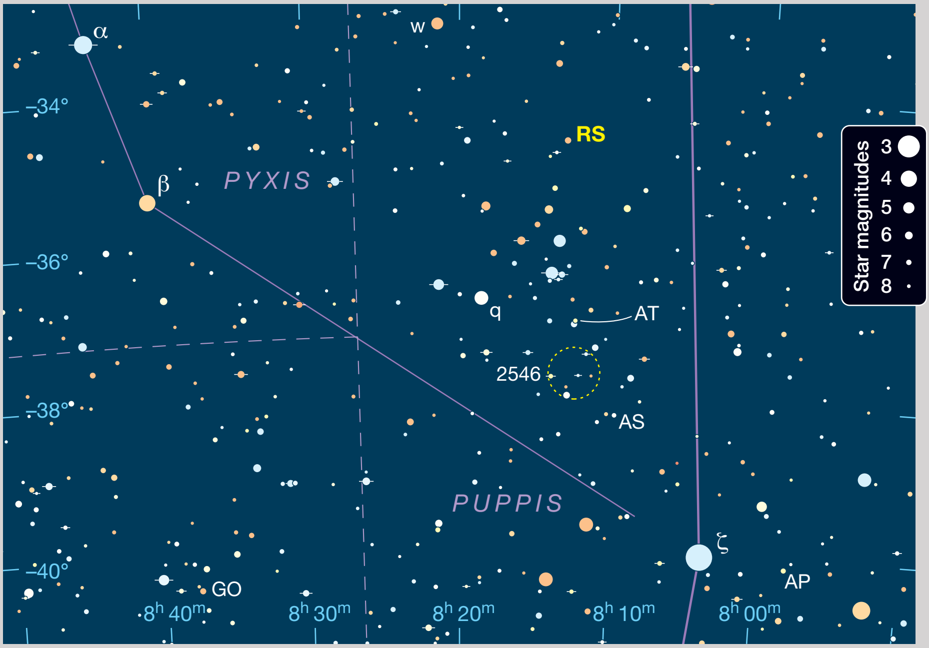
The shape of RS Pup's light curve reveals that it's a Cepheid variable; the relationship between its luminosity (intrinsic brightness) and period of variability is directly proportional. The longer a Cepheid's period, the more luminous it is. RS Pup turns out to have one of the longest periods of any Cepheid in our galaxy, so it's also one of the most luminous Cepheids discovered.

Although Cepheids are famous for their utility in measuring galactic distances (using the period-luminosity relation, astronomers can determine a Cepheid's absolute magnitude, and from that, along with its apparent magnitude, calculate the distance), there remains some uncertainty about the distance to RS Pup. In 1961, Bengt Westerlund (Uppsala Southern Station) discovered that RS Pup is embedded in a reflection nebula, parts of which exhibit a variation in brightness related to the star's pulsation period. In 2008, astronomers using the European Southern Observatory's New Technology Telescope geometrically analyzed these "light echoes" in the nebula and determined the distance to RS Pup to be close to 6,500 light-years. Geometric analyses based on Hubble Space Telescope data shaved about 300 light-years off that number in 2014. A geometric parallax measurement based on the Gaia Data Release 2 dropped the distance to about 5,600 light-years.

It's fun to think about RS Pup "getting closer," but its distance doesn't make any practical difference for backyard observing. But because the star's period is long, it's useful to watch it over the course of a couple months. This is an easier task for those who live in the Southern Hemisphere, but it's not out of the question for observers in the north. In January, RS Pup is a late riser, transiting around 2:00 a.m. local standard time on New Year's morning. In mid-January, it shines about 15° above the southern horizon as it culminates an hour after midnight. Observing conditions improve as February begins, with the star gaining another degree of altitude before it transits near midnight. At mid-month, RS Pup's altitude has dropped 1°, but culmination occurs near 11 p.m. By the end of February, RS Pup transits at a convenient 10 p.m., but you'll probably be scraping the edges of your observing zone as it stands only 12° at its highest.

If observing variable stars is just your thing, consider participating in an observing campaign led by the American Association of Variable Star Observers (AAVSO); visit **aavso.org/observers** for more information.

FURTHER READING: To watch a time-lapse of the light echoes around RS Puppis as captured by the Hubble Space Telescope during a 5-week observation period, visit **spacetelescope.org/videos/heic1323a**.



▲ The variable star RS Puppis lies 5¾° north-northeast of the 2.3-magnitude star Zeta Puppis.

Asteroid Occultation

EARLY ON THE MORNING of February 11th, the 15.5-magnitude asteroid **301 Bavaria** temporarily blocks the light of a 9.3-magnitude star for observers in parts of North America. The occulted *F6/F7*-type main-sequence star, HD 144893 (HIP 79094), lies 390 light-years away in the direction of Scorpius. At the time of occultation, 301 Bavaria, a 55.5-km-wide main belt asteroid, will be about 2.6 astronomical units from Earth. The occultation lasts a maximum of 2.3 seconds.

Johann Palisa, observing from the University of Vienna with a 27-inch f/15.4 Grubb refractor, discovered 301 Bavaria on November 16, 1890. It was his 75th asteroid discovery. The asteroid's Germanic name was suggested the next year by Benjamin Gould, founder of the *Astronomical Journal*. He proposed using the designation to commemorate the August 1891 meeting of the German Astronomical Society (*Astronomische Gesellschaft*) in Munich, Bavaria's capital.

The predicted path of visibility crosses North America from Colorado through South Carolina to Bermuda. The region of visibility for an occultation of a star by an asteroid (minor planet) can be uncertain by about 0.5 path widths (pw) for most events. In this case, the uncertainty is 0.35 pw, meaning the path may actually be a bit narrower or broader. Multiple observations from across (and beyond) the predicted path will produce a more accurate outline of 301 Bavaria's shape.

The 6.2-magnitude drop in brightness should occur within a minute or two of 10:17 UT for observers in the central United States (3:17 MST for Fort Collins, 4:17 CST for Kansas City and Nashville) and within a minute or two of 10:18 UT for those in the southeast (5:18 EST for Charleston). The involved star, which shines about 3½° north-northeast of Nu (ν) Scorpii, stands fairly high at these times, around 20° high for Kansas and 35° high for South Carolina.

Precise predictions and a path map are available from Steve Preston's minor-planet occultation website (**asteroidoccultation.com**). For more on planning your observations, setting up your equipment, and reporting your results, visit the International Occultation Timing Association (IOTA) website (**occultations.org**). Asteroid and lunar occultation enthusiasts may also join an active online discussion group at **groups.yahoo.com/neo/groups/IOTA-occultations**.

Minima of Algol

Jan.	UT	Feb.	UT
3	15:53	1	8:06
6	12:42	4	4:55
9	9:32	7	1:45
12	6:21	9	22:34
15	3:10	12	19:23
17	23:59	15	16:13
20	20:49	18	13:02
23	17:38	21	9:51
26	14:27	24	6:41
29	11:17	27	3:30

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

● **FIND YOUR CLUB:** **skyandtelescope.com/astronomy-clubs-organizations**

Action at Jupiter

JUPITER SHINES in Ophiuchus on February mornings, rising before 4 a.m. local standard time. As its westward elongation increases through the month, the giant planet rises a bit earlier. Jupiter grows bigger and bolder every morning, brightening from magnitude –1.9 to –2.0 and fattening from 33½″ to 36″ wide by the 28th.

Any telescope shows the four big Galilean moons, and binoculars usually show at least two or three. Use the diagram on the facing page to identify them at any date and time. The dates at the diagram's left are in Universal Time.

Virtually any telescope shows the interaction of the Galilean moons and their shadows with Jupiter. All of the February interactions are tabulated on the facing page. Find events timed for when Jupiter is at its highest in the early morning hours.

More aperture and steady seeing will reveal Jupiter's Great Red Spot (GRS). Here are the times, in UT, when the GRS should cross Jupiter's central meridian. The dates, also in UT, are in bold. (Eastern Standard Time is UT minus 5 hours.)

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

Feb. 1, 3:55, 13:50, 23:46; **2,** 9:42, 19:38; **3,** 5:33, 15:29; **4,** 1:25, 11:21, 21:16; **5,** 7:12, 17:08; **6,** 3:04, 12:59, 22:55; **7,** 8:51, 18:47; **8,** 4:42, 14:38; **9,** 0:34, 10:29, 20:25; **10,** 6:21, 16:17; **11,** 2:12, 12:08, 22:04; **12,** 8:00, 17:55; **13,** 3:51, 13:47, 23:43; **14,** 9:38, 19:34; **15,** 5:30, 15:25; **16,** 1:21, 11:17, 21:13; **17,**

7:08, 17:04; **18,** 3:00, 12:56, 22:51; **19,** 8:47, 18:43; **20,** 4:38, 14:34; **21,** 0:30, 10:26, 20:21; **22,** 6:17, 16:13; **23,** 2:08, 12:04, 22:00; **24,** 7:56, 17:51; **25,** 3:47, 13:43, 23:38; **26,** 9:34, 19:30; **27,** 5:25, 15:21; **28,** 1:17, 11:13, 21:08.

These times assume that the spot will be centered at System II longitude 294°. If the Red Spot has moved elsewhere, it will transit 1⅔ minutes earlier for each degree less than 294° and 1⅔ minutes later for each degree more than 294°.

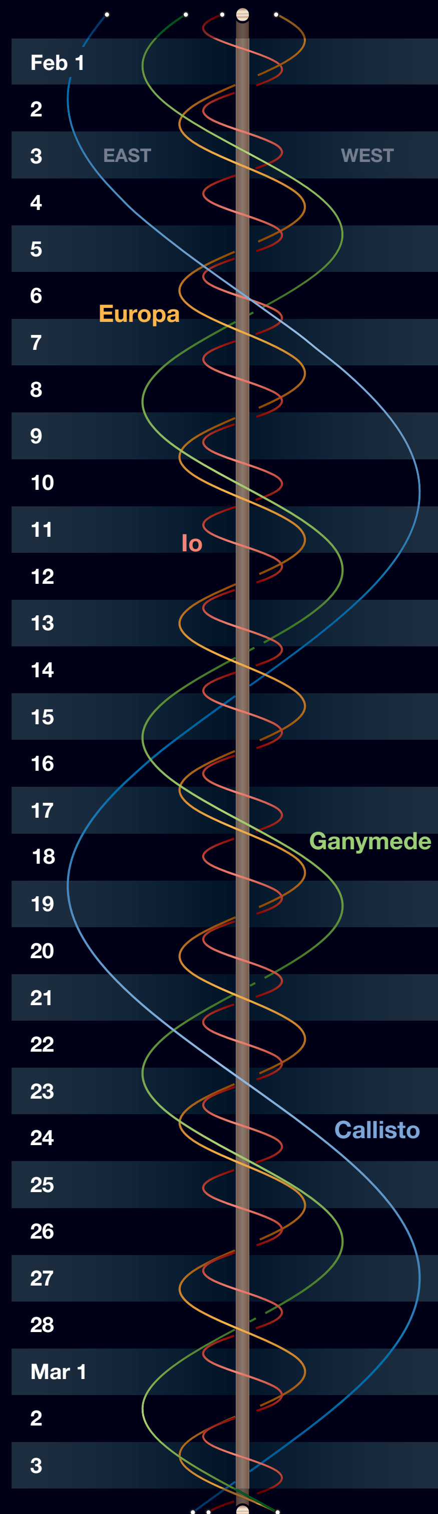
Features on Jupiter appear closer to the central meridian than to the limb for 50 minutes before and after transiting. A blue or green filter increases the contrast and visibility of Jupiter's reddish and brownish markings.

Phenomena of Jupiter's Moons, February 2019

Feb. 1	3:20	I.Sh.I
	4:20	I.Tr.I
	5:30	I.Sh.E
	6:31	I.Tr.E
	19:16	II.Ec.D
	23:45	II.Oc.R
Feb. 2	0:38	I.Ec.D
	3:50	I.Oc.R
	21:48	I.Sh.I
	22:50	I.Tr.I
	23:59	I.Sh.E
Feb. 3	1:01	I.Tr.E
	4:13	III.Sh.I
	6:14	III.Sh.E
	8:22	III.Tr.I
	10:30	III.Tr.E
	14:15	II.Sh.I
	16:17	II.Tr.I
	16:35	II.Sh.E
	18:40	II.Tr.E
	19:06	I.Ec.D
	22:20	I.Oc.R
Feb. 4	16:17	I.Sh.I
	17:19	I.Tr.I
	18:27	I.Sh.E
	19:30	I.Tr.E
Feb. 5	8:34	II.Ec.D
	13:08	II.Oc.R
	13:35	I.Ec.D
	16:49	I.Oc.R
Feb. 6	10:45	I.Sh.I
	11:49	I.Tr.I
	12:56	I.Sh.E
	14:00	I.Tr.E
	18:25	III.Ec.D
	20:29	III.Ec.R
	22:43	III.Oc.D
Feb. 7	0:53	III.Oc.R
	3:32	II.Sh.I
	5:38	II.Tr.I
	5:52	II.Sh.E
	8:01	II.Tr.E
	8:03	I.Ec.D
	11:18	I.Oc.R
Feb. 8	5:14	I.Sh.I
	6:18	I.Tr.I
	7:24	I.Sh.E
	8:29	I.Tr.E
	21:51	II.Ec.D
Feb. 9	2:30	II.Oc.R
	2:31	I.Ec.D
	5:48	I.Oc.R
	23:42	I.Sh.I
Feb. 10	0:48	I.Tr.I
	1:53	I.Sh.E
	2:59	I.Tr.E
	8:10	III.Sh.I
	10:12	III.Sh.E
	12:37	III.Tr.I
	14:45	III.Tr.E
	16:49	II.Sh.I
	18:58	II.Tr.I
	19:09	II.Sh.E
	20:59	I.Ec.D
	21:21	II.Tr.E
Feb. 11	0:17	I.Oc.R
	18:10	I.Sh.I
	19:17	I.Tr.I
	20:21	I.Sh.E
	21:28	I.Tr.E
Feb. 12	11:09	II.Ec.D
	15:28	I.Ec.D
	15:52	II.Oc.R
	18:46	I.Oc.R
Feb. 13	12:39	I.Sh.I
	13:46	I.Tr.I
	14:49	I.Sh.E
	15:57	I.Tr.E
	22:22	III.Ec.D
Feb. 14	0:27	III.Ec.R
	2:56	III.Oc.D
	5:07	III.Oc.R
	6:05	II.Sh.I
	8:18	II.Tr.I
	8:26	II.Sh.E
	9:56	I.Ec.D
	10:41	II.Tr.E
	13:15	I.Oc.R
Feb. 15	7:07	I.Sh.I
	8:16	I.Tr.I
	9:18	I.Sh.E
	10:27	I.Tr.E
Feb. 16	0:27	II.Ec.D
	4:24	I.Ec.D
	5:13	II.Oc.R
	7:44	I.Oc.R
Feb. 17	1:36	I.Sh.I
	2:45	I.Tr.I
	3:46	I.Sh.E
	4:56	I.Tr.E
	12:09	III.Sh.I
	14:12	III.Sh.E
	16:50	III.Tr.I
	18:59	III.Tr.E
	19:22	II.Sh.I
	21:38	II.Tr.I
	21:42	II.Sh.E
	22:52	I.Ec.D
Feb. 18	0:01	II.Tr.E
	2:13	I.Oc.R
	20:04	I.Sh.I
	21:14	I.Tr.I
	22:15	I.Sh.E
	23:25	I.Tr.E
Feb. 19	13:45	II.Ec.D
	16:08	II.Ec.R
	16:09	II.Oc.D
	17:21	I.Ec.D
	18:35	II.Oc.R
	20:42	I.Oc.R
Feb. 20	14:32	I.Sh.I
	15:43	I.Tr.I
	16:43	I.Sh.E
	17:54	I.Tr.E
Feb. 21	2:19	III.Ec.D
	4:24	III.Ec.R
	7:06	III.Oc.D
	8:38	II.Sh.I
	9:17	III.Oc.R
	10:58	II.Tr.I
	10:59	II.Sh.E
	11:49	I.Ec.D
	13:20	II.Tr.E
	15:11	I.Oc.R
Feb. 22	9:01	I.Sh.I
	10:12	I.Tr.I
	11:11	I.Sh.E
	12:23	I.Tr.E
Feb. 23	3:02	II.Ec.D
	5:25	II.Ec.R
	5:29	II.Oc.D
	6:17	I.Ec.D
	7:55	II.Oc.R
	9:40	I.Oc.R
Feb. 24	3:29	I.Sh.I
	4:41	I.Tr.I
	5:40	I.Sh.E
	6:52	I.Tr.E
	16:06	III.Sh.I
	18:10	III.Sh.E
	20:59	III.Tr.I
	21:55	II.Sh.I
	23:08	III.Tr.E
Feb. 25	0:15	II.Sh.E
	0:17	II.Tr.I
	0:45	I.Ec.D
	2:39	II.Tr.E
	4:09	I.Oc.R
	21:58	I.Sh.I
	23:10	I.Tr.I
Feb. 26	0:08	I.Sh.E
	1:21	I.Tr.E
	16:20	II.Ec.D
	18:44	II.Ec.R
	18:50	II.Oc.D
	19:14	I.Ec.D
	21:16	II.Oc.R
	22:38	I.Oc.R
Feb. 27	16:26	I.Sh.I
	17:39	I.Tr.I
	18:37	I.Sh.E
	19:50	I.Tr.E
Feb. 28	6:16	III.Ec.D
	8:23	III.Ec.R
	11:11	II.Sh.I
	11:13	III.Oc.D
	13:25	III.Oc.R
	13:32	II.Sh.E
	13:35	II.Tr.I
	13:42	I.Ec.D
	15:58	II.Tr.E
	17:07	I.Oc.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 5 hours ahead of Eastern Standard Time). Next is the satellite involved: **I** for Io, **II** Europa, **III** Ganymede, or **IV** Callisto. Next is the type of event: **Oc** for an occultation of the satellite behind Jupiter's limb, **Ec** for an eclipse by Jupiter's shadow, **Tr** for a transit across the planet's face, or **Sh** for the satellite casting its own shadow onto Jupiter. An occultation or eclipse begins when the satellite disappears **(D)** and ends when it reappears **(R)**. A transit or shadow passage begins at ingress **(I)** and ends at egress **(E)**. Each event is gradual, taking up to several minutes. Predictions courtesy IMCCE / Paris Observatory.

Jupiter's Moons



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

It All Depends on Dikes

The appearance of volcanic lunar features has everything to do with what was happening below the surface eons ago.

Volcanic landforms, such as sinuous rilles, domes, cones, dark-halo craters, floor-fractured craters, pyroclastic deposits, and even young lava flows are often favorite targets for lunar observers. Scientists have published many studies describing the morphologic characteristics and possible origins for these volcanic features. Recently, Lionel Wilson (Lancaster University, U.K.) and James Head (Brown University) have proposed a conceptual model that links all these lunar volcanic landforms with different stages in the rise and eruption of magma. While their formal publications are detailed and massive — Head calls one a "doorstop" — a general awareness of their model will enrich your observing with understanding and wonder.

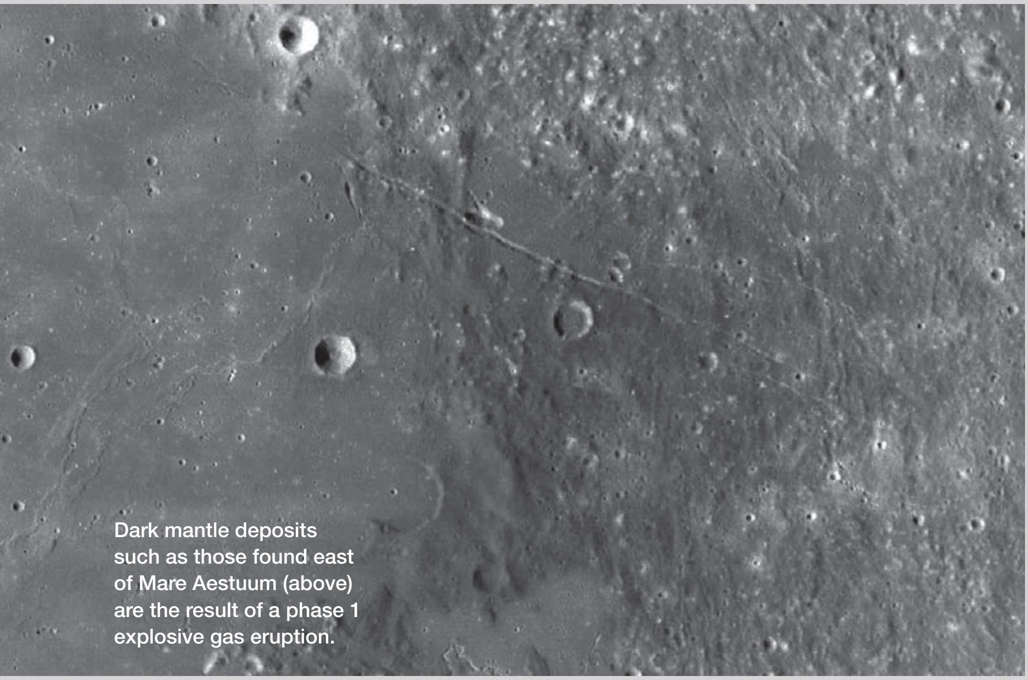
Magma is generated deep within the lunar mantle, and large blobs of it known as *diapirs* ascend to within a few hundred kilometers of the surface. The continuing upwelling of additional magma into the diapir increases the pressure at its top until the overlying brittle crustal rocks crack, and a dike of magma fractures its way towards the surface. Whether this dike reaches the lunar surface and what kind of eruption it produces depend on several factors, such as the volume of magma, its eruption rate, duration, and gas content, as well as the period in lunar history that it occurred.

A dike is much smaller than the diapir it ascends from, but it may still be enormous. Wilson and Head calculate that a dike feeding a large eruption may be shaped like a giant penny, 60 to 100 kilometers (37 to 62 miles) high and wide but less than 100 meters thick. If a dike from a diapir is stalled relatively near the surface, it can maintain a connection to its source region, but dikes that rise from greater depths detach from their feeder diapirs and fracture their way upward in just a few hours — imagine the Moon quakes!

Wilson and Head propose that once the dike reaches the surface, there are four phases of eruption, and the resulting landforms directly relate to how much of the dike is in the mantle and how much is in the crust. Magma in the mantle is less dense and more buoyant than the surrounding rocks. The crust is likely to be lower density than the dike magma, which tends not to rise upward but is still pushed up by the magma rising through the mantle.

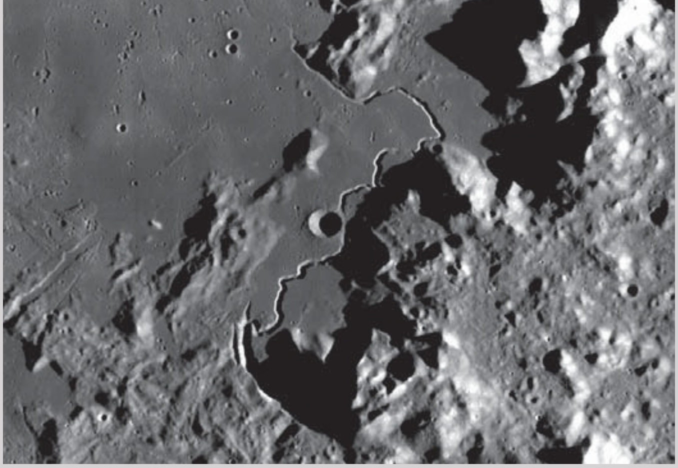
The first phase occurs when the top of a dike first penetrates the surface, and gas explosively erupts into space. Without wind, the entrained microscopic magma droplets follow ballistic paths, creating a thin circular rain of pyroclastic debris around the dike breech. Some of this forms dark mantle deposits, like those seen east of **Sinus Aestuum**, and also widely dispersed glass beads. The dike penetrates the surface at a single point, but as it continues to ascend it creates a fissure typically 15 km long, with pyroclastics and, later, lava streaming out.

Following the explosive degassing, phase 2 consists of rapid eruption of large volumes of lava as the entire dike continues upsurging. Giant fire fountains discharge magma as rapidly as one million cubic meters per second. When the individual droplets of lava hit the surface, they are still extremely hot and coalesce into a lava lake that ultimately flows over the lowest topographic barrier and races downslope, sometimes for hundreds of kilometers. If the eruption is short-lived, it produces a single lava flow complex. But if it's longer, say, a week or more in duration, the lava erodes down into underlying material and rapidly cuts a sinuous rille, such



Dark mantle deposits such as those found east of Mare Aestuum (above) are the result of a phase 1 explosive gas eruption.

NASA / GSFC / ARIZONA STATE UNIVERSITY (4)



▲ *Left:* Hadley Rille was formed when large volumes of lava flowed for a week or more, eroding a sinuous channel in the underlying strata. *Right:* Some phase 4 eruptions produce dikes that spread laterally beneath impact craters, forcing their surfaces upward and fracturing the floors like that of Vitello crater located in the southwestern lunar quadrant.

▲ The Marius Hills formed when the eruption rate of a dike's magma slowed sufficiently to result in the building of discrete pyroclastic cones like the ones seen here.

as **Hadley Rille** seen at the Apollo 15 landing site.

In phase 3, more than half of the dike's magma is now located in the crust, decreasing its buoyancy and drastically slowing its eruption. Additionally, the magma starts to cool, and the dike sidewalls begin to contract, because the magma's pressure is not as high as earlier. All of this slowing of movement gives time for gas bubbles within the magma to coalesce into single voids that grow as wide as the dike. This stops the continuous eruption of magma, breaking it up into individual pulses, each erupting a discrete layer of pyroclastic material. Small, abundant pyroclastic cones form, much like those found in the **Marius Hills**.

The dike continues to close during phase 4, restricting the eruption of pyroclastic particles, but lava flows are still pushed out, often rich with *vesicles* — hollows that once contained gas bubbles. Some of these flows are short, building up low domes around the vent, such as the well-known ones near **Hortensius** and **Milicius** craters. In one case, a small circular lava pond was built up and the escape of gas in lateral feeding dikes caused collapse pits along rilles, and a caldera collapsed at the summit — this, of course, is **Hyginus**.

Some dikes intrude into brecciated spaces beneath impact craters and spread laterally. In craters smaller than about 40 km across, the center of the lava pile tends to thicken (a laccolith), pushing up and deforming the floor of the crater. In larger craters, the inflowing lava forms a *sill* — a flat slab of lava — elevating the entire floor but with less central deformation. An example of a smaller floor-fractured crater is **Vitello** in southern Mare Humorum; **Humboldt** near the eastern limb is larger and has a flat, shallow floor. In cases such as **Plato**, **Archimedes**, and **Hercules**, rising lava finds an easy path to the surface, submerging the craters' floors and central peaks with smooth ponds of lava.

Earlier I mentioned that the period in lunar history in which a dike forms was critical for its future. Evidence suggests that during its first billion years, heat left over from the accretion of the Moon, in addition to heat generated from the decay of radioactive minerals, put the early Moon into an extensional stress pattern, stretching the lunar crust. This made it easier for cracks to propagate from diapirs to the surface. Additionally, the warm Moon could partially melt portions of the mantle more readily, generating voluminous amounts of magma. This theoretical conclusion is consistent with the fact that most lunar mare lavas were erupted between 3.9 and 3.1 billion years ago, and most sinuous rilles formed before 3 billion years ago.

As the early Moon cooled, its interior contracted slightly, creating a compressional environment that inhibited mantle fracturing and dike formation. Small amounts of lava did reach the surface between 2 to 3 billion years ago, and even tinier amounts erupted until about a billion years ago, testifying that despite magma source regions becoming smaller and deeper, lithosphere thickening, and a more compressive mantle structure, a few dikes did reach the surface in special circumstances. The paucity or even complete absence of younger volcanic features makes it doubtful that transient lunar phenomena or irregular mare patches are associated with young volcanism. Perhaps we will be surprised someday, but the Moon seems to be volcanically dead. For an observer spotting traces of ancient volcanism, however, the moment is alive with awe.

■ Contributing Editor **CHUCK WOOD** is sorry to have missed seeing the surges of lava flows spreading across Mare Imbrium. For more on lunar dikes see Wilson and Head paper at **https://is.gd/lunardikes**.

Several observers independently discovered the open cluster M41, including Giovanni Hodierna (before 1654), John Flamsteed (1702), Le Gentil (1749), and finally Charles Messier (1765). The cluster has about 100 member stars.

ALAN DYER / STOCKTREK IMAGES / GETTY IMAGES

The Dog Star's Realm

The brilliant beacon of winter leads us to wonderful things.

When wooded knoll is white with snow
And Boreas's breezes blow,
When early fades Sol's afterglow,
Resplendent, scintillating low,
The winter's dogstar beams.

Unrivalled, solitary, bright
As brilliant beacon's blazing light
Or diamond in the dome of night,
Resplendent and transcendent sight,
The evening's dogstar gleams.

— Charles Nevers Holmes,
Canicula, 1918

As the brightest star in the night sky, the Dog Star immediately draws the eye whenever it graces the heavens. This brilliant beacon doesn't journey alone through space. Although variations in the motion of **Sirius** led Friedrich Bessel to propose a companion star in 1844, it remained unseen until famed telescope-maker Alvan Clark noticed it while using Sirius to test a new 18.5-inch lens in 1862. Our Dog Star's little companion is affectionately known as the Pup.

You won't need an 18.5-inch scope to see the Pup, but you'll certainly need good seeing: atmospheric steadiness, as well as a scope that's at the outdoor temperature and not aimed above heat-emitting objects such as roofs or pavement. At my home, Sirius is low in the sky and rarely offers the atmospheric calm I often enjoy with objects at greater altitudes, so I've confined most of my Pup quests to times at the Winter Star Party in the Florida Keys.

My most recent successes came with my 130-mm refractor and 10-inch reflector. In the refractor at 273×, the 8.4-magnitude Pup looked faint next to blazing Sirius, but it stood out much better on steadier nights through the reflector at 299× and 427×. High magnifications are required to pull the Pup away from the overwhelming glare of Sirius. The Pup is one of the few white dwarf stars visible to the average backyard scope. If you manage to nab it, keep in mind that the Pup is approximately the mass of our Sun, yet only 90% as big across as the Earth. Its big brother Sirius is about twice the mass of our Sun and 1.7 times as big across, sparkling at us from a neighborly distance of 8.6 light-years.

If you've never seen the Pup, this is a good time to start looking. Following their 50.1-year orbit, the stars are currently 11.09″ apart, with the Pup east-northeast of Sirius. To determine direction, let Sirius drift from the center to the edge of your field of view. The direction of the motion is west; therefore, the Pup will be nearly on the opposite side of Sirius. The separation is widening and will be at its maximum of 11.33″ from early 2022 to mid-2023, and then it will narrow toward a minimum of 2.54″ in 2043.

Much easier quarry dangles 4° south of Sirius in the guise of **Messier 41**. This large open cluster is neatly framed through the 130-mm scope at 37×, displaying 50 bright to faint stars penned into 40′. The stars are most concentrated within the group's central 15′, a region embellished with several colorful stars. The most prominent include the two bright stars near the center, yellow-orange and yellow, and three slightly dimmer golden stars that enclose the pair in a 13.5′-tall triangle, its pointy end in the north. The cluster is quite beautiful in the 10-inch scope at 44×. It gleams with more than 100 stars, many in raggedy chains splayed outward from the center.

M41 is an intermediate-age open cluster, 240 million years old, parked 2,300 light-years away from us. According to recent papers, members cover a diameter of about 1½° on the sky and conservatively total about 880 solar masses.

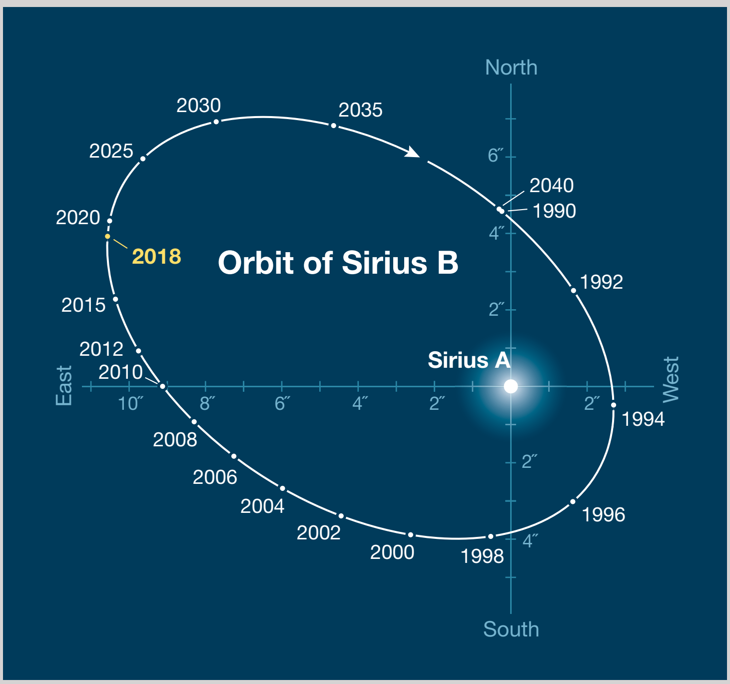
Our next target is the emission nebula **NGC 2359**, popularly known as Thor's Helmet for its resemblance to the Norse god's apocryphal headgear, variously depicted as having wings or horns. From home, Thor's nebula is easily spotted in a 23× sweep with the 130-mm refractor and the aid of a narrowband filter. I simply begin by pointing the scope at a spot one-third of the way from Theta (θ) to Gamma (γ) Canis Majoris and then push the scope east. At 48× with an O III filter, there's a roundish glow with a tail that starts at its southern edge and strikes out toward the west-southwest. Keeping the O III filter and boosting the magnification to 102×, the round bubble looks brightest along a fat arc that curves north through west to south so that it and the tail form a backward numeral 2 in my mirror-reversed field of view.

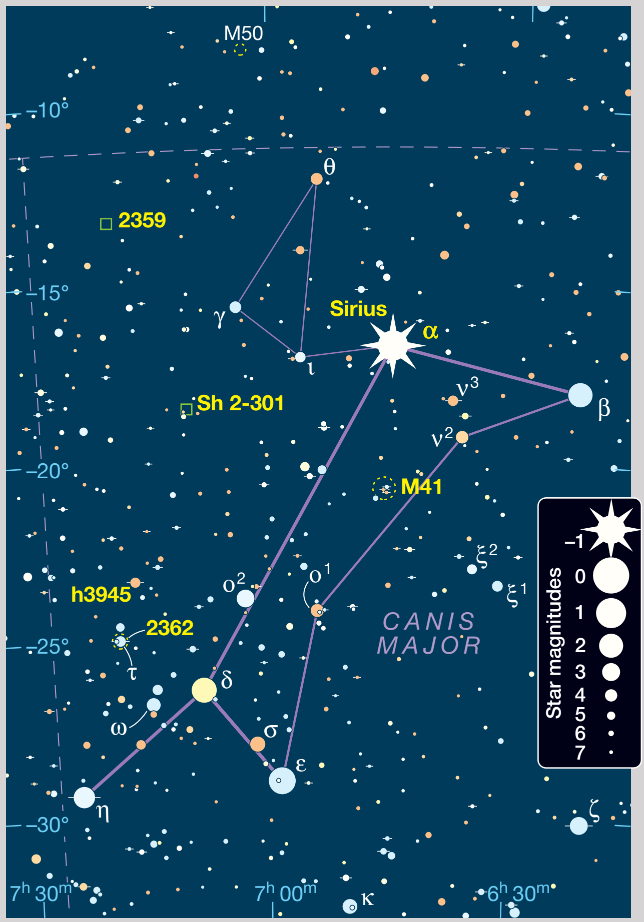
NGC 2359 appears more complex when studied with my 10-inch reflector at the Winter Star Party. At 70× with an O III filter, the boldface 2 stands about 6½′ tall and isn't mirrored. Fainter extensions proceed east and northwest from the top of the 2, and another stretches the 2's tail westward. The western extensions stand out better than the eastern one, and they make the helmet's wings or horns. A star marks each end of the 2's curve, and one more sits along the inside edge. A narrowband filter also gives a nice view, but the brighter parts of the nebula are obvious even without a filter.

The round part of NGC 2359 is a Wolf-Rayet bubble blown by a fierce

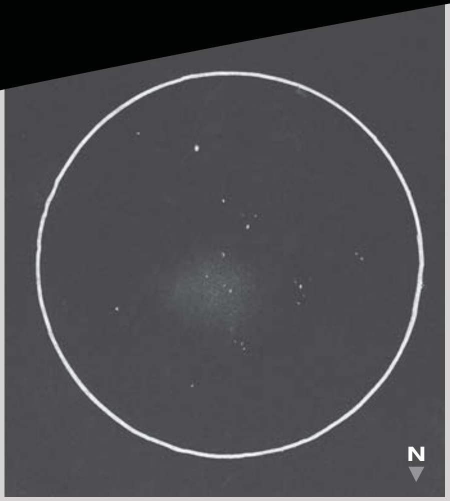
▲ The massive Wolf-Rayet star WR7 gives the nebula NGC 2359 (also cataloged as Sharpless 2-298) its evocative shape. Winds from the star blow through a surrounding molecular cloud, creating and distorting a nebulous bubble as they move.

▼ The figure below shows the apparent orbit of Sirius B with respect to Sirius A, as projected onto the plane of the sky. The true orbit is inclined 43° to the sky. The dates are for the beginning of the year.





JOHN VERMETTE



▲ *Left:* The bright nebula Sharpless 2-301 resembles an irregular triangle in the eyepiece, with three stars embedded in the brightest part. This sketch shows the view through a 14.5-inch f/3.8 reflector at 118×. *Right:* Giovanni Hodierna discovered the open cluster NGC 2362 before 1654; it was independently (re)discovered by William Herschel in 1783. This young cluster includes about 60 stars.

SH 2-301 SKETCH: RAUL LEON; NGC 2362: JIM THOMMES

wind from the extremely hot star along the 2's inner curve pounding against a surrounding molecular cloud. The star is about 12,000 light-years distant and will only survive for an astronomically brief time before it destroys itself in a spectacular supernova explosion.

One of my favorite sights in Canis Major is **NGC 2362**, also named the Tau Canis Majoris Cluster for its brightest star. This is a pretty cluster even at 23× in the 130-mm scope, showing radiant Tau (τ) closely guarded by several lesser lights. It becomes quite lovely at 102×, with 25 stars, including one very near Tau, drawn to Tau like moths to a flame. The gathered moths envelop Tau within a triangle whose narrowest corner points south-southwest, and several strays trail northward from the triangle's base. At 164× I count 30 stars spanning 9′, none close to rivaling Tau's blue-white splendor. The 10-inch scope at 171× teases out 45 stars and brings to mind a dazzling brooch with Tau as the showpiece jewel.

NGC 2362 is a very young star cluster. According to the WEBDA database (**univie.ac.at/webda**), it's about 8 million years old and 4,500 light-years away from us.

While in the neighborhood of NGC 2362, I like to climb 1.7° north-northwest to drop in on the optical double star **h3945** (HJ 3945). This is a much-loved pair for many amateur astronomers, who often compare it to summer's Beta (β) Cygni by calling it the Winter Albireo. Through my 105-mm refractor, the stars are widely separated at 28×. The primary star looks firelight-gold, but the companion doesn't appear to have the blue-white glow I see in the companion to Albireo. Instead, I usually perceive it as white, sometimes with a touch of yellow. What colors do you see?

Let's finish our tour with the seldom-visited emission nebula **Sharpless 2-301**, centered 12′ north-northwest of the 6th-magnitude star HD 54958 (HIP 34617). Sh 2-301 is easy to pick out with a narrowband filter using the 130-mm scope at 37×. It appears vaguely roundish and harbors one faint star. The filter is unnecessary at 102×, and the nebula grows irregular in brightness with 3 stars nested in the most conspicuous part. A star 2.3′ southwest of the trio inhabits a dimmer area of the nebula's main mass, which sprawls across 5′. Diaphanous mist wafts north from the 5′ mass and fades away a bit before reaching a tight little arc of three stars. A 10th-magnitude star marks the nebula's southeastern edge, accompanied by a yellow, 7th-magnitude gem farther out. Give this little-known wonder a try!

Near the Dog Star

Object	Type	Mag(v)	Size/Sep	RA	Dec.
Sirius	Double star	–1.5, 8.4	11.1″	$6^h 45.1^m$	–16° 43′
M41	Open cluster	4.5	39′	$6^h 46.0^m$	–20° 45′
NGC 2359	Bright nebula	~10½	9′ × 6′	$7^h 18.5^m$	–13° 14′
NGC 2362	Open cluster	3.8	6′	$7^h 18.7^m$	–24° 57′
h3945	Double star	5.0, 5.8	26.4″	$7^h 16.6^m$	–23° 19′
Sh 2-301	Emission nebula	—	9′ × 8′	$7^h 09.9^m$	–18° 30′

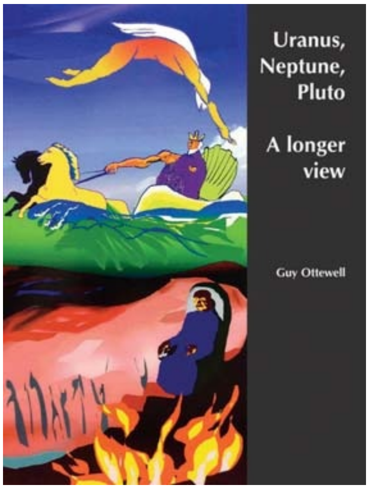
Angular sizes and separations are from recent catalogs. Visually, an object's size is often smaller than the cataloged value and varies according to the aperture and magnification of the viewing instrument. Right ascension and declination are for equinox 2000.0.

■ Contributing Editor **SUE FRENCH** visits the realm of the Dog Star as often as possible in the winter observing season.

Into the Future

URANUS, NEPTUNE, PLUTO: *A Longer View*

Guy Ottewell
Universal Workshop, 2018
73 pages, ISBN 978-0-934546-75-1
$19.95, softcover.



IT'S FASCINATING TO CONSIDER what happens in our sky over the long term. I recently encountered just such a farsighted celestial outlook in Guy Ottewell's new book, *Uranus, Neptune, Pluto: A Longer View*, published by Ottewell's own Universal Workshop. Well-known in the astronomical community as the creator of the annual *Astronomical Calendar*, which ran from 1974 to 2016, Ottewell lends a unique artistic eye to his astronomical views of the near and far future.

Uranus, Neptune, Pluto looks at the outermost planetary bodies of our solar system, discussing where they've been, what they've traversed since they were discovered, and where they're headed, complete with orbital resonances, conjunctions, and peculiarities. Ottewell accompanies his astronomical perspectives with unique star charts showing the orbits and paths of the outer planets with a look familiar to longtime readers of his *Astronomical Calendar*.

Ottewell presents an excellent consideration of the future of our solar system's outer worlds. It's sobering to think, for example, that Neptune has journeyed around the ecliptic only once since its discovery in 1846, completing one 165-year orbit only recently (in 2011) to return to its original discovery point in Capricornus near its border with Aquarius. And remote Pluto has only moved from Gemini, where Clyde Tombaugh discovered it in 1930, to its present position in the star-rich fields of Sagittarius.

Strip charts created by the author show the celestial paths of the outer planets through the coming decades, and their future course through the constellations. There's an especially interesting discussion on the motions of the moons of the outer planets over the coming years and how to view them from the Earth. Ottewell also describes the sky as viewed from each of the planets (for example, one pole star for Pluto is currently naked-eye Epsilon Aquarii). Another fun fact from the book: The first transit of a Uranian moon (Ariel) was captured by the Hubble Space Telescope on July 26, 2006.

So much for the almost present tense: Ottewell also follows the strange worlds of the far solar system into the distant future. He notes the peculiar circumstances of the 1993 conjunction of Uranus and Neptune, and that one planet laps the other in their journeys around the Sun in just a little less than once every 172 years. Perhaps Uranus will actually occult (pass in front of) Neptune many years from now. Both are small targets, though, with Uranus presenting a 4″-disk near opposition, and Neptune an even smaller one at 2.4″ across. Seeing this event would be a true observing victory.

This got me thinking, so I ran some simulations in Occult 4.2 and Stellarium. I discovered no true occultations of Neptune by Uranus between now and AD 10,000. The nearest runner-up will be a close 27″ conjunction on November 2, 4567 (mark your calendars). Let's see, by then I'll be . . .

The first edition of the book contains a very few grammatical errors, but they were addressed by Ottewell in subsequent printings. And I was surprised that no "eye candy" images of Pluto courtesy of NASA's New Horizons flyby in 2015 were included in the book.

> Ottewell presents an excellent consideration of the future of our solar system's outer worlds.

Uranus, Neptune, Pluto: A Longer View is a great volume for observers of the outer planets. If you read and loved Ottewell's *Astronomical Calendar*, consider this compendium a deeper dive into these fascinating worlds. On his website (**universalworkshop.com/blog**), Ottewell mentions the possibility of a similar book for the planet Venus; that's something to look forward to. Now, we just need to perfect time travel, so we can follow all these curious planetary events into the future.

■ **DAVID DICKINSON** is a freelance science writer, high school science teacher, retired enlisted U.S. Air Force veteran, and avid stargazer. He also writes science fiction in his spare time, and he shares the universe and more on his own website, **astroguyz.com**. He, with Frasier Cain, is author of *The Universe Today Ultimate Guide to Viewing the Cosmos*. He currently resides with his wife, Myscha, in the Tampa Bay area.

Sky-Watcher AZ-GTi and Evostar 72 Refractor

This duo brings new meaning to the old saying that good things come in small packages.

▲ The Sky-Watcher Evostar 72 APO Refractor combined with the AZ-GTi Go To mount is an excellent grab-and-go observing package.

Sky-Watcher AZ-GTi

U.S. Price: $379

Evostar 72 APO Refractor

U.S. Price: $465

skywatcherusa.com

What We Like

Ultra-portable combination

Intuitive mobile apps

Reasonable color performance for a budget APO

What We Don't Like

Requires two devices on iOS for planetarium app control

Equatorial mode not completely thought out

I'M A FAN OF Sky-Watcher's Star Adventurer mount, a small, portable sky-tracker designed primarily for use with DSLR cameras and lenses. For its stated purpose, it works great. But some of the advertising shows it with a small telescope attached, and I've found this configuration to be less than optimal. Immersed in the world of large mounts and high-end imaging, I often find myself yearning for a small Go To mount that can hold a small telescope for visual use but is also small enough to fit in airline carry-on compartments.

Enter the Sky-Watcher AZ-GTi mount. It's small and lightweight, weighing just 8.6 pounds including its surprisingly sturdy tripod. The mount runs on 12 volts DC and can be powered by eight AA batteries housed in the mount body or by an external DC power source.

The AZ-GTi is rated to carry an 11-pound payload, which is sufficient for a small telescope. You can buy the mount separately, but there are two packages that include optics: one with a 102-mm f/13 Maksutov-Cassegrain ($555), and one with a 127-mm f/12 Maksutov-Cassegrain ($725). For this review, however, I paired the mount with Sky-Watcher's new Evostar 72 APO Refractor. This affordable 72-mm ED doublet has a focal length of 420 mm, producing an f/ratio of f/5.8. It's potentially a very nice grab-and-go combination.

The Evostar 72 comes with tube rings and a Vixen-style dovetail plate, as well

ALL PHOTOS BY THE AUTHOR

as an aluminum-sided carry case. While it includes a mounting bracket for a finder scope, none is supplied, nor any eyepiece, or a 90° star diagonal.

I borrowed the mount and scope from Sky-Watcher USA at the Texas Star Party. They had been used as demos at several astronomy gatherings. When I opened the box, I initially thought I forgot to grab the hand controller, but it turned out the mount doesn't come with one even though the AZ-GTi includes a port for Sky-Watcher's SynScan hand controllers. Instead, the AZ-GTi creates a Wi-Fi hotspot, and you connect to it with a free app that is available for both iOS and Android devices.

The *SynScan* app works with any Sky-Watcher Wi-Fi mount, including the AZ-GTi. There is also a free "PRO" version of the *SynScan* app that can control the company's equatorial mounts. This is notable because there is an experimental firmware update for the AZ-GTi that allows you to put it on the company's Star Adventurer equatorial wedge to operate in equatorial mode. I tried it out and it does work, and it at least cracks open the door for longer exposure astrophotography with the mount. But this mode seems an afterthought rather than a planned feature, as the form factor could use a little finessing to function properly. To get it to work, I had to replace the counterweight shaft, and I had to replace some of the bulky knobs on the wedge borrowed from my Star Adventurer mount as they were too close to the body of the unit to turn by hand. The *SynScan Pro* app seamlessly detected the firmware upgrade, and the mount was easy to use in either mode.

▲ Each Evostar comes with tube rings, a Vixen-style dovetail mounting bar, and a foam-lined aluminum travel case.

Controlling the mount with the app is simple and intuitive. Third-party planetarium apps can also control the mount by connecting to the *SynScan* app or directly to the optional hand controller. A quirk for users with iOS devices is you need two separate devices to accomplish this, because iOS apps do not run in the background.

First Light

After spending some time familiarizing myself with the Wi-Fi control and *SynScan* app, I took the mount to an open space in my neighborhood. The entire setup was easy to carry a couple of blocks down the street.

I leveled the mount, aligned it pointing north according to the compass app on my iPhone, and then selected the one-star alignment routine. A list

▲ *Left:* Although the scope includes a saddle plate for attaching a finderscope, users may need to purchase one separately. However, a 55-mm eyepiece produces a low-magnification view (7.6×) with the scope that may eliminate its need for visual observers. *Right:* The Evostar 72 includes a 2-inch, dual-speed Crayford-style focuser with two set screws to secure a star diagonal (purchased separately).

of bright stars, visible planets, and the Moon were given as alignment choices, including Jupiter, which was well-placed in the south. I selected the gas giant, and the scope slewed around to the bright planet dutifully, though I could tell just sighting down the tube of the scope that it was off quite a bit, probably due to the compass app pointing to magnetic north rather than celestial north several degrees away. I then loosened the altitude and azimuth clamps and just moved the scope to where Jupiter was located. With most mounts, this would immediately ruin the alignment routine. But the AZ-GTi has internal encoders that detect the movement of the axes when you do this, and it knows how much you've moved the scope, as if it was done with the hand controller.

I was using a 55-mm Tele Vue Plössl eyepiece, which produces an extremely wide field at 7.6×, essentially eliminating the need for a finder scope. With this combination, Jupiter really looked like a bright star, but I could tell what it was from the bright Galilean moons close by the planet. I centered Jupiter in the field with the slow-motion controls in the app and synced on it.

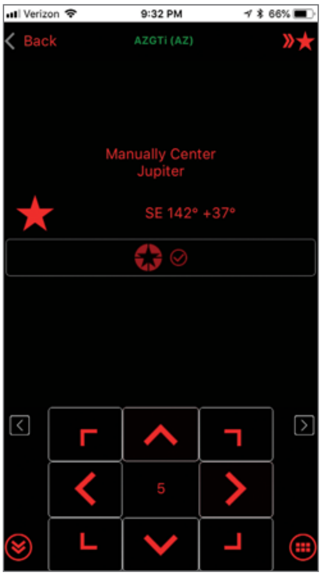
I then popped in a 13-mm Tele Vue Type 5 Nagler, producing 32×. Jupiter was a big blob that quickly snapped into focus using the Evostar's dual-speed 10:1 Crayford-style focuser. The gas giant's ruddy Northern and Southern Equatorial Belts were easy to see, though not much else was as I cursed myself for not bringing one of my higher power eyepieces.

As a veteran user of Go To mounts, I'd long ago learned not to expect much accuracy from a single-star alignment with an alt-azimuth mount, but just for fun I decided to slew to my favorite globular cluster M13 to see how far I was off. I knew when I looked in the eyepiece it would not be there, and I was right. Dreading the hunting game, before popping in the even wider eyepiece I decided to move just a little bit around, and on my first jog, in came the faint, fuzzy, round object that was unmistakably M13. In my light-polluted Florida skies with only a 72-mm optic, the scope didn't resolve any stars in the cluster, but it was there, and it reminded me of the first time I'd ever found this object with my 60-mm department-store scope decades earlier. Notably, this was certainly much easier than that had been way back then.

For my next evening out with the system, I set up in my own driveway with a wider range of eyepieces on hand to better gauge the Evostar's optical performance. A bright Moon was out, so that, along with several bright planets, was easy prey. Again, I pointed north and was on Jupiter in less than five minutes from the time I stepped out my front door (I'd previously put the scope outside to acclimate to the temperature).

▶ Sky-Watcher's free *SynScan* app for Android and iOS devices is extremely easy to use. It includes several alignment routines, a basic catalog of named stars, several dozen double stars, and several deep-sky object catalogs. The mount can also be controlled with other planetarium apps, though they need to connect through the *SynScan* app.

▼ *Left:* The 72-mm doublet objective includes an ED element for superior color correction. *Middle:* Sky-Watcher's AZ-GTi Go To mount includes "Freedom Find" auxiliary encoders that precisely track movements on both axes regardless of whether you move the mount using the app controls or the optional SynScan hand controller, or you loosen the clutches (arrowed) and move the scope manually. *Right:* The AZ-GTi includes ports to connect an optional SynScan hand controller, an external DC power supply, and a SNAP port that connects directly to most DSLR and Mirrorless cameras.



▶ The *SynScan* single or multi-star alignment routines are simple. Point the mount north, select a bright star, the Moon, or a bright planet, and slew to it. Then manually center the target. Click the check mark, then do the same for your second alignment object.

At 32×, Jupiter was just grand again. Although a bit small, any observer would still be able to spot the main equatorial belts, moons, and even the Great Red Spot, which in recent years has appeared a deep orange hue. Positioning the bright planet in the middle of the field exhibited no color fringing that I could discern. When the planet was placed near the edge of the field, it sported a distinct green fringe on the edge. Stepping up the magnification to 84× with a 5-mm Tele Vue Nagler, Jupiter was a good bit larger, still glorious and crisp. Finally, I decided to put the 72-mm scope really to the test with a 2.5-mm Nagler that produced a magnification of 168×. Focusing was surprisingly easy on such a light mount, with vibrations damping out within a second or two. I honestly did not expect much from this combination, and while Jupiter was a bit soft, I was really quite surprised by how usable this combination actually was. The Great Red Spot was well defined, and the edges of the equatorial belts as well as some of the narrower bands were dissolving into a wavy pattern of clouds, the details of which were tantalizingly just out of reach but still perceptible. There's something to be said for a small scope that cools off quickly and doesn't need to be collimated.

Vibrations caused by bumping the tripod took less than two seconds to dampen out. Some of this is due to the tripod mechanics, some to the fact that it's a small scope on top; case in point, the two work well together.

I moved on to Saturn, and found the butterscotch-toned ringed planet looked a good bit better than Jupiter at all magnifications I tried. I attribute this to the fact that Saturn isn't as bright, and it was also a little higher in the sky. Even at the edge of the field, Saturn did not exhibit the green fringe that Jupiter had. The Cassini Division was visible at all magnifications as well, and I could easily identify the planet's largest moon, Titan.

My next target was the Moon, which exhibited the green fringe when placed off center in the field much like Jupiter, but only on the bright limb. Along the cratered terminator I could not see anything but sharp, clear lunar craters. I moved the bright limb to the center of the field of view, and there was a faint purple edge that I could not see at all on Jupiter or Saturn.

At 168×, the Moon held up quite a bit better than the planets. Along the terminator, there was no discernible coloring, and I felt I was simply in orbit, flying over the Moon in my own personal spaceship.

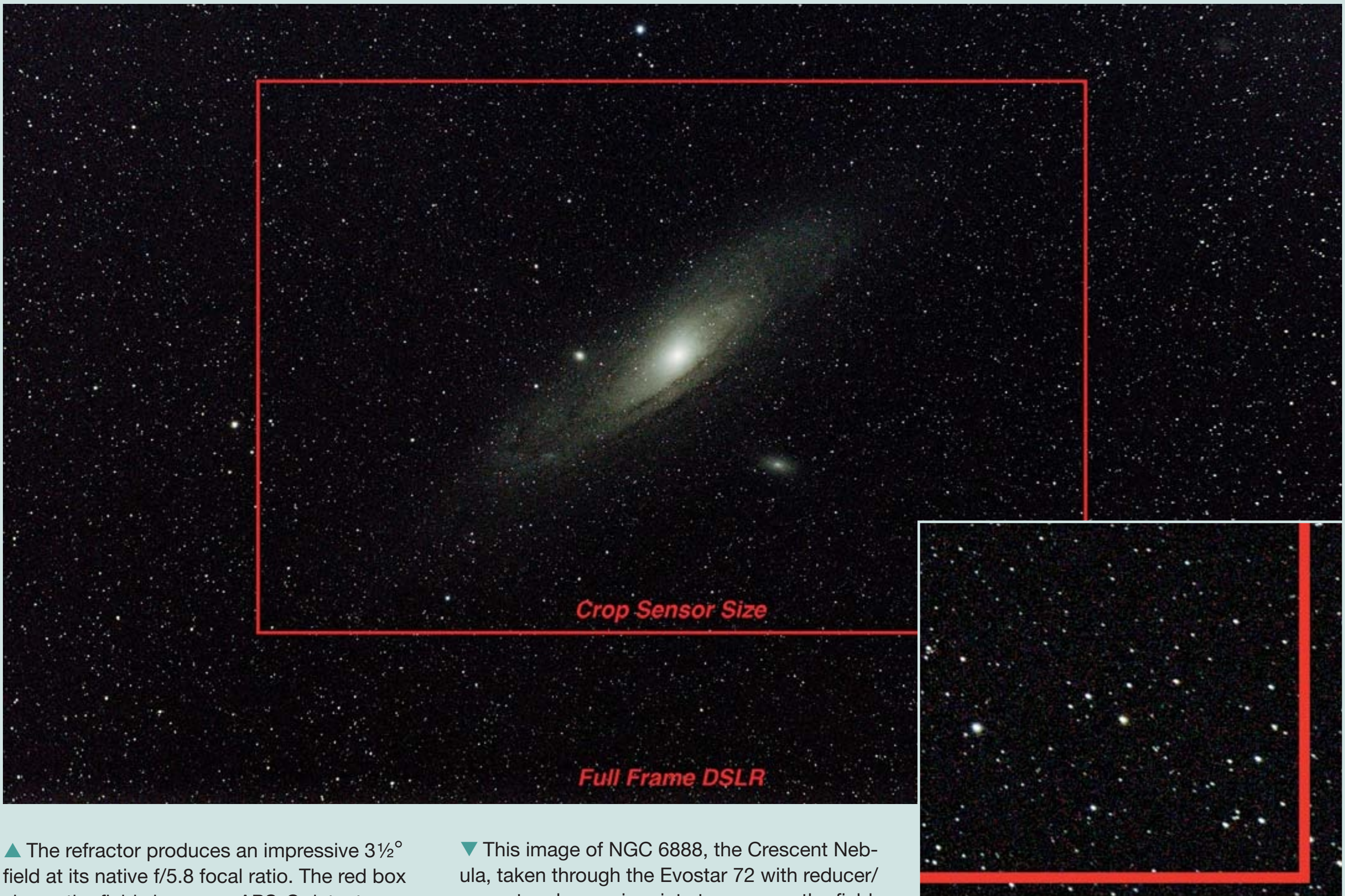
Later at my dark-sky site, I had the opportunity to try this combination out visually on some fainter targets. This time I performed a two-star alignment using Mars and Vega. Vega in the center of the field was a brilliant, sparkling diamond. Out at the edges of the field, I could clearly see the star being pulled apart and flaring into a triangle-shaped pattern of green, blue, and red light. Testing the Go To performance of the alignment, I then slewed to the Double Cluster. The pair was well-centered and well resolved at 32× with both clusters comfortably fitting in the field of view. The stars were tiny pinpricks of light surrounded by inky black sky, and when I slewed around I didn't see any color changes at the edges, or even any change of shape for the stars. The color and flaring are really only noticeable on the brightest targets.

Imaging Performance

The AZ-GTi mount isn't intended as a deep-sky imaging platform, so to test the Evostar 72 doublet's suitability for astrophotography, I put the scope on my Paramount MYT and tried it from my own backyard, not too far from Orlando, Florida.

While the human eye can be very accommodating to field curvature, any doublet refractor will need a field flattener to produce round stars across most cameras these days. I used Sky-Watcher's own 0.85× flattener/reducer ($249), plus I needed an additional

▼ The AZ-GTi's collapsible aluminum tripod extends to a maximum height of 43⅓ inches. The extension pier is recommended for use with long OTAs.



▲ The refractor produces an impressive 3½° field at its native f/5.8 focal ratio. The red box shows the field size on an APS-C detector. *Inset:* Stars near the very corners of the APS-C field show some elongation.

▼ This image of NGC 6888, the Crescent Nebula, taken through the Evostar 72 with reducer/corrector shows pinpoint stars across the field of a Starlight Xpress Trius-SX694 CCD camera equipped with a hydrogen-alpha filter.

adapter to thread this to the Evostar body ($49) as well as an adapter to connect my CCD camera to the flattener. Note that with the reducer/flattener, the scope is operating at a focal length of 357-mm, producing a focal ratio of just under f/5.

My first test was to shoot the Moon with and without the reducer (see below) with a Canon 5D Mark III DSLR. In the center of the field, the Moon was sharp and well-defined in both cases, with no color fringing evident photographically. Even without the field-flattener, the Evostar 72 can likely be used for objects near the center of the field of view.

Sky-Watcher states all Evostar refractors will satisfactorily cover an APS-C-sized sensor or smaller without the use of a field-flattener. I put a full-frame DSLR on it just to see how large the usable field is, and I took a test shot of M31 from my backyard. The image shown on the opposite page is a single calibrated and stretched frame which shows just how wide the field of view is. I've superimposed a rectangle showing the size of an APS-C sensor's coverage; it's still plenty to capture all of M31.

Naturally, the stars at the edges of the full-frame image are a good bit elongated, but curiously, one of the corners actually held up okay. It is possible there was some tilt in my prototype adapter, or perhaps some sag with a heavy camera attached. Performance is better inside the crop-sensor rectangle, of course, but still you can see the correction fall off at the edges and corners of the APS-C frame. Anything smaller than an APS-C should produce round stars across the entire image, while APS-C detectors will show acceptable stars until you get to the very corners of the frame.

Color-wise, there was some lateral color separation of stars radially towards the center of the image, with stars displaying a blue edge on one side and a red one on the other. This is normal for a doublet APO in this price range without using a field-flattener, and I've even seen worse on more-expensive APO triplets.

A backyard on the far side of Orlando from Disney World is not the best place to do color images, and so I thought I'd try some narrowband with this little scope. A doublet APO should excel when shooting with filters as a much narrower range of wavelengths needs to be focused in the same place. Slightly under-sampled on a Starlight Xpress Trius-SX694 monochrome camera at f/5, I knew I could get some nice images with short 5-minute exposures, even at narrowband wavelengths.

I focused all of these images by hand using the stock focuser. Florida summers are pretty stable temperature-wise, and I focused once and left it for the night. I shot four targets total over several nights in automated runs that included meridian flips, and the focuser never slipped.

▲ Although the Evostar 72 can cover detectors smaller than APS-C format with minimal aberrations as seen on the facing page, a field-flattener is recommended for optimal performance for full-field correction on detectors as large as 24×36 mm. Additional adapters are necessary to properly space your camera's detector from the corrector for best performance.

◀ The Evostar 72 Apo performs well on the Moon both with (near left) and without (far left) Sky-Watcher's reducer/corrector for its ProED 80 refractor. With the reducer/flattener, the telescope operates at 357 mm, f/4.9.

Conclusion

I started my astronomical life strictly a visual observer, and now after several years as a hardcore imager, I've only recently returned to visual astronomy. I must admit, I had forgotten the simple joy of just taking five minutes to set up a telescope for a quick look at an object or two. It really was a pleasure, certainly better than my first experience with a Go To mount and scope combination many years back, which was of course the biggest scope I could afford (the #1 mistake beginners often make). The AZ-GTi is simple, stress-free, and easy to use.

The Evostar 72 is a budget APO, and yes, I could tell the difference between it and some of my top-shelf scopes, most of which, however, would require adding an extra zero to the price. It has good color performance in the middle of the field, with only a touch of color visible at the edges when viewing the brightest objects. For astrophotography, I found the Evostar 72 to be a pretty reasonable starter scope, and combined with the AZ-GTi, it's also a nice, portable visual package.

■ **RICHARD S. WRIGHT, JR.** can often be found sharing views of the night sky at his local Starbucks.

▶ MODULAR MOUNT

Losmandy introduces a new mount to its series of Go To German Equatorial mounts. The G11T ($4,445 including tripod) is rated to hold up to 75 lbs. Its right-ascension and declination axes can be quickly disassembled for transport in the field. Breaking the mount down reduces the weight of its largest component, the RA axis, to 44 lbs. The RA axis also offers complete, 360° rotation to permit tracking well past the meridian. The mount, which boasts a periodic error of +/- 5 arcseconds or better, uses DC servo-motor drives controlled by the Gemini 2 Go To electronics that incorporate a database of more than 40,000 objects; the database can be updated via an internet connection. The G11T includes a removable 1¼-inch-diameter counterweight shaft, a 21-lb counterweight, a machined aluminum folding tripod, the Gemini 2 hand controller, and a DC power cable. More options are available.

Losmandy Astronomical Products
747-283-1075; losmandy.com

▼ MID-SIZED DOME

SkyShed, producer of roll-off-roof and dome observatories, announces the POD MAX (starting at $14,995). This 12½-foot (3.81-meter) dome is designed to accommodate up to 32-inch telescopes. Its walls and dome are manufactured of recyclable high-density polyethylene (HDPE) designed to last for decades through extreme temperature swings. Its aperture slit is 44 inches wide with a shutter that opens 22 inches beyond the zenith. The dome includes 6-foot wall sections. Its residential-style fiberglass door features a strong deadbolt lock to protect the dome's contents. Up to 6 MAX bays can be added, each offering 18 inches of additional interior workspace. See the manufacturer's website for additional options and accessories.

SkyShed
519-272-9081; skyshedpodmax.com

▼ REFRACTOR PACKAGE

Explore Scientific now offers the FirstLight 102-mm Doublet Refractor with Twilight I Mount ($449.99). This observing package features a 4-inch, f/9.8 achromat paired with a lightweight but sturdy alt-azimuth mount. The scope comes with tube rings, a Vixen-style dovetail mounting plate, a red-dot finder, a 2-inch 90° star-diagonal with 1¼-inch eyepiece adapter, a 25-mm Plössl eyepiece, and a smartphone camera adapter that's useful for taking snapshots of the Moon and planets. The Twilight I Mount can bear a load of up to 18 lbs and features stainless-steel legs that extend from 38.5 to 55.5 inches. It includes flexible slow-motion control and an adjustable tangent arm to accommodate almost any viewing angle. A powder-coated aluminum spreader has holders for 3 eyepieces.

Explore Scientific
1010 S. 48th St., Springdale, AR 72762
866-252-3811; explorescientific.com

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

 by Timothy Jensen

DEEP COLOR Adding narrowband image data, particularly data recorded through a hydrogen-alpha (Hα) filter can add faint details and rich color to images taken under less-than-ideal skies. The author took this example of the emission nebulosity IC 434 surrounding the Horsehead Nebula using a one-shot color camera to record color and Hα that were combined in *ImagesPlus.*

Giving Nebulae a BOOST

Here's a novel technique to bring out emission nebulosity in your astrophotos.

Among the most photographed objects in the night sky are emission nebulae. These expansive fields of eye-catching red and magenta nebulosity, with occasional flourishes of orange, make for beautiful celestial portraits. However, getting those rich colors isn't always easy, particularly if you live and shoot from light-polluted locations. While one-shot color cameras like DSLRs or mirrorless cameras can capture the entire spectrum of visible light, often their utility is compromised by light pollution and skyglow.

One way around this limitation is to image through narrowband or other specialized filters to increase the contrast in the images. Ultra High Contrast (UHC) filters sold by various manufacturers are a type of combined narrow-bandpass filter. They work by passing specific wavelengths of light, commonly found in nebulae, while blocking unwanted wavelengths from most sources of skyglow. Oceanside Photo and Telescope's new Triad filter works in a similar fashion.

Individual narrowband filters allow only a fraction of the visible spectrum to be seen by the camera. Most commonly used is the hydrogen-alpha (Hα) filter that blocks all wavelengths except those surrounding ionized hydrogen emitting light at 656.3 nanometers. Since hydrogen emission is typically the most common light from emission nebulae, this is an excellent filter for highlighting details in faint nebulosity. It's most effective when paired with monochrome cameras, since it only passes a very small portion (often between 3 and 7 nm) of the deep-red region of the spectrum, so images recorded through this filter with a color camera (such as a DSLR) appear as a washed-out red.

However, it is still possible to use these monochrome images captured with Hα filters to enhance an ordinary color image obtained using a one-shot color camera. The trick is to blend the Hα image into a color photograph to bring out the nebula while at the same time maintaining a natural color balance. One common practice is to replace the luminance channel with a Hα image in a color photo. However, this can lead to an odd color bias that will require much work to correct. A better solution is to blend the Hα data into the red channel of an RGB color image. Care must be taken, since the Hα data can overpower the broadband red image. Additionally, ionized hydrogen doesn't just emit light in the red. It also produces emission at 486 nm (the blue/green hydrogen-beta line), and another, weaker emission at 434 nm (blue). So if we take our Hα data and mix a little into the green and blue channels as well as the red, we can achieve a much more natural color balance with a lot of detail in the nebula.

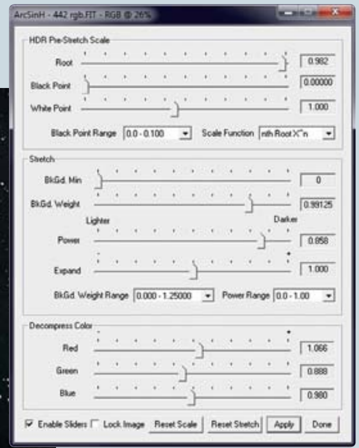
This sounds complicated, but fortunately, most astro-imaging software includes tools to do this. I prefer *Images-Plus* (**mlunsold.com**), which makes this sort of work very easy to do. Here's how I incorporate the technique into my image-processing workflow.

Start with the Stars

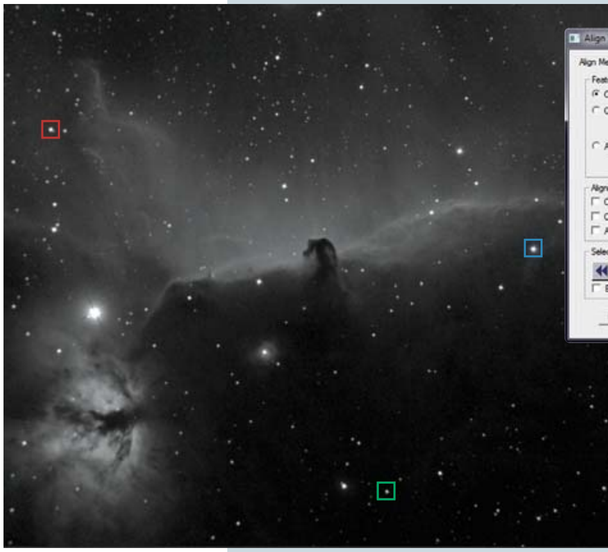
Begin by collecting your color data, as well as the narrowband or UHC-filtered images. It doesn't matter if your camera is a DSLR or monochrome deep-sky camera, as the process for combining the narrowband and color images is the same, though let's assume you are using a color camera. Process both sets of images to bring out the most detail you can without enhancing noise. When processing the color photo, don't worry too much about enhancing the nebula. Concentrate instead on bringing out the stars in the picture. The goal is to make stars appear as natural as possible without imparting a bloated or washed-out look to them, nor a color bias; you should see a good deal of blue, yellow, and orange stars in the stretched result.

I prefer to use the ArcSinH tool to stretch my images, found in the pull-down menu (Stretch > ArcSinH). When this tool opens, start by changing the Scale Function from None to nth Root X^n in the top-right of the window. In the middle section, move the BkGd Weight and Power sliders to bring out the stars in the image. Try to avoid the temptation to enhance the nebula at this point, as that will occur later with the addition of the narrowband data.

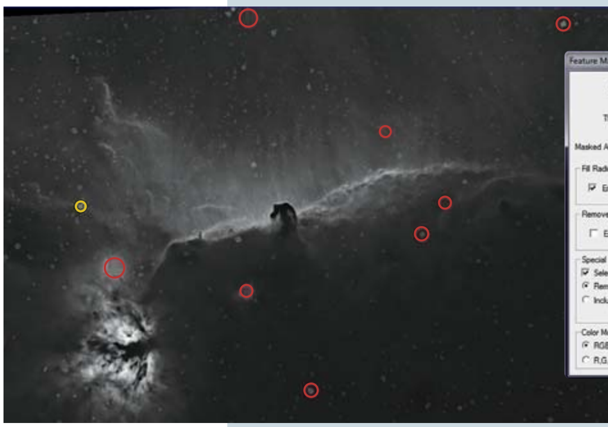
Use the red, green, and blue sliders in the Decompress Color section at the bottom of the ArcSinH window to help preserve the star colors during the stretching process. Some imagers prefer to use a sun-like star (known as a *G2V* star) as a color reference and adjust the colors until that star appears neutral white without becoming saturated.

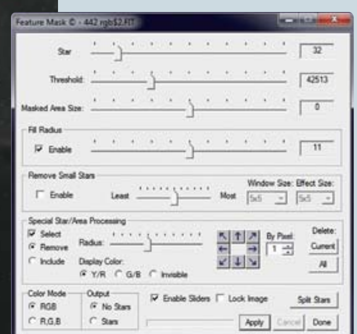


◀ **COLOR STRETCH** Begin by stretching the stacked color image with an emphasis on preserving the colors and profiles of the stars using the ArcSinH tool.



◀ **ALIGNMENT** After stretching the individual color and narrowband images, both pictures should be aligned. Be sure to click Translate + Scale + Rotate and choose 3 alignment points.





▲ **STAR MASK** After alignment, the stars in the narrowband image need to be masked out so that they don't affect their appearance in the final color image. Some bright stars, particularly ones embedded within bright nebulae, can be removed from the mask before applying the tool, so the result shouldn't contain any odd holes that could create artifacts in the final image.

While this is excellent advice, it's sometimes hard to find a *G2V* reference star in an image. The ArcSinH function is a very powerful tool, and small adjustments with the sliders can have a strong impact on the image.

When you're satisfied with the stars in your image, click the Apply button on the bottom right, and then save the image as a 16-bit TIFF file.

Nebulae Boost

When working on your narrowband image to combine with your color version, you can ignore the stars and make the nebula pop as much as you like before noise becomes particularly noticeable. If you shot your Hα images with a one-shot color camera, you'll want to convert it to a greyscale image in order to mix it with the individual red, green, and blue channels of your color image. To do this, open your Hα image in *ImagesPlus* and select Color > Split Luminance from the pull-down menu.

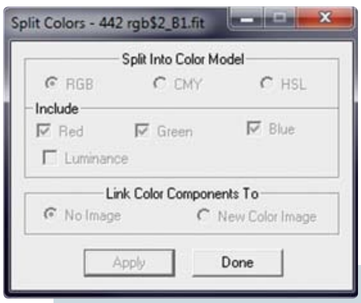
I prefer to begin to enhance the narrowband image using the ArcSinH tool, and then apply more adjustments with the Micro Curves tool (Stretch > Micro Curves). This tool permits you to apply various degrees of enhancement to different brightness ranges by using the Min and Max check boxes to set the working range for the tool. Simply click the check box and then click on an area of your image to set the intensity limit. To apply multiple iterations of Micro Curves, you need to press the button labeled Set View Using Image Currently Displayed after each adjustment (the blue eye button). Otherwise, the next correction with the tool simply replaces the previous one.

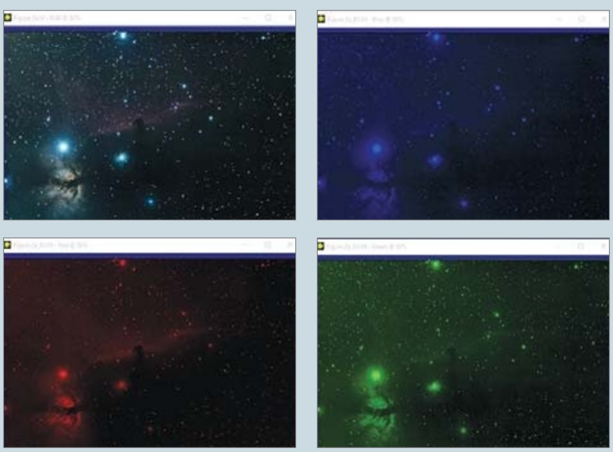
Once your narrowband image is stretched to your liking, you can perform noise reduction by selecting Smooth Sharpen > Multiresolution Smooth/Sharpen in the pull-down menu. Moving the sliders to the left will smooth the image, though I recommend starting with the Finest slider first. Again, you can apply this to different intensity ranges within the picture by clicking the Set View Using Image Currently Displayed button between each correction.

Preparing to Merge

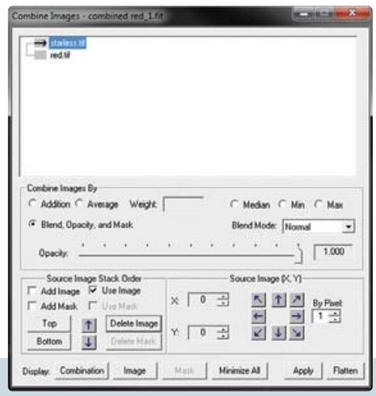
Before you combine the narrowband and color images, you'll first have to align the two. This is accomplished in *ImagesPlus* by opening Image Set Operations > Align Files > Align files - Translate, Scale, Rotate, and then select the two files to align. When the window opens, click on the options for On Each Image, Translate + Scale + Rotate, and change the Number of Points to 3. In the Alignment Feature Selection, first choose the Common Point or Star option, and then click on a fainter star that appears in both images. Next, select Common Angle Defining Point or Star, and click on a different star in each image, followed by Additional Scale Defining Point or Star and select your third star. When all three stars are chosen, the Align button becomes active. Click it, and in a few moments, *ImagesPlus* will save aligned copies of the two registered pictures.

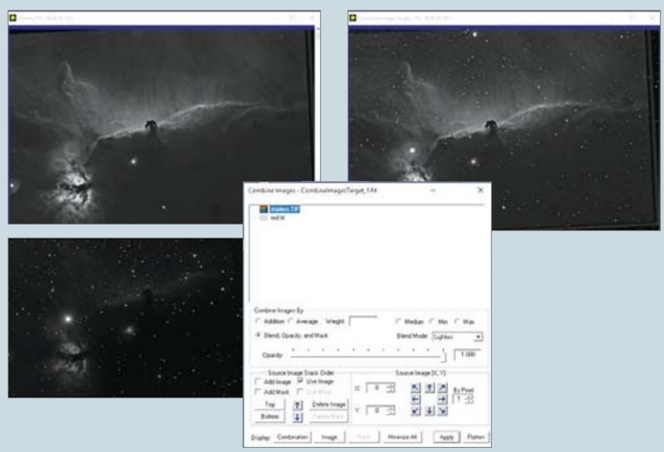
Now that the two images are aligned, you'll need to remove the stars from the Hα image using the Feature Mask tool, which appears as a blue





▼ **CHANNEL SPLIT** In order to combine the hydrogen-alpha image with each color channel at varying degrees, the color image has to be split into individual red, green, and blue monochrome images. *ImagesPlus* displays these by their respective color.





▼ **NARROWBAND BOOST** Adding the Hα to each color channel (with the most going to the red image) is performed with the Blend Mode, Opacity, and Mask tool. Be sure to change the Blend Mode to Lighten, and lower the opacity so that the narrowband image doesn't oversaturate areas in the image.

▲ **FINAL COMBINATION** Many targets within the Milky Way can benefit from adding narrowband data to a normal color image. This picture of the Rosette Nebula (NGC 2244 in Monoceros) takes on new life with the addition of several hours of Hα data.

"+" icon found along the left side of the screen. You'll need to experiment with the Star, Threshold, and Masked Area sliders to get the right mix of star removal without adding artifacts to the image. For some very bright stars, it may be best to leave them in the image. Do this in the Special Star/Area Processing section at the bottom of the window. Check the select box and the Include button, and then click on the stars you want to keep in the image, and increase the selected area using the Radius slider. If you find that removing a star leaves too big a hole, you can try increasing the Radius slider setting for that star. Once you have an image you are happy with, hit Apply and save the result as a new TIFF file.

Adding Hydrogen-Alpha

Now that both images are ready, open the color shot and split it into its individual channels by choosing Colors > Split Colors from the pull-down menu, and choose RGB. In a moment, you'll be presented with the three color channels, and each will be a color corresponding to its particular channel (red will appear red). Convert these images to greyscale using the Colors > Interpret - Mix Colors command with the Grey button selected.

To blend in the Hα image, choose Special Functions > Combine Images Using > Blend Mode, Opacity, and Masks tool from the pull-down menu. When selected, the Combine Images window opens, as well as a smaller Combine Images Setup window; input the name of your combined red and narrowband image in the Combination File Name area (for example, red+Hα) then click OK. In a moment, all of the open images that you have will appear in the Combine Images window.

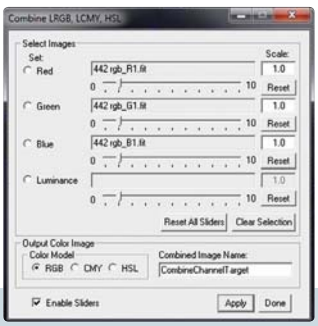
You only need to combine the starless Hα and the red channel images at the moment, so remove the blue and green images from the list by clicking on their file names, and press Delete Image at the bottom left. Make sure the Hα image is on the top of the stack with the red channel image below it using the up or down arrows. Now, with the Hα image selected, set the Blend Mode to Lighten and lower the Opacity slider to about 0.70. Click the Combination button in the Display: section to preview how your combined red and Hα will appear. You can adjust the Opacity setting until you get the effect you like. Press flatten and then save the image. Your enhanced red channel is ready. Repeat this process on the green and blue images, with an opacity setting of around 0.3 for the green and 0.25 for the blue.

Once the three enhanced color channels are ready, recombine them into a color image using Color > Combine LRGB, LCMY, HSL. In this window, assign the appropriate image to its color channel by clicking on the desired color button and then the corresponding image. Now hit the Apply button, and your enhanced color image will appear. Use the Crop tool to trim off any non-overlapping areas around the edge of the frame, and be sure to save your result.

This processing technique can help you create stunning, highly detailed images of nebulae even under less-than ideal skies. And don't be afraid to experiment with other narrowband wavelengths. Some nebulae have large contributions from other ionized elements, particularly doubly ionized oxygen (O III), which is found in the blue-green region of the spectrum at both 495.9 and 500.7 nanometers. These narrowband enhancements can often turn an ordinary image into an eye-popping portrait.

■ **TIMOTHY JENSEN** images the night sky from his backyard observatory in rural North Carolina.

▼ **FINAL COMBINATION** When the narrowband image is combined with each color channel, they can be re-combined using the Combine LRGB, LCMY, HSL tool. Additional color balance adjustments can be made using the sliders for each channel before clicking Apply.



▲ Mel Bartels with his 25-inch f/2.6 scope.

A 25-inch Breakthrough

This innovative scope incorporates new ATM advances on three separate fronts.

MEL BARTELS HAS BEEN ON something of a crusade lately. Long a proponent of large, thin mirrors, he has also become a proponent of fast mirrors, resulting in what he calls "richest-field telescopes." You saw his 13-inch f/3 scope in our January 2012 issue, and his 6-inch f/2.8 scope in our September 2014 issue. He's since taken it up a notch both in size and speed: He has just finished a 25-inch f/2.6.

That in itself would be exciting enough, but Mel has come up with an innovative new twist on the standard alt-azimuth mount that completely eliminates "Dob's hole" (see sidebar).

But wait, there's more! Pierre Lemay (originator of the tracking ball scope years before I came up with the same concept, most recently featured in our March 2016 issue) has come up with a new two-speed helical Crayford focuser for the same scope. Together, these design elements have created a completely new observing experience.

> The solution was simple, elegant, and apparently brand-new: add a second altitude axis!

Mel caught the thin-mirror bug from Oregon ATM David Davis, who did much of the pioneering work in slumping thin glass in a kiln and finishing out mirrors as thin as a quarter-inch over 16 inches of diameter. With that success, Mel reasoned that he could get away with ¾″ plate glass for a mirror up to at least 42 inches. Mel ground a 13-inch f/3 first, then pushed faster to a 10-inch f/2.7 and a 6-inch f/2.8 that he made in tandem.

All three scopes were wildly successful, so he decided to push onward with larger, faster mirrors. Next up was a 25-inch blank that was slumped to f/2 by ATM Greg Wilhite, who presented it to Mel as a gift. F/2 was way faster than Mel wanted to go, but as he says, "I do not look gift horses in the mouth and took the glass with many thanks."

MEL BARTELS (3); FLEX ROCKER: JERRY OLTION

▲ Mel's grinding machine can handle up to 42-inch mirrors. Here it's polishing the 25-inch mirror.

He decided to grind it back to f/2.6, which would leave him with a half-inch-thick edge. He did that in about a month of hand grinding, then fine-ground it for another 70 hours. He had to stop at 20-micron grit, since the thin mirror flexed too much and scratched with finer grits.

There was no way Mel was going to polish and parabolize a mirror that size and that rough by hand. So he spent a year making a grinding and polishing machine. Because he eventually plans to make a 42-inch ultra-fast scope, Mel designed it to handle up to that size. He put the 25-inch on the machine, and 74 hours of polishing later, using pads on the grinding tool, there were no pits left. But polishing pads leave an irregular figure, so Mel made a hydrostone-and-pitch tool and polished for another 69 hours, eventually bringing it to spherical.

Then came the hard part: parabolizing. I'll spare you the gory details, other than to point out that Mel did the entire process with the matching Ronchi test and star testing, eventually (after 181 hours) coming up with a parabola that provides (with a coma corrector) pinpoint stars from edge to edge of the field. The temptation to tweak it further was great, but as Mel says, "Somewhere in the intersection between personal skill, Ronchi matching test and star test results, and the risk of making the mirror's profile worse and having to start over, the 'observer' seizes the mirror from the 'maker' and sends it off to be aluminized."

With the mirror done, Mel turned to the scope that would hold it. At f/2.6, the eyepiece would be below eye level at zenith, which meant he had some room to play around with a concept he had been considering while he polished: how to eliminate the dreaded Dob's hole with an alt-az mount.

The solution was simple, elegant, and apparently brand-new: add a second altitude axis! When the scope is raised toward the zenith, instead of twisting it in azimuth for sideways motion the way a regular Dobsonian mount requires, just push it sideways on another axis 90° from the standard one. Mel built a second flex rocker on top of the first, placed the OTA on it, and shoved. It worked beautifully! And thus the alt-alt-az mount was born.

When aimed near the horizon, the scope behaves just like a standard Dobsonian: You raise and lower it for altitude, and you push and pull it around in a circle for azimuth. As you raise it up toward the zenith, however, the second altitude axis comes into play. By 60° elevation or so, the scope gently starts to rock sideways as well as rotate when you push, and the higher you're pointed the more rocking and less rotation you get. At the zenith it's all rocking motion, no matter which direction you push.

▲ The mirror box also folds up to protect the primary during travel.

Mel designed the second altitude axis to have about 15° — one hour — of motion. He also gave himself an extra 7½° beyond vertical in the regular altitude direction. That lets him observe an object right on through the zenith without twisting the scope in azimuth.

Dob's Hole

"Dob's hole" is the gymbal lock experienced when observing near the zenith with a Dobsonian mount, although Mel points out that it's "rather unfair to call this Dobson's hole since John Dobson hardly wanted the telescope he invented to be called the Dobsonian in the first place."

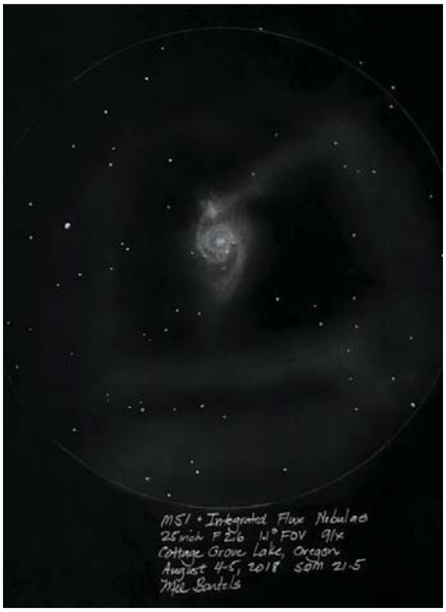
◀ An extra flex rocker provides a second altitude axis, completely eliminating "Dob's hole."

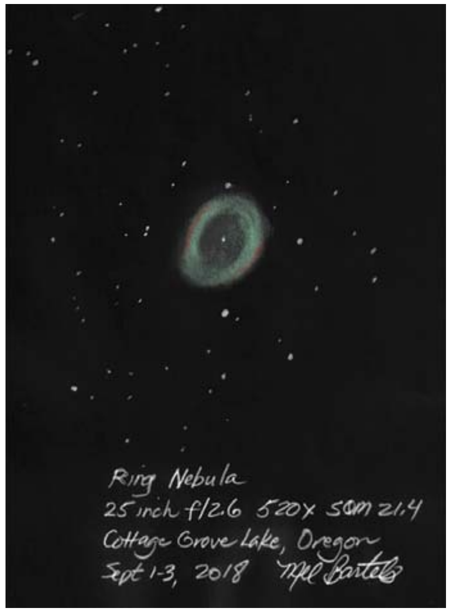
With a telescope this fast, a coma corrector is essential. At f/2.6 Mel can just squeak by with a 2-inch Paracorr, but he wanted the capability to use a 3-inch corrector for a wider fully illuminated field. That would require a 3-inch focuser, which is both heavy and expensive.

Mel and Pierre Lemay were in constant contact during the building process, and when Pierre heard about this problem, he said, "Why don't you use the barrel of the coma corrector as the drawtube of a helical Crayford focuser?" In fact, Pierre offered to make just such a focuser for him.

A helical Crayford foregoes the threaded barrel that standard helical focusers use in favor of angled bearings that rest against the drawtube. Rotating the tube makes it crawl inward or outward along the bearings' angle of attack, while a friction pad holds the tube against those bearings and provides the right amount of resistance.

Somewhere along the line as he was designing the focuser, Pierre had a brainstorm: If he put the friction block on a screw that pulled it from side to side, he could provide a fine motion control. And thus the two-speed helical Crayford focuser was born.





▲ *Left:* Using the 25-inch, Mel traced out tendrils of galactic cirrus all around M51. *Right:* The Ring Nebula shows color in a scope this large.

M51, M57 SKETCHES: MEL BARTELS (2); FOCUSERS: JERRY OLTION (2)

The focuser coarse-focuses with a twisting motion like any helical design, and it fine-focuses with a threaded shaft that pulls and pushes the friction block tangentially across the drawtube. The pitch of the screw determines how incremental the fine motion is. Experimentation quickly showed that Pierre would need a coarse thread to keep from making multiple turns for even the finest adjustment. He settled on a multi-lead screw with a draw of 3 turns per inch, which gave a coarse-to-fine focus ratio of about 32:1, which is perfect for fast telescopes where the tight depth of field leaves no room for error.

Pierre's first attempt, using a cylindrical Delrin friction block, proved too slippery, but he re-did the friction block with a rectangular cross section

▼ *Left:* Pierre Lemay's two-speed helical Crayford focuser incorporates the 3-inch paracorr as a drawtube. *Middle:* The fine-motion mechanism moves a nylon block sideways to provide minute adjustment to the helical twist. *Right:* A helical Crayford focuser uses angled bearings to direct the drawtube inward and outward as it's twisted.

▶ Pierre has designed an easy and inexpensive two-inch plywood version of his two-speed helical Crayford focuser.

and that worked like a charm. Mel reports that the focuser works beautifully on his new scope.

An interesting detail: The coma corrector intrudes into the light path by an inch or so. That allowed Mel to use a smaller secondary mirror, which provides less overall obstruction than if he had moved the coma corrector farther out.

One of Mel's big observing interests is tracing out the delicate web of galactic cirrus, the gas and dust within our galaxy that's illuminated not by any single star but by the combined glow of the entire Milky Way Galaxy. He wrote about it in our April 2017 issue, and he continues to search out new patches of galactic cirrus whenever he can. This new scope is great for that. With its wide field and large aperture, faint nebulosity really stands out nicely. Mel reports that the Ring Nebula (M57) also sports color when viewed directly on.

I had the pleasure of viewing through this innovative optical masterpiece, and I can confirm that it is a joy to use. With the Veil Nebula nearly straight overhead, I was guiding the scope with the ease of a ball-mounted scope and enjoying the sharp-focused view from a 25-inch aperture mirror, seeing details I'd never seen before — all with both my feet flat on the ground.

Now that's what I call a multiple breakthrough.

For more information about this telescope and many of Mel's other designs, visit Mel's website at **bbastrodesigns.com**.

Visit Pierre Lemay's website at **telescopelemay.com** if you'd like to learn more about the focuser, including plans for a plywood 2-inch version seen above that can be built for about $15 in parts with little more than hand tools and a drill press.

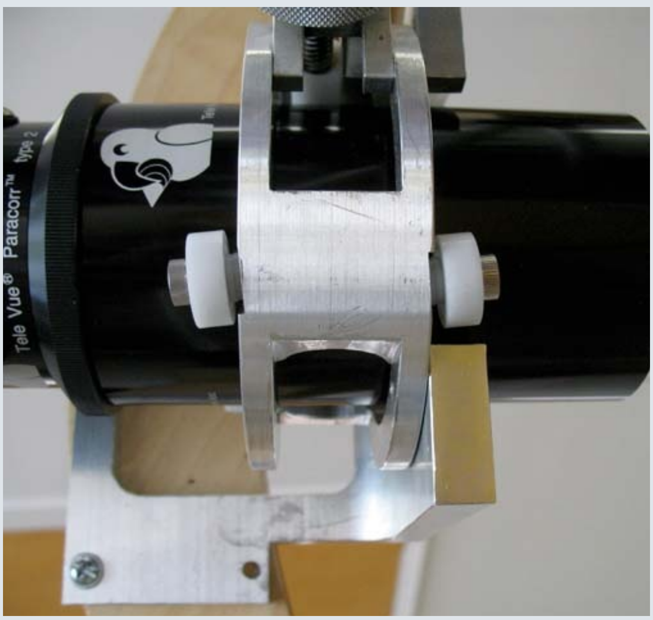
■ Contributing Editor **JERRY OLTION** is easily impressed . . . with innovations as impressive as these!

▲ Mel barely hunches down to look in the eyepiece of the scope near zenith.

SHARE YOUR INNOVATION

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

PLYWOOD FOCUSER: PIERRE LEMAY; SECONDARY MIRROR: MEL BARTELS; MEL AT SCOPE, BEARINGS: JERRY OLTION (2)



▲ The secondary mirror is supported using solid wire and only requires minor adjustment after each setup.

SMARTPHONE NIGHTSCAPING

Mehdi Momenzadeh

An imager prepares to capture the night sky to the south while the constellation Perseus, along with NGC 869 and NGC 884, the Double Cluster, are seen to the right rising above the village of Filband, Iran.

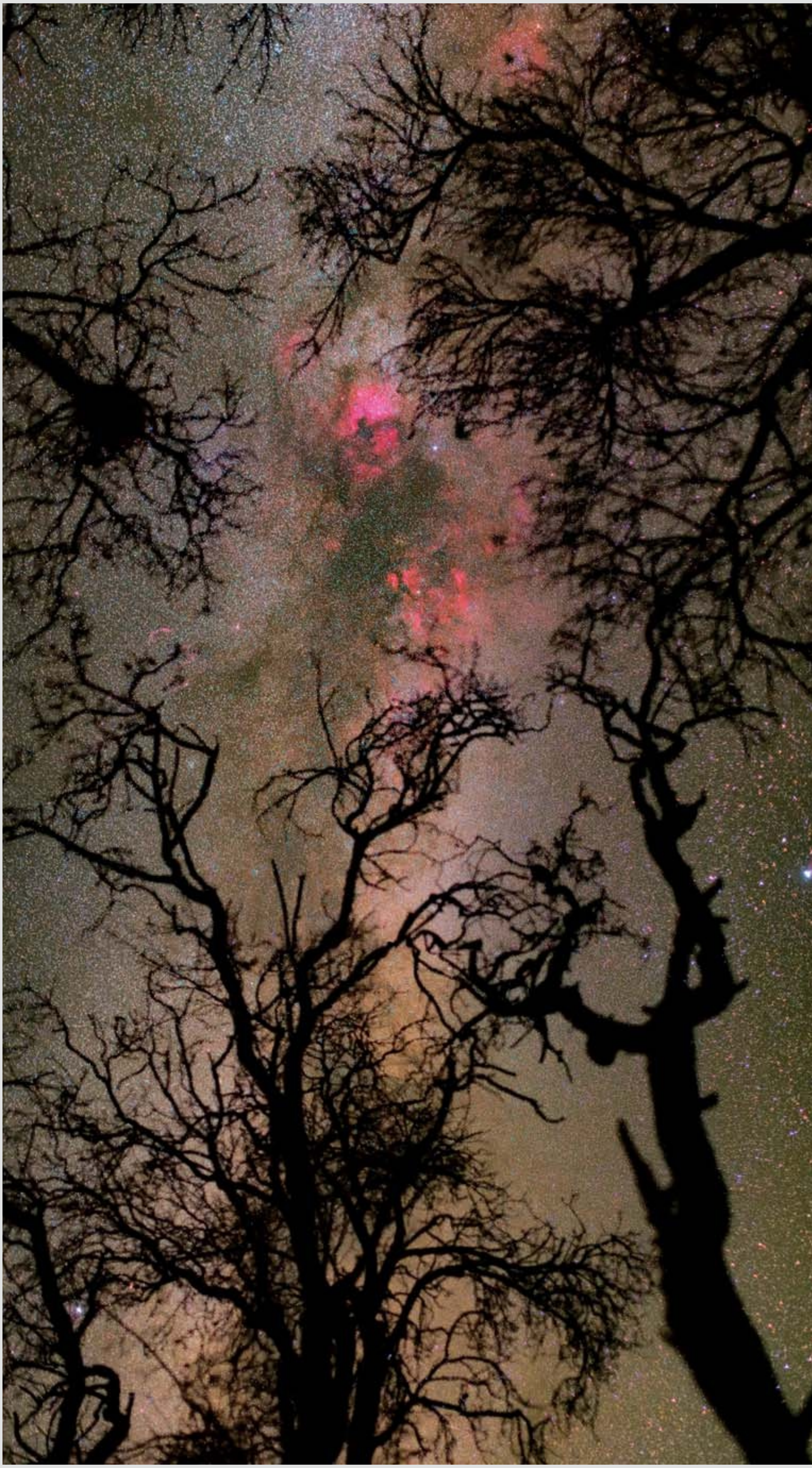
DETAILS: *Huawei P20 Pro smartphone. Panorama of several 30-second exposures at ISO 1250, f/1.8.*

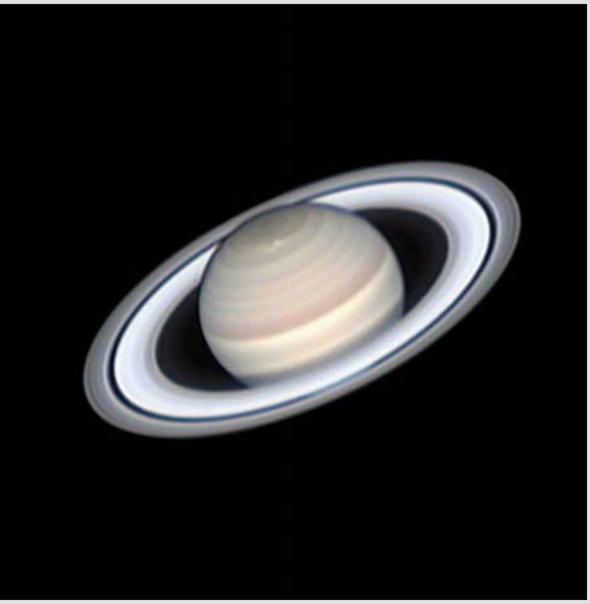
▷ SPYING THE SWAN

Amir Shahcheraghian

Large regions of emission nebulae in Cygnus, including NGC 7000, the North America Nebula (upper middle), and IC 1318, the Butterfly Nebula (middle), peek through the trees in Iran's Khar Turan National Park.

DETAILS: *Canon EOS 6D DSLR camera with 50-mm lens at f/2. Total exposure: 25 seconds at ISO 4000.*





△ SATURNIAN STORM

Antonio Checco

Among the many atmospheric belts in Saturn's cloudtops, a small, white storm is seen near the Ringed Planet's north polar region at 3:07 UT, July 7, 2018.

DETAILS: *Homemade 13-inch Newtonian reflector at f/20 with ZWO ASI290MC video camera. Stack of roughly 15,000 frames.*

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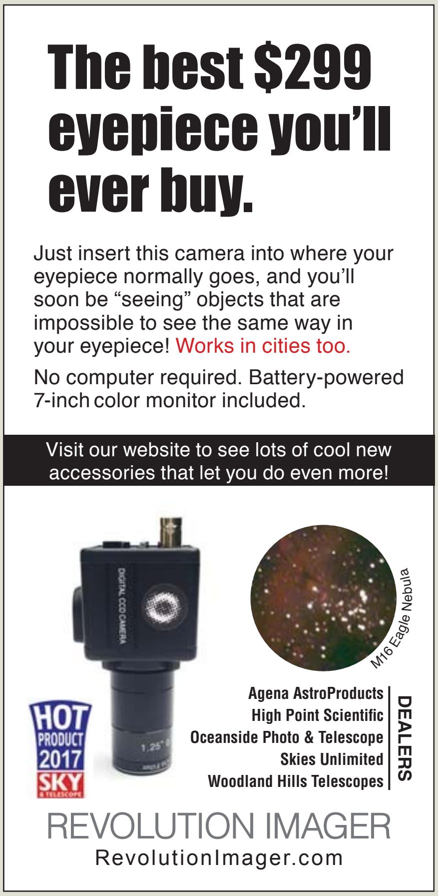

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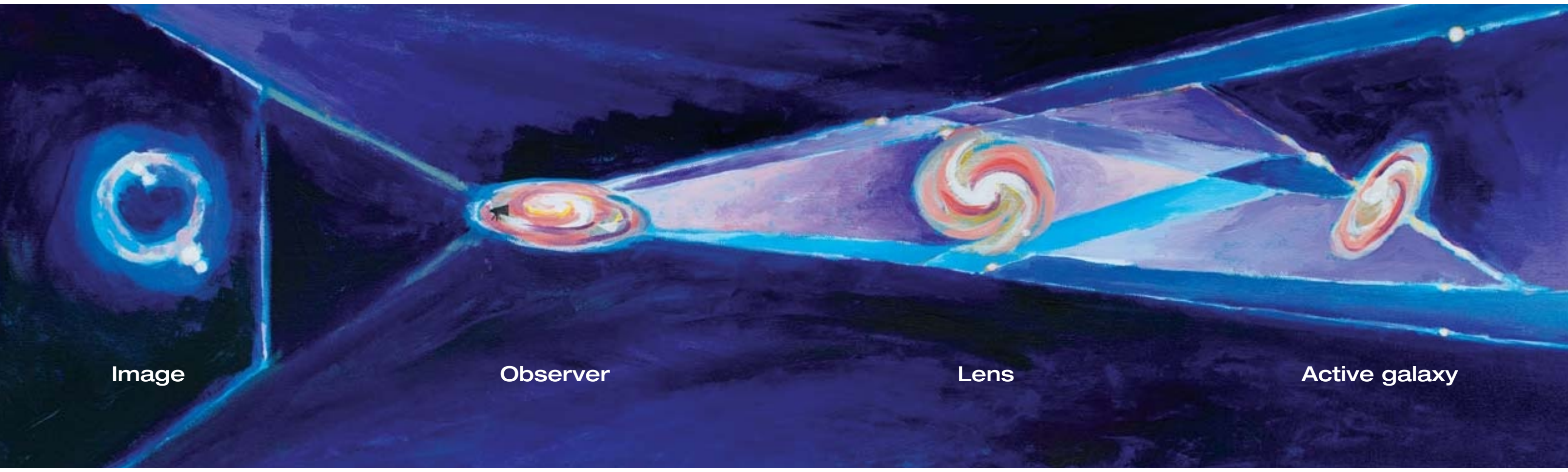

The Art of Gravitational Lensing

To share the elegant but deeply complex phenomena she studies, an astrophysicist turns to an artist.

INTERACTIONS BETWEEN the arts and sciences have long influenced the way we perceive and understand our world. In the Renaissance, artists focused on accurately depicting depth by using math to rediscover linear perspective, which had been lost in medieval times. In the 1880s, artists captured impressions of their surroundings by exploring the mixing of light and color as described by physicist and color theorist Ogden Rood. Today, however, our scientific endeavors have become so dazzlingly complicated that they limit possibilities to inspire and communicate.

I use *strong gravitational lensing* to uncover complex structures of distant, active galaxies. In my enthusiasm to share my research, I've taken listeners on virtual trips from Earth to an intervening galaxy and beyond it to the background source it lenses. Like an aircraft marshaller, I've relied on theatrical hand gestures to guide others along the multiple paths into which a lensing galaxy splits light. Unfortunately, because of those trajectories' intricacies, I'd lose even the most curious people somewhere between the lens and the source. This was often just before I could share what I actually work on: the origin of outbursts from powerful jets launched near supermassive black holes within those background active galaxies.

The challenge to keep my listeners' attention ended thanks to a collaboration with artist Marlena Bocian Hewitt. Marlena employs art to empower girls and promote women in STEAM (Science, Technology, Engineering, Arts, and Math). Eager to incorporate the arts into my research, I invited Marlena to illustrate my work on lensing. After a dozen drawings, we converged on a scientifically satisfying solution, which Marlena rendered into a captivating piece of art (above).

The painting beautifully illustrates a lensed active galaxy with a pair of relativistic jets (beams of ionized matter accelerated close to the speed of light). The light escaping the jet travels toward the observer and encounters a galaxy along the observer's line of sight. The intervening galaxy curves spacetime, which acts as a lens that magnifies and splits the light of the source along multiple paths. These paths have differing lengths and traverse various depths of the lensing galaxy's gravitational well. As a result, light traveling different paths arrives at different times at the observer (note tiny telescope within the "Observer" galaxy). We can measure these time delays, and because they depend on the location of the source, we can study them to find out where along the relativistic jet the light originated.

Marlena drew on both cubism and futurism to depict gravitational lensing. Interestingly, both cubism and relativity were inspired by the mathematician Henri Poincaré's work on geometry. In his general theory of relativity, Einstein used the geometrization of space and time to predict light bending. In cubism, Picasso, Braque, and others abandoned a single viewpoint and relied on geometric shapes and interlocking planes to represent reality.

We scientists have to stay true to the laws of physics and boundaries set by observations. Thankfully, though, abstract artists can take a viewer beyond the four dimensions of spacetime and into a universe limited only by their imaginations.

■ **ANNA BARNACKA** is an astrophysicist at the Harvard-Smithsonian Center for Astrophysics and Jagiellonian University in Poland. She is also an inventor-turned-entrepreneur. In her free time, she enjoys neuroscience, martial arts, and flying airplanes.

MARLENA BOCIAN HEWITT