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THE ESSENTIAL GUIDE TO ASTRONOMY

What We've Learned About MARS

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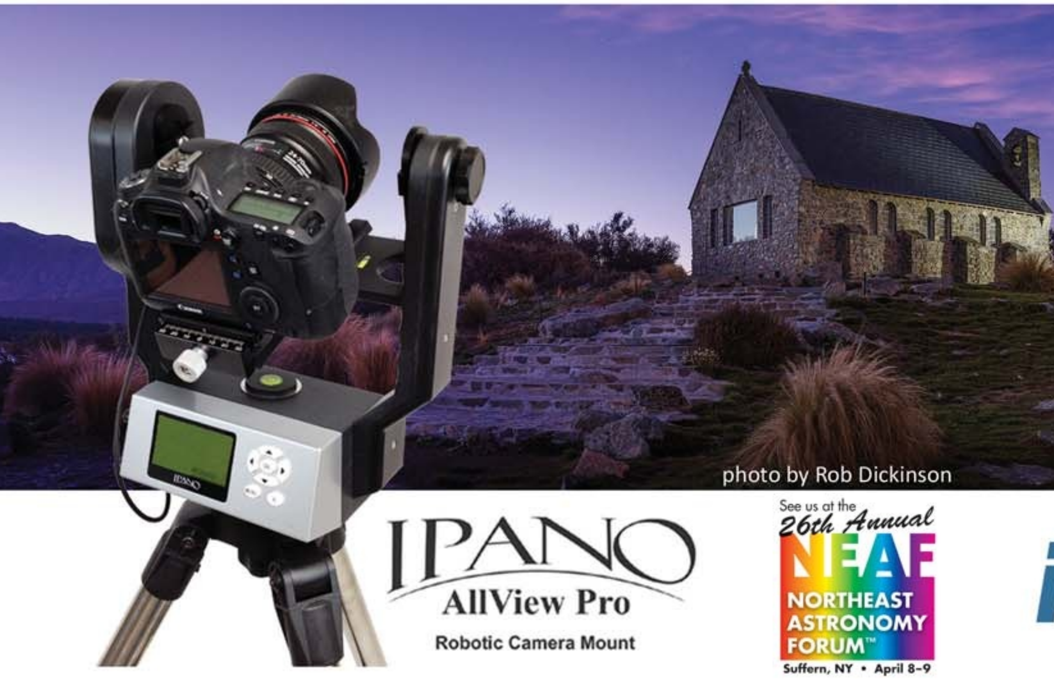

photo by Rob Dickinson

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THE ESSENTIAL GUIDE TO ASTRONOMY

ROGELIO BERNAL ANDREO

April 2017 VOL. 133, NO. 4

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NASA's plutonium-powered rover has trekked more than 15 km across Mars.

NASA / JPL-CALTECH

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On the Alert for Apparitions

ASTRONOMERS AND ASTROPHYSICISTS believe in ghosts. It's kind of a professional hazard not to.

Before they glimpsed the long-sought Higgs boson in 2012, for instance, CERN researchers put their hope in chasing these subatomic things that go bump in the night. LIGO scientists dreamed of specters before they picked up the fleeting blip, in 2015, of gravitational waves from the merger of two black holes (*S&T:* May 2016, p. 10).

In this issue, we report on a number of other ethereal phenomena. In "Spirits of Our Galaxy's Past" (page 22), Web Editor Monica Young dives into the wraith-like streams of stars coursing through the halo that enshrouds our galaxy. These stellar ribbons — erstwhile dwarf galaxies that the Milky Way's gravity unraveled long ago — are helping astronomers analyze our galaxy's dark matter (a phantom if there ever was one).

The ghostly Sagittarius Stream enwraps the Milky Way in this artist's concept. See page 22.

AMANDA SMITH, INSTITUTE OF ASTRONOMY, UNIVERSITY OF CAMBRIDGE

In "Herschel's Ghosts" (page 30), amateur astronomer Mel Bartels focuses on the nebulous streamers of gas and dust that extend far above and below the plane of the Milky Way disk. First detected by William Herschel in the late 1700s, this "galactic cirrus" offers amateurs a challenging observing prospect.

Harvard's Andrew Vanderburg sought the singular when he noticed, in Kepler's K2 data, something odd about a white dwarf known as WD 1145. This moribund star showed weird fluctuations in brightness. Further work has shown that WD 1145 appears to be gobbling up one or more planets that ventured too close — as we watch. Advanced amateur Mario Motta, who has been assisting Vanderburg by recording these variations using his 32-inch home telescope, tells that captivating tale of pro-am collaboration on page 66.

Astronomers *have* to believe in ghosts; otherwise they might miss something big. Sometimes huge discoveries are predicted, as gravitational waves were, but other times they come out of the blue. Radio astronomers Arno Penzias and Robert Wilson weren't looking for the cosmic microwave background when they stumbled upon it in 1964. When Saul Perlmutter, Brian Schmidt, and Adam Riess set out in the 1990s to observe distant supernovae, they weren't expecting to uncover dark energy. But those serendipitous revelations earned these men the Nobel Prize in Physics in 1978 and 2011, respectively.

So keep an eye out for the wispy, the half-seen, the fantastically transitory. You might just unmask a chimera that actually exists.

Peter

Editor in Chief

SKY&TELESCOPE
The Essential Guide to Astronomy

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Photo credit: Vince Bygrave

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ATIK CAMERAS

A New Look for *S&T*

Congratulations on the very handsome upgrade to the magazine. Everything is, indeed, more readable, and the logo is much improved. Do I detect a slight bias toward visual observing, perhaps in honor of the new look? Seeing the night sky well is a cultivated skill. I particularly enjoyed the excellent graphic illustrations of January's issue — you have successfully reduced complex data to compelling visuals. I started my love affair with *Sky & Telescope* almost 50 years ago but fell off the wagon to pursue more terrestrial adventures. It is a delight to return to astronomy with such a faithful companion.

Fred Housel
Roche Harbor, Washington

Congrats on the new layout and cover — definitely an improvement! I started subscribing to *S&T* 25 years ago, and I liked the cover with the telescope icon in the upper right and the unobtrusive magazine name that left the focus on the cover image. The new look goes back to those roots, with more focus on the cover picture but absolutely contemporary. This holds for the fresher, more modern look of the interior as well. Well done!

Dieter Kreuer
Düren, Germany

Just a note to congratulate Pat Gillis-Coppola and the others involved in *S&T*'s superlative makeover. I'm retired from the magazine business, so I know firsthand of the work, creativity, and labor of love involved. Kudos!

Dave Howard
Ajo, Arizona

I like *Sky & Telescope*'s new logo. Good job! However, I shall always miss the huge, sprawling (sky-spanning) lettering of the 1960s-era masthead.

Tom Mehl
posted via Facebook

When I received January's issue in the mail, I didn't recognize it — and that isn't a compliment. Your magazine has gone from easily identifiable, both in the mail and on the newsstand, to one of the many, many, minimalist designs that blend in instead of standing out.

Karl Kleese
Hollywood, Florida

I liked the old logo design. Stood out in a stack of magazines. BIG red square made it easy to spot.

John Rockis
posted via Facebook

I like the new logo's equal emphasis on the words "Sky" and "Telescope." For many of us, the telescope is as big a part of the hobby as observing.

Chris Monck
posted via Facebook

I wish to register my strong protest of your decision to remove any mention of Pluto from your monthly Planetary Almanac. I understand that it's no longer officially considered a "planet," but Pluto remains a viable and popular observing target for amateur astronomers, and I have always relied on *S&T* to provide me with accurate positional information. The decision seems odd in the face of a considerable bit of wasted space introduced by the redesign. It's visually nice, but too much space is wasted on form to justify the elimination of a useful function.

As with many amateurs, I am attracted to observing Pluto partly because of its historical significance and partly because it is the only example of its class of object available to me for direct observation. Rational or not, Pluto is a hot-button topic among amateurs and professionals right now. Does it seem wise to antagonize a portion of your readership like this?

Rick Woods
Black Canyon City, Arizona

S. N. Johnson-Roehr replies: *Most of the discussion in Sun, Moon & Planets and in Planetary Almanac concerns naked-eye objects. A small fraction of that space was given over to Uranus, Neptune, and Pluto. We'll still cover Pluto fully in Celestial Calendar near its opposition each year — including detailed finder charts — should any readers desire to locate it.*

Proxima Centauri's Planet

Thank you for the informative report on Proxima Centauri b (*S&T:* Dec. 2016, p. 10). While looking at the radial-velocity plot on page 11, I couldn't help but

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notice the steady downward tilt of the curve, and I wonder what caused it. My first guess was that it's due to the orbital motion of the Proxima Centauri system within the Alpha Centauri system, but I wasn't sure that this would be so noticeable in a period of just 90 days. Is there another cause, or is the tilt just an artifact of some sort?

Bob Eramia
Seattle, Washington

Camille Carlisle replies: *I wondered about that slant, too! It's caused either by stellar activity or by an additional (unconfirmed) planet. The discoverers aren't sure which — they're still gathering data and hope to pin down the answer next year. At this point it's difficult to tell how long that "extra cycle" is. The most likely period is between 40 and 200 days, but this could be influenced or entirely caused by the star's rotation (about every 80 days), which tends to "inject" spurious signals that are half as long as the full rotation period. We don't know what it is yet — real or an artifact — but it could be exciting.*

Universe According to Poe

I enjoy articles that explore the astronomical connections of historical figures such as Stonewall Jackson (*S&T:* May 2013, p. 32) and Edgar Allan Poe (Dec. 2016, p. 30). The people who came before us lived under the sky, just as we do.

Is it possible that, in his *Eureka*, Poe made an intuitive leap from observing, say, M31 or NGC 891 to his thoughts on the Milky Way? I'm assuming his skies were better than ours and that he had access to larger scopes than his own. Tracking down this question might make for an interesting follow-up article.

Steven Heckenlively
Camarillo, California

A "Virtual" Skyscraper

In Eli Maor's article about witnessing the 1925 total solar eclipse from New York City (*S&T:* Jan. 2017, p. 66), the Empire State Building is prominently depicted — presumably to set the stage for the greatest spectacle of the age for that city. However, its construction did not start until 1930, with its grand opening celebrated on May 1, 1931.

Mike Dahl
Weston, Connecticut

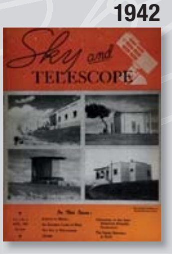
FOR THE RECORD

- The comment about the siege of Leningrad (*S&T:* Jan. 2017, p. 7) should note that valuable items at Pulkovo Observatory were moved prior to the Germans' (not Russians') assault.
- The longtime meteor observer quoted regarding the Ursid meteor shower (*S&T:* Dec. 2016, p. 49) is Robert Lunsford.

LETTERS TO THE EDITOR: *Sky & Telescope,* 90 Sherman St., Cambridge, MA 02140-3264 or email: letters@skyandtelescope.com. Please limit comments to 250 words.

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

1942



1967

1992

April 1942

Heavenly Veil "Study of the composition of the interstellar medium calls for powerful instrumental equipment, because the interstellar lines are to be observed only on a background of the spectra of distant stars. . . .

"Dr. Joel Stebbins [reported] his photoelectric measures of the irregularly distributed absorbing clouds in the galactic plane. These data have given a final answer to the question of whether the quality of the absorption (in its effect on light of different colors) is different in different parts of the sky. It is the same everywhere."

Joel Stebbins, then director of Washburn Observatory, pioneered the use of photoelectric devices in astronomy. Here, Cecilia Payne-Gaposchkin reported highlights from a conference at Mexico's Tonantzintla Observatory, soon to play its own key role in the photoelectric photometry of bright stars.

April 1967

Galactic Heart "The very small, dense center of the Milky Way galaxy has finally been observed in infrared radiation. E. E. Becklin and G. Neugebauer of California Institute of Technology reported their observations to the American Astronomical Society at Los Angeles in late December.

"The initial detection, in the wavelength range 2.0 to 2.4 microns, was made last summer with the 24-inch reflector on Mount Wilson . . . The infrared emission agrees in position and size with the radio source Sagittarius A, which is believed to lie at the galactic center. . . . [A]t the center of the source there is a core of radiation 30 seconds of arc in diameter (1.5 parsecs)."

Fifty years' observations have refined this picture greatly. A supermassive black hole, at a point called Sagittarius A, is today considered the true galactic center. Several stars, within a few tenths of an arcsecond away, show clear orbital motion around this site.*

April 1992

Why the Spin? "In the 1980's astronomers found a number of young solar-type stars spinning at dizzying speeds. For example, some Pleiades members rotate in just six hours, whereas the Sun takes a leisurely 25 days to complete one turn. This led to speculation that all low-mass stars go through a period of extremely rapid rotation and then gradually slow as their stellar wind carries away angular momentum. . . .

"Using telescopes at observatories in Chile and Arizona, Douglas Duncan (Space Telescope Science Institute) determined the spin rates and ages for 40 pre-main-sequence stars in Orion. He found that . . . most took between four days and two weeks to complete a rotation. More importantly, he detected no correlation between a star's age . . . and its spin rate."

Last year, NASA's Kepler was used to survey spin rates in the Pleiades. One finding: The least massive stars are the fastest spinners.

RADIO ASTRONOMY

Fast Radio Burst Has Surprising Source

FOR THE FIRST TIME, astronomers have placed a mysterious type of radio signal on the cosmic map — and it's in a dwarf galaxy.

The source, FRB 121102, was first detected in 2012 as a *fast radio burst* (FRB): an ultrabright, ultrabrief burst of radio waves with mysterious, likely extragalactic origins (*S&T:* July 2016, p. 24). But unlike its cousins, which have only burst once before disappearing, FRB 121102 has flared up several times, making it the only one known to repeat.

FRB 121102's repetitions have caused trouble for theorists, because many thought that FRBs must be catastrophic, one-time events, like collisions between neutron stars or collapsing supernovae. That couldn't be universally true if one were to repeat, as this one has; its source clearly survived.

The puzzling repetitions have now helped astronomers, by enabling them to finally tie this fast radio burst to its home galaxy.

Shami Chatterjee (Cornell University) and colleagues used the Karl G. Jansky Very Large Array in New Mexico to catch nine bursts from FRB 121102, localizing it to within 0.1 arcsecond. That's 0.006% the diameter of the full Moon.

The team then used the Arecibo radio telescope and the continent-spanning European VLBI Network to further winnow down its location. They determined that the bursts originated from a 25th-magnitude smudge. The emissions also coincided with a persistent radio source at the same location. Follow-up observations with the Gemini North Telescope on Mauna Kea, Hawai'i, revealed that the smudge was actually a dwarf galaxy 2.5 billion light-years away. The team reported the result on January 4th at the American Astronomical Society meeting in Grapevine, Texas, and in the January 5th *Nature*.

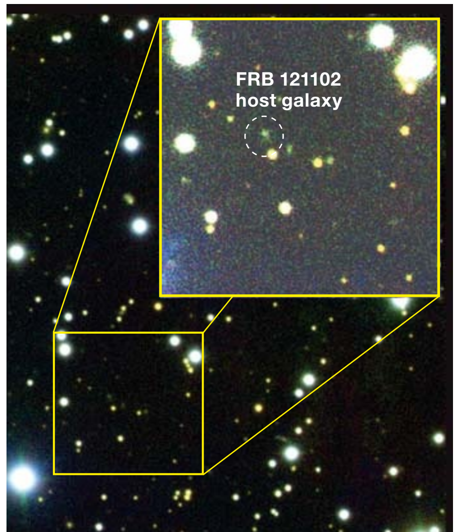
"The location is so precise that there's no question about the host galaxy," says Emily Petroff (Netherlands Institute for Radio Astronomy), who was not involved in this study. "So we finally have some answers!"

One of those answers is the original brightness of the source. "Just for an instant, when this burst flashes, the luminosity of that burst outshines all the stars in its own galaxy by far," says study coauthor Sarah Burke-Spolaor (West Virginia University). It even rivals active galactic nuclei (AGN), which are powered by accreting supermassive black holes.

Because the few stars the dwarf galaxy contains seem relatively young, the FRB likely doesn't come from a neutron star. These stellar corpses have been a popular explanation for the bursts. There is, however, a persistent nearby radio source within the galaxy, which might or might not be related.

One speculative scenario is that the persistent radio source is an AGN that blows bubbles of plasma into space, which glow for a snapshot of time before they're destroyed, flashing as the radio burst. Since the galaxy will likely replenish those bubbles, this could happen again and again.

■ SHANNON HALL



This Gemini North composite image of the field around FRB 121102 shows the 25th-magnitude dwarf galaxy (circled in inset) that hosts the repeating radio burst.

GALAXIES

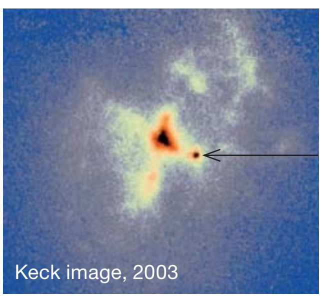
Mystery Object in Cygnus A

ASTRONOMERS have discovered an object in the active galaxy Cygnus A that wasn't there before. Rick Perley (NRAO) and colleagues discovered the whatever-it-is using the Very Large Array (VLA) in New Mexico. The object (circled) lies roughly 1,300 light-years southwest of the galaxy's central black hole, which powers two gigantic jets. The last time VLA looked at Cygnus A was 1989, and the source wasn't there. Perley announced the find at the American Astronomical Society meeting in Grapevine, Texas.

It turns out, however, that the discovery is a *rediscovery*. In 2003 Gabriela Canalizo (now at University of California, Riverside) and colleagues found the source in infrared images from the Keck II telescope in Hawai'i. Both teams have also found it in some (but not all) Hubble images.

The whatchamacallit is about twice as bright as the brightest known supernova at these radio frequencies. In fact, it's much brighter than just about any transitory radio signal known, except for accreting supermassive black holes and *tidal disruption events*, outbursts created when a black hole eats a star. Both teams suspect that the object is the core of a small galaxy that Cygnus A tore apart and ate; perhaps a black hole lies within.

■ CAMILLE M. CARLISLE



• **Read more about the mystery: https://is.gd/cygmystery.**

GEMINI NORTH: GEMINI OBSERVATORY / AURA / NSF / NRC; CYGNUS A: G. CANALIZO ET AL. / *ASTROPHYSICAL JOURNAL* 2003

STELLAR

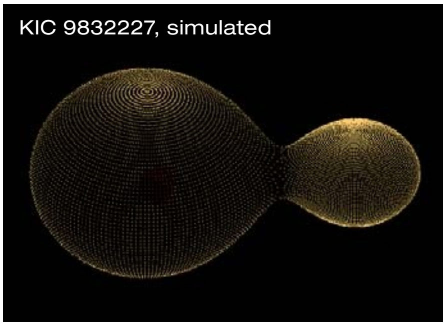
Paired Stars in Cygnus En Route to Merger?

IF LAWRENCE MOLNAR (Calvin College) and his colleagues are correct, the two stars in the binary KIC 9832227 are about to merge.

Stellar mergers are not a new idea. Astronomers suspect they happen in densely populated places, such as the ancient balls of stars known as globular clusters. Craig Wheeler (University of Texas, Austin) and a team of undergraduates also recently suggested that Betelgeuse might be the result of a merger, explaining its unusually fast spin. (The union of two stars should create a whirligigging superstar.)

Astronomers have already observed a stellar merger. In 2008, the star V1309 Scorpii revealed its existence when it suddenly flared. Follow-up work by Romuald Tylenda (Nicolaus Copernicus Astronomical Center, Poland) and colleagues using archival observations determined that V1309 Sco was likely a contact binary star — paired suns that orbit so close together, they kiss.

At first, V1309 Sco's two stars orbited each other about every 1.4 days. That period shortened as the stars' outer



atmospheres combined to wrap them both in a single envelope. When this happened, the object began to brighten, then faster, until the two stellar cores merged, releasing energy and dazzling observers with an outburst 10,000 times brighter than the pair's original luminosity.

Molnar's team argues that KIC 9832227 is en route to the same fate. This 12th-magnitude binary in the constellation Cygnus has a current orbital period of about 11 hours. The astronomers have been following the system for several years due to its shrinking period, suspecting it's akin to V1309 Sco.

Now, using observations spanning 17 years, Molnar's group has confirmed there's no distant, unseen companion star messing with the binary's period. They also found that the period has continued to shorten — by about 1 second, overall.

Using V1309 Sco as a model, the astronomers predict that KIC 9832227's duo will merge in 2022, give or take a year. Molnar announced the gutsy prediction January 6th at the American Astronomical Society meeting in Grapevine, Texas.

Other binary-star astronomers are skeptical. Statistically, researchers should have had to trawl through a much larger number of stars before turning up this kind of system, Tylenda points out. Another astronomer wondered whether the model used to predict the timing for this whole process is really dependable enough to pinpoint 2022.

KIC 9832227's location and magnitude make it an excellent target for amateurs. Molnar is currently working on a website where amateurs will be able to upload their observations and which will calculate how well those data match the team's predictions. That way they can test whether this bold prognostication is true.

■ CAMILLE M. CARLISLE

• **Find the paper with coordinates and more info at https://is.gd/cygnusmerger.**

IN BRIEF

"Brightest Supernova Ever" a Shredded Star?

Hailed as the "most luminous supernova," the object dubbed ASASSN-15lh (*S&T:* Nov. 2015, p. 12) is still mystifying astronomers. It appeared to be the death of an extreme type of star, exploding with twice the brightness of any other known supernova, then threw researchers for a loop when it rebrightened (*S&T:* Sept. 2016, p. 8). A new study by Giorgios Leloudas (Weizmann Institute of Science, Israel) and colleagues using the Hubble Space Telescope refines ASASSN-15lh's location, placing it within 1,000 light-years of its host galaxy's center — and possibly in the center itself. Paired with spectroscopic observations, the result suggests the burst might instead be the death of a star ripped apart by the galaxy's supermassive black hole, the team argues in the December 12th *Nature Astronomy*. But other researchers dispute the spectral lines' meaning, and the mystery remains.

■ MONICA YOUNG

Read the details at **https://is.gd/asassntde**.

Astronomers Discover Roundest Star

Stars, planets, and other celestial objects generally bulge out along their equators as they spin. But Laurent Gizon (Max Planck Institute for Solar System Research, Germany) and colleagues have now found a star that's round to within 0.0002% — "the most spherical natural object ever measured," the authors claim in the November *Science Advances*. The *A*-type star, KIC 11145123, is more than twice as wide as the Sun. By following its brightness variations over four years, the observers watched the star expand and contract slightly as sound waves rang through its interior, and from that information they determined its oblateness. The result is only one-third as squat as expected, given the star's slow, 100-day rotation rate. One caveat: Mercury and Venus might be equally round, but we don't have their shapes measured to this level of precision.

■ MONICA YOUNG

Deaths of Note

Two notable figures in space exploration and astronomy passed away in December. Astronaut John Glenn (1921–2016) became the first American to orbit Earth in 1962. In 1998 he returned to orbit as the oldest man to fly in space, serving on the Space Shuttle *Discovery*. Astronomer Vera Rubin (1928–2016) confirmed the existence of dark matter, thanks to her careful observations of stars' rotation speeds around their galaxies.

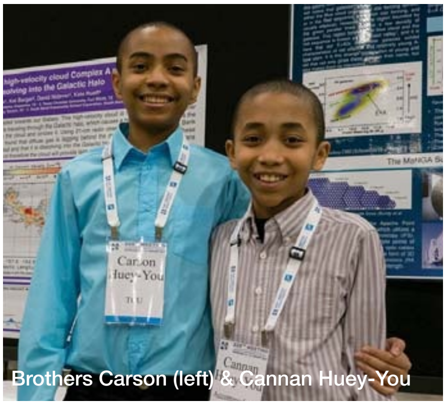
■ *S&T* EDITORS

Read Shannon Hall's remembrance of Rubin at **https://is.gd/rubinobit**.

L. MOLNAR / CALVIN COLLEGE

COMMUNITY

• Read more about the Huey-You brothers at https://is.gd/aasbrothers.


Brothers Carson (left) & Cannan Huey-You

Preteen Astronomer Shines at AAS Meeting

JUST 11 YEARS OLD, Cannan Huey-You presented a poster of his research on January 6th at the American Astronomical Society meeting. His research topic, a massive intergalactic gas cloud known as Complex A, is destined to crash into the Milky Way's disk as a high-velocity cloud, triggering a burst of star formation (*S&T:* Jan. 2017, p. 16).

Already a high-school senior, Cannan has been working with astronomer Kathleen Barger (Texas Christian University) for the past 2½ years. Together, they studied Complex A, which has about 2 million times the mass of the Sun and is just one of many gas clouds surrounding our home galaxy. Now only about 15,000 light-years out, this huge mass of hydrogen should collide with the galaxy's disk in a few hundred million years.

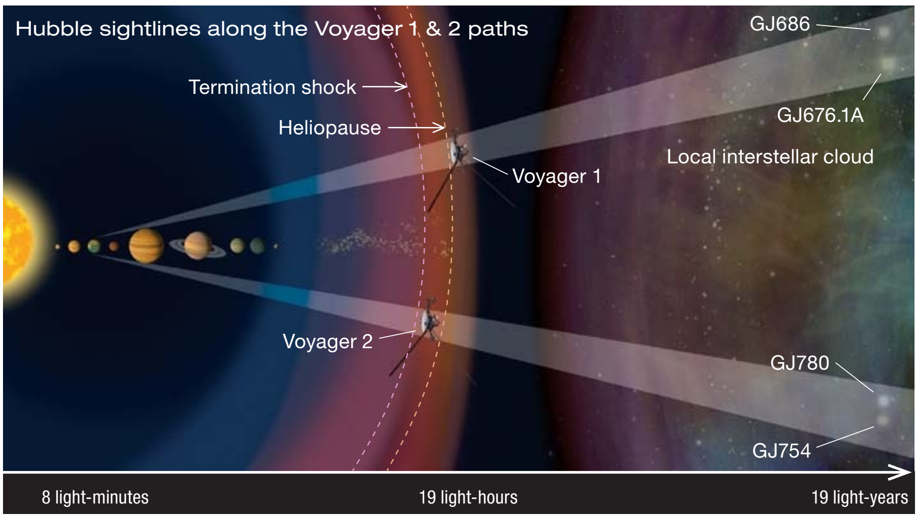
But in the meantime, the cloud is eroding as it passes through our galaxy's halo. As Cannan explained during his presentation, radio observations made with the Green Bank Telescope show that diffuse gas is lagging behind this high-velocity cloud, and it's also being ionized by ultraviolet light from stars in the galaxy's disk.

Cannan and older brother Carson, now 13, were homeschooled by their mother until they were five. When Carson entered school, he tested for eighth grade, so he started attending a private school in Grapevine, Texas. Cannan chose to stay at the same level as his peers until the age of 7, when he was tested and placed into eighth grade.

Both of them now spend their days on TCU's campus, and their mother, Claretta, credits the school with helping her boys assimilate. Carson is about to graduate college with a degree in quantum physics and plans to work on a doctorate. Cannan wants to earn a Ph.D. in astrophysics and perhaps an engineering degree, to improve his chances of becoming an astronaut.

■ NOLA TAYLOR REDD

MISSIONS



Voyagers Flying Through Galactic Clouds

ASTRONOMERS HAVE COMBINED data from the Voyager 1 and 2 spacecraft and the Hubble Space Telescope to probe the stuff between the stars.

The interstellar medium (ISM) is mostly sparse gas, with an average density of roughly 1 atom per cm^3. Astronomers study the ISM by looking at how it absorbs light from distant stars, which has to pass through it to reach us. Using this technique, Julia Zachary (Wesleyan University) and colleagues probed what the two Voyagers are flying through. They presented the results at January's American Astronomical Society meeting.

The team used Hubble to look at two stars along the same lines of sight as each of the Voyager spacecraft (see above). The spectra of the stars revealed that magnesium and carbon atoms had absorbed some of the starlight en route. There were multiple absorption features, spread out in space (indicated by the Doppler shift of the spectral lines), revealing that there were several clouds.

The total amount of starlight absorbed, paired with other observations — including ongoing density measurements by the craft themselves — also reveals the ISM's density. Putting everything together, the team was able to paint this picture:

There is an interstellar cloud that both Voyager 1 and Voyager 2 will pass through just as they leave the solar system behind. However, their divergent trajectories will take them through different clouds after that. Voyager 2 will move out of the cloud that swaddles the Sun in about 1,000 years. Two additional clouds exist along its sightline; based on the craft's speed, it will spend 90,000 years in the first one it reaches, then move into the next one after that.

Voyager 1's fate is less clear: one of its stars has two clouds in front of it, the other doesn't, so the team can't say what the craft will hit.

■ CAMILLE M. CARLISLE

X-RAYS

1,000 Black Holes in Deepest Chandra Image

THIS COMPOSITE IS a segment of the "deepest" X-ray image ever made: a 7-million-second total exposure of a patch of sky about two-thirds the size of the full Moon, gathered by NASA's Chandra X-ray Observatory during 102 pointing sessions between 1999 and 2016. Most of the 1,008 sources in the full image are supermassive black holes at the centers of galaxies billions of light-years away. Neil Brandt (Penn State University) unveiled the image, known as the Chandra Deep Field South, at January's meeting of the American Astronomical Society.

Among the results presented from studying this deep field is a study of black hole evolution. Supermassive black holes appear to grow at a rate that parallels that of star formation (*S&T:* Feb. 2017, p. 18). Guang Yang (Penn State University) and colleagues showed that this growth connection appears to be a secondary effect. Instead, a black hole's growth rate seems more strongly connected to a galaxy's total stellar mass than to the number of new stars forming in it. In other words, more massive galaxies appear to be more efficient in feeding their central black holes — though why this should be the case is unclear. Read more about the Chandra results at **https://is.gd/cdfs2017**.

■ MONICA YOUNG

CHANDRA: NASA / CXC / PENN STATE UNIV. / B. LUO ET AL.; LIBRARY: DONALD FICKEN

COMMUNITY

"Library Telescope" Program Takes Off

From humble beginnings in 2008 (*S&T:* Oct. 2014, p. 66), a simple idea — equipping public libraries with loaner telescopes — has caught on. Today hundreds of specially modified Orion StarBlast 4.5 telescopes can be checked out, just like a book, across the U.S. In this scene from last August, members of the St. Louis Astronomical Society and 11 neighboring clubs spent all day modifying 48 StarBlast telescopes destined for the region's libraries. The alterations include permanently installing an 8-to-24-mm zoom eyepiece (yields 19× to 56×). The society has placed 131 modified StarBlasts in libraries in east-central Missouri and west-central Illinois. Meanwhile the New Hampshire Astronomical Society, whose members conceived the library-telescope concept, have placed more than 100. In neighboring Massachusetts, the Aldrich Astronomical Society has already delivered 97 telescopes and has requests for 15 more.

■ J. KELLY BEATTY

• For more information, see **https://is.gd/library_telescope**.

IN BRIEF

NASA Announces New Missions

Two new asteroid missions, named Lucy and Psyche, will visit eight new worlds in the coming decade. Lucy launches in 2021 and heads to Jupiter's Trojan asteroids, exploring several worlds from the populations both ahead of and behind Jupiter in its orbit (*S&T:* June 2016, p. 16). The Psyche mission launches in 2023 to visit the strange asteroid 16 Psyche, which seems to be a naked metallic core.

■ DAVID DICKINSON

Read more about both missions and Lucy's complex route at **https://is.gd/lucypsyche2017**.

Water Is Everywhere on Ceres

NASA's Dawn orbiter has found that 1 Ceres, the largest asteroid (and a dwarf planet), must possess a global layer of water ice that lies just below its dark, dusty surface. As detailed in *Science* for December 15th, the broken-up rubble on Ceres' surface contains high concentrations of hydrogen — and, cosmochemically speaking, water ice is the only likely compound to account for all that hydrogen. As Thomas Prettyman (Planetary Science Institute) and colleagues explain, the near-surface rocks contain up to 10% water by mass, and this global ice layer likely extends to great depth. The finding confirms researchers' decades-long suspicion that Ceres contains abundant water.

■ J. KELLY BEATTY

Learn more at **https://is.gd/wateryceres**.

Curiosity's Discoveries on Mars

After four Earth years on the Red Planet, the intrepid rover has found evidence of long-gone water and habitable environments.

NASA's Mars Science Laboratory, a.k.a. the Curiosity rover, is the most complex machine ever sent beyond Earth. Since its 2012 daredevil landing inside a broad crater called Gale, it has ventured 15 kilometers (9 miles) across the crater's interior, trundling 17 cameras, several spectrometers, a suite of weather sensors, and two miniature laboratories along as it investigates whether Mars was ever habitable.

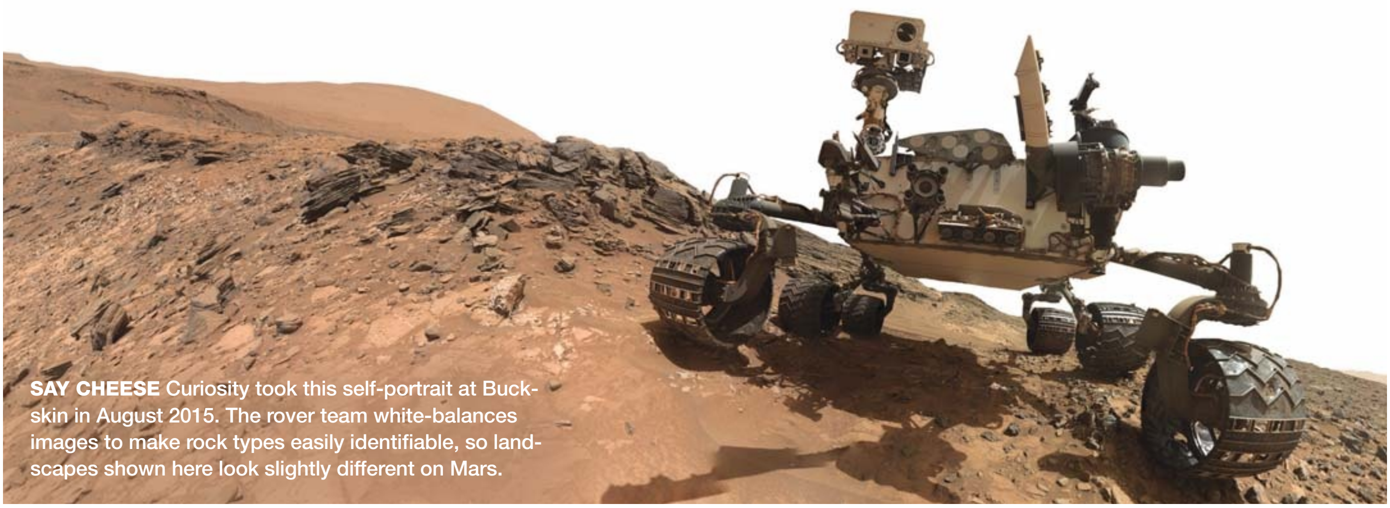
A habitable environment needs three things: liquid water to facilitate chemical reactions, sources of energy and organic (that is, carbon-bearing) material, and long-term stability — time in which chemistry can take place in that water. It's better if the water is not so acidic or saline that it inhibits chemical reactions, and if a thick atmosphere or magnetic field (or both) shields the surface from harmful radiation.

Geochemists think the Red Planet had all these conditions early in its history. Evidence from recent orbiters suggests that the place to confirm such clement environments once existed is in Mars's oldest rocks, specifically in places where we can see clay minerals from orbit (*S&T:* Sept. 2013, p. 16). These clays formed when volcanic rocks were drenched in neutral or alkaline water, an environment in which microbial life could originate and prosper.

But the mission's scientists hoped to do more than study clays; they hoped to find sedimentary environments like placid ancient lakes, whose rocks would have had a chance of preserving any organic molecules that may have been in the ancient environment.

Curiosity's landing site offered a place to do that. One of the deepest holes on Mars, Gale is located just south of the equator, punching about 4 km deep into the boundary between Mars's southern highlands and northern lowlands. Gale displays clear evidence that water once flowed down its rim, depositing fans of sediment on the crater floor, and it also possesses a 5-km-tall central mound of layered sediments formally named Aeolis Mons. NASA's Mars Reconnaissance Orbiter had spotted spectral signs of clays, sulfates, and hematite (an iron oxide) in the mound's lowermost layered rocks, all of which form in different kinds of wet environments. Also, the stack was the thickest section of sedimentary rock seen on Mars, recording several potentially habitable environments that went, from bottom to top, in a roughly wet-to-dry order.

The grand challenge for Curiosity would be getting to those rocks.



SAY CHEESE Curiosity took this self-portrait at Buckskin in August 2015. The rover team white-balances images to make rock types easily identifiable, so landscapes shown here look slightly different on Mars.

NASA / JPL-CALTECH / MSSS

EXPEDITION ROUTE
The Curiosity rover has traveled some 15 km (9 mi), drilled 15 rock holes (white circles), and investigated many additional sites. The meandering route is engineers' attempt to navigate a safe path around sharp rocks and dangerous dunes (see page 20) to the base of Aeolis Mons, which begins around Murray Buttes. (*Yardangs* are ridges formed when winds erode the rock's surrounding material.)


YELLOWKNIFE BAY

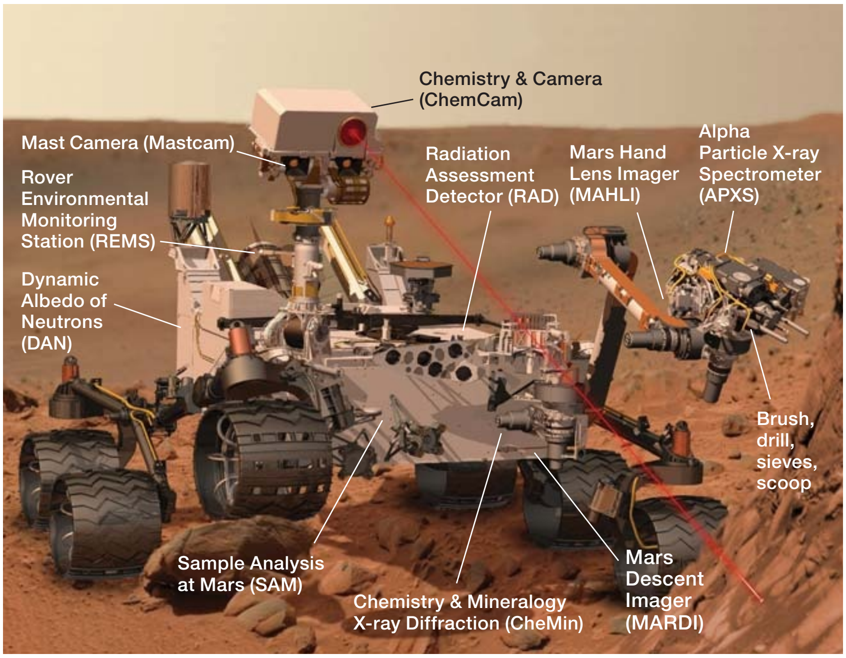

THE KIMBERLEY


HIDDEN VALLEY


PAHRUMP HILLS


MURRAY BUTTES

MAP: *S&T* GREGG DINDERMAN AND EMILY LAKDAWALLA, SOURCE NASA / JPL-CALTECH; INSETS: NASA / JPL-CALTECH / MSSS



Mars Science Laboratory

Curiosity's instruments perform four tasks: remote sensing, environmental sensing, contact science, and laboratory analysis. Remote sensing instruments include the Mastcam, color cameras, and ChemCam, which can determine the composition of materials up to 7 meters away by zapping them with a laser and then analyzing the resulting rock vapor. Environmental instruments include REMS, a suite of weather instruments; DAN, which searches for subsurface hydrogen by pulsing the ground with neutrons; and RAD, which measures incoming radiation. There are two science instruments on the end of the arm: MAHLI, a color camera; and APXS, which measures elemental composition. Finally there are two lab instruments that can ingest drilled rock powder: CheMin, which measures mineral composition; and SAM, which heats cups of sample in a high-temperature oven, measuring composition and isotopes to search for organics.

• Explore the rover at **https://is.gd/curiosityinst**.

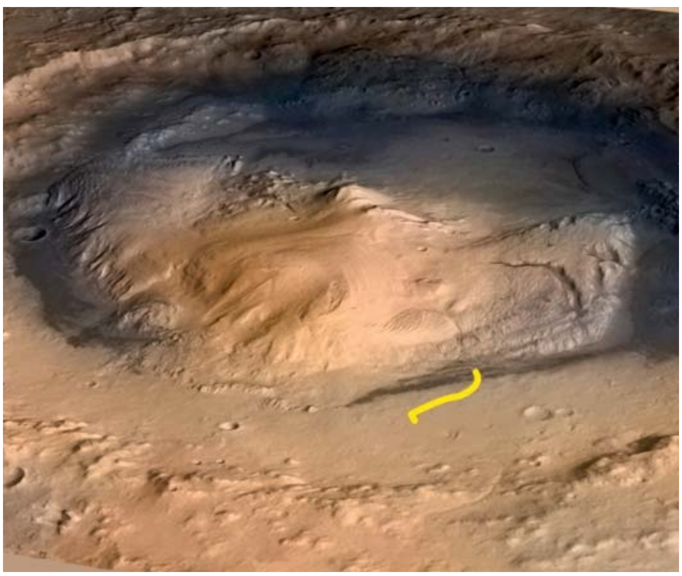
The Yellowknife Bay Campaign

For safety reasons, the engineering team landed the rover far from the mountain, in the flat rocks of the crater floor to its north. Access to the material they had traveled to Mars to study lay 8 km (5 mi) to the southwest, across a hummocky plain of mostly unexciting rocks and soil, then across a break in a dangerous band of active sand dunes (see below).

Near the landing site sat some light-toned rocks that appeared to be the end of a fan of sediment once carried by water that entered the crater from the northwest. Although there was no orbital signature of clay minerals, the appearance of this rocky expanse, named Yellowknife Bay, suggested that scientists might expect to find fine-grained sediments once deposited in standing water. Yellowknife Bay was in the opposite direction from the rover's planned route but held a chance of satisfying the mission's goals. So the science team made the tough decision to drive east instead of southwest. The rocks Curiosity initially encountered en route were mostly isolated boulders, but a few outcrops of bedrock jutted out of the ground. One rock type in particular thrilled geologists: *sedimentary conglomerate*. Seen at locations named Link and Hottah, it consists of loosely bound chunks of rock. The rounded pebbles in Gale's conglomerates offered clear evidence they had been tumbled in fast-moving water 10 to 100 centimeters deep — ancient Martian hillside streams.

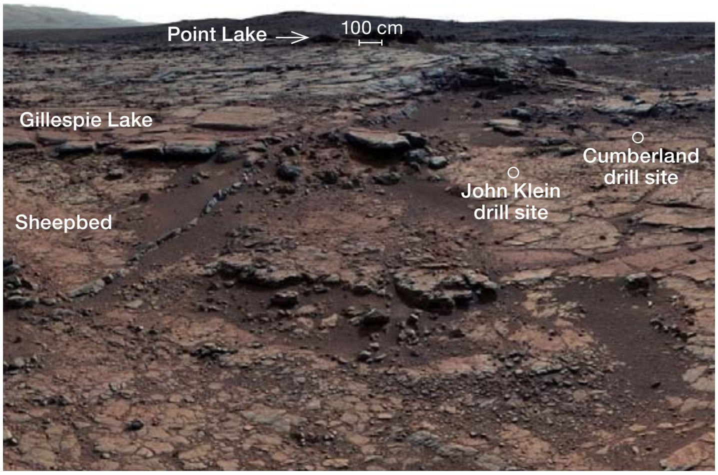
As the rover approached Yellowknife Bay, it entered a geological wonderland. At a site called Shaler: crossbedded, fine-grained sandstones speaking of sediment-rich streams fanning out across the landscape. At Point Lake: a massive, dark rock of enigmatic origin — was it volcanic or sedimentary? At Gillespie Lake: a coarse sandstone, its rounded grains made up of various minerals that must have been plucked from many sources in the plains outside Gale before riding down into the basin and being deposited there.

Finally, at the expanse's lowest point, Curiosity examined what the team named the Sheepbed member, a layered, light-toned rock crisscrossed by bright veins. The sediment was so fine that even Curiosity's highly magnifying MAHLI camera held as close as possible to the rock could not discern individual grains: It had once been silt or mud. Tiny grains



▲ **GALE CRATER** Curiosity landed in the northwest section of Gale, near the foot of its central mountain. This image is derived from a combination of elevation and imaging data from three Mars orbiters and looks southeast. Also shown is the approximate route the rover took to reach the mount's base (yellow). The crater is 154 km (96 miles) wide.

ROVER: NASA / JPL-CALTECH; CRATER: NASA / JPL-CALTECH / ESA / DLR / FU BERLIN / MSSS



▲ **YELLOWKNIFE BAY Left:** This mosaic of Mastcam images shows three major parts of Yellowknife Bay, where Curiosity took its first two drill samples (both in the Sheepbed mudstone). Point Lake is about 30 meters (100 feet) from the rover's location. **Right:** This close-up of the Link outcrop shows the gravel fragments that make up its conglomerate. The rounded bits most likely formed in quickly flowing water.

would've been suspended in the downhill flow and carried out into a lake until, in the still water, they slowly settled to the lakebed, trapping other materials floating nearby, possibly even organic compounds.

It was precisely the kind of environment that Curiosity had been sent to find.

The rover drilled in the Sheepbed rock twice, at sites the team named John Klein and Cumberland. The initial analysis by the Sample Analysis at Mars (SAM) instrument suite confirmed the rock was a mudstone, containing about 20% clay minerals that formed in direct contact with water (see page 21). And not the acidic, sulfate-rich water that the Spirit and Opportunity rovers had seen evidence of; this was gentler water, neither acid nor alkaline — the still, neutral water of a crater lake, an ancient habitable environment.

Methane with SAM

Success in hand, the team's next goal was to understand how Yellowknife Bay related to the crater's central mound — was it older or younger than the mountain? How different were the environments, and how many climatic turns did Gale's geologic story contain?

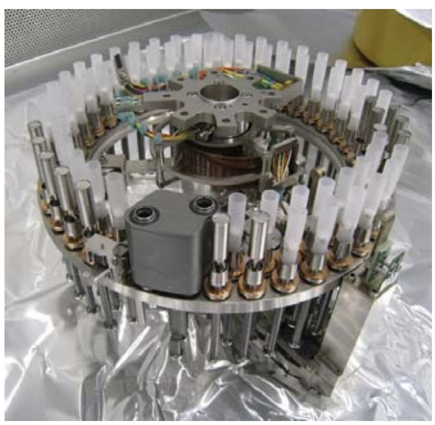
The rover now set off in a hurry. The Yellowknife Bay campaign, though productive, had taken seven months. Engineers estimated it would take about 200 "drive" sols — roughly another year, given that the rover doesn't drive every sol — to travel the 8 km to the entry point to the base of Aeolis Mons, or "Mount Sharp" as the team calls it (after beloved Caltech geologist Robert Sharp). And the nominal mission was only two years long.

Curiosity moved rapidly toward the mountain, covering nearly half the distance in the last six months of 2013. As the rover drove along, SAM periodically sniffed the air, searching for methane. Sunlight destroys methane in Mars's atmosphere in about 300 years, so if methane were present, its abundance should drop slowly. Yet Earth-based and orbiter observations had occasionally detected short-lived spikes, suggesting something — whether biotic or abiotic — was actively releasing and destroying methane on Mars. Curiosity's first several attempts to find atmospheric methane only set an upper limit of 1.3 parts per billion (ppb).

Suddenly, on sol 466, the rover detected a 5½-ppb surge. Methane abundance climbed rapidly over the next 60 sols. Then, in the next measurement on sol 573, the methane level had plummeted, back to less than 1 ppb.

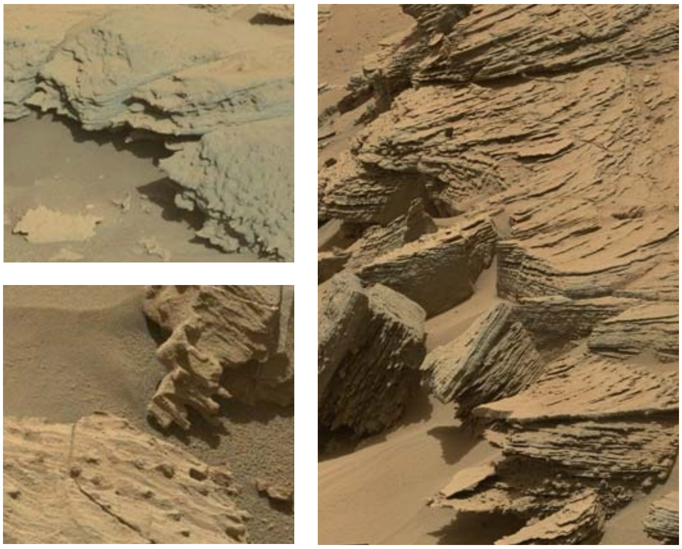
What caused the methane spike? Researchers still don't know. But they've measured methane periodically at intervals ever since. Over two Martian years (45 months), they have seen its abundance shift seasonally: lowest (about 0.3 ppb) near southern winter solstice, rising to a high of around

◀ **JOHN KLEIN** Curiosity's first drill site, in the Sheepbed mudstone. The column of tiny dark dots is where ChemCam's laser sampled the rock's composition. Powder from the drilling process surrounds the hole.



◀ **SAM: MARTIAN LAB** The Sample Analysis at Mars suite analyzes elements and compounds separated from soil, rock, and atmosphere samples. The wheel moves small "cups" (test tubes) of powdered samples to the next analysis step. The majority of the system's 74 cups are quartz, which can be heated to release trapped atmospheric gases.

YELLOWKNIFE BAY, LINK, AND DRILL SITE: NASA / JPL-CALTECH / MSSS; SAM: NASA / GSFC



▲ **ERODED ROCK** Wind has worn down Gale's terrain, as seen in these rocks from Naukluft Plateau *(left top and bottom)* and Upheaval Dome *(right, near Pahrump Hills)*.

0.8 ppb in southern summer. After exploring many possible correlations, the SAM team now thinks that the seasonal variation in this tiny amount of methane *isn't* from microbes; instead, it's tied to seasonally varying levels of solar ultraviolet radiation breaking up organic material on the ground. Curiosity measures the intensity of sunlight with a deck-mounted UV sensor that's part of its REMS weather suite. A small amount of carbon-rich material rains year-round onto the ruddy terrain as micrometeorites. When Mars is closest to the Sun (a period coinciding with southern summer), the stronger-than-average sunlight breaks down organics into much smaller molecules, including methane, causing the seasonal methane cycle.

Isotopic Ages

As the rover drove, SAM's science team continued to perform different kinds of lab analyses on Cumberland material that had been "doggie bagged" inside some of the instrument's sample cups. By studying the amount of argon produced by potassium-40's radioactive decay, the researchers determined an age for the rocks of 4.2 billion years (give or take 350 million). Since these were sediments, this age represents that of the original rocks, once part of the highlands and crater rim, that were ground down and later deposited on Gale's floor.

At the same time, SAM measured another isotope of argon as well as those of helium and neon, produced when cosmic rays bombarded near-surface atoms in the rock. The amounts of these noble-gas isotopes showed that the rocks had only been exposed at the surface for 80 ± 30 million years. Together, the results mean that the rocks within Gale are old but — at least at Cumberland — have only been exposed recently, presumably by the activity of sandblasting winds that have eroded Gale's rocks into sometimes fantastic shapes. Such short exposure ages are good for organics-hunting scientists, because there's been less time for solar and cosmic radiation to break down any interesting molecules contained within the upper few centimeters of rock accessible to Curiosity's drill.

SAM also hunted for organics in the doggie-bagged Cumberland samples, and an analysis of one of them yielded the detection of chlorobenzene — a ring of six carbon atoms bonded to five hydrogens and one chlorine. Chlorobenzene likely formed when perchlorate ions present in the rock reacted with some hydrocarbon molecules. Perchlorate is a powerful oxidizer that was detected in modern Martian soil by the Phoenix lander. In water, perchlorate will attack complex organic molecules, breaking them into smaller pieces.

Thus, the mission had succeeded in detecting organic material locked within the rocks when they first formed, billions of years ago. If life had existed then, evidence of it could be preserved in Martian rocks — a promising find for future paleobiology missions.

Wheel Problems

The drive toward Mount Sharp took a toll on the rover: Mission engineers discovered serious damage to the wheels. The wind had eroded the hard rock of the crater floor into spiny prominences that stuck up like sharks' teeth; embedded in the ground, they neither shifted out of the way nor collapsed under the rover's weight. Instead, they speared the wheels like so many can openers.

The wheel damage put the brakes on the mission's rapid driving progress.

While the engineers drove more carefully and studied the problem, they steered the rover into sandy valleys among ridges of layered rock, heading for an interesting, striated-looking outcrop they named the Kimberley formation. Sticking to valleys rather than the plateau tops meant a twistier path

▲ **HOLEY ROLLER** Despite their careful design, Curiosity's wheels became increasingly punctured by pointy, immobile rocks the rover drove over. (The regular-shaped rectangular holes, on the other hand, are intentional: Scientists use the marks they leave in the rover's tracks to verify the distance the rover has traveled.)

ALL IMAGES: NASA / JPL-CALTECH / MSSS

toward Mount Sharp, in part because it limited how far ahead the rover could see. The driving pace slowed dramatically.

Pulling up to Kimberley, they discovered the striations to be eroded, tilted beds of sandstone. After much debate, the scientists determined the beds had formed in that tilted orientation, as the toes of deltas that formed when a fast-moving stream carrying sand particles emptied into a still body of water, dropping its sediment load. Isotopic age-dating revealed that the rocks had also been exposed for several tens of millions of years.

From there, the team proceeded cautiously, mapping the terrain ahead to plot a wheel-safe course. That often meant keeping to the edges of sandy valleys where the wheels could get traction but avoid pointy bedrock.

CROSSBEDDING The Stimson sandstone crisscrosses the Murray rocks in this mosaic from Curiosity. Such *crossbedding* is common on Earth in wind- or water-deposited sandstone.

Onward and Upward

Curiosity reached Mount Sharp in late 2014, just after an extension of its original two-year mission. In images the summit appeared to be as far away as ever, but the rover had never been aiming for the peak: It was after the layered sediments at the base.

Although the dunes continued to block the path to the mountain, their migration across the ground had scoured clean a 14-meter-thick section of rock that represented the very lowest — therefore, oldest — exposed strata of Mount Sharp. There scientists encountered another very fine-grained mudstone, called the Murray formation. Scientists had expected that the progression from streambed rocks seen near the landing site, to sandy deltas observed along the traverse, should end with fine-grained lake sediments. Their discovery at Mount Sharp validated the idea that billions of years ago, the crater's interior was a lake that slowly filled with sediment.

The Murray formation interfingered with the tilted beds of the Kimberley-like stream deltas but also climbed over them, showing this new rock was younger than the stuff Curiosity had explored before. The rover was, indeed, beginning to ascend Mount Sharp, fulfilling the promise of reading its layers like chapters in a book.

At a site called Pahrump Hills, the rover walked the outcrop as a human geologist would do, scoping it out, looping through a second trip to examine it in detail with MAHLI and APXS, and finally drilling in three locations. The Murray layers were incredibly thin and regular, the sort of sediments that form on Earth, when pulses of very fine sediment slowly settle in still lake waters. The number of muddy layers Curiosity has climbed imply that Gale's lake lasted for millions of years — longer if there were any gaps in the existence of the lake.

The Murray sediments also showed many other signs of water's action upon the rocks after burial: a network of thin veins of the salt calcium sulfate mixed with boron, which may suggest brine concentrated thanks to evaporation. Curiosity also found desert-rose-like mineral concretions. These can form after a sediment is buried deeply and begins to fuse into rock.

Departing Pahrump Hills, Curiosity drilled a final time into the Murray formation at Telegraph Peak and then headed westward, skirting the northern edge of the dune field and moving in and out of valleys, slowly ascending. At Buckskin, the rover discovered an unusual silica mineral called tridymite. On Earth, tridymite is only found in environments with low pressures but extremely high temperatures — typically, explosive, silica-rich volcanic eruptions. These kinds of volcanoes were not thought to exist on Mars. But geologists can't figure out any other way to make it. Another tantalizing clue to Mars's past.

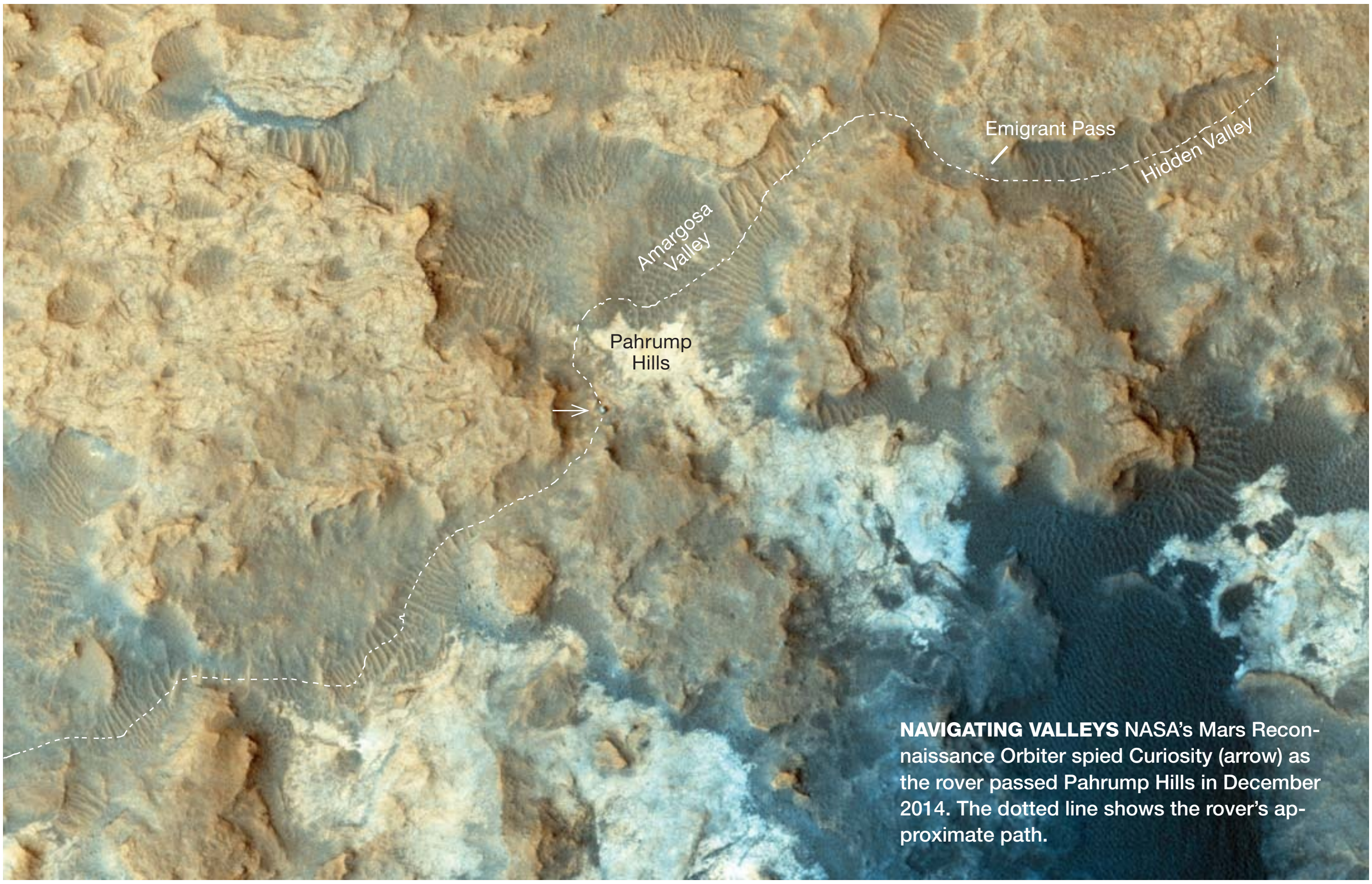
Near Buckskin, the rover had its first encounter with the next rock unit, named the Stimson formation. Stimson turned out to be a coarse sandstone, likely deposited by wind. It clearly cuts across Murray in a relationship called an *unconformity*: The Murray sediments were laid down, buried, turned to rock, exhumed, and eroded in some kind of arid environment where windblown sands then covered them up.

Cumberland's Atmospheric Window

◖ One other discovery made in the Cumberland sample: The SAM team found evidence that Mars is missing some of its atmosphere. This was no surprise. Many different missions, most recently the MAVEN orbiter, have confirmed that Mars has lost (and continues to lose) its atmosphere to the stripping action of the solar wind (*S&T:* Sept. 2014, p. 20). The modern Martian atmosphere has six times as much deuterium — a hydrogen isotope with both a proton and a neutron in its nucleus — as single-proton hydrogen. The original ratio was probably closer to 1:1.

In Cumberland, Curiosity found a record of a Mars that had lost only some of its atmosphere, with a deuterium-to-hydrogen ratio of 3:1. Those ancient rocks therefore formed in a time when Mars hadn't yet lost its youth, under much thicker air.

NASA / JPL-CALTECH / MSSS



NAVIGATING VALLEYS NASA's Mars Reconnaissance Orbiter spied Curiosity (arrow) as the rover passed Pahrump Hills in December 2014. The dotted line shows the rover's approximate path.

Sedimentologists even found torn-up bits of Murray incorporated within the base of Stimson. There is probably a lot of time separating the formation of the Murray and Stimson units; the latter might well be the youngest rock that Curiosity will explore. Understanding these kinds of stratigraphic relationships will eventually enable the science team to tell the full story of the climatic evolution of Mars at the Gale Crater site. It's work that can only be done with field geology, at the outcrop level, from a rover or astronaut's point of view.

Beyond Buckskin, the rover drove up and onto the Stimson formation, crossing ridge after sandstone ridge. Fractures crosscut the Stimson exposures, but unlike previous fractures Curiosity had seen, these were surrounded by bright halos. Curiosity drilled the Stimson unit both inside and outside such a halo, at Big Sky and Greenhorn. In the halo (Greenhorn), the CheMin instrument found a rock containing silica-rich clays and not much else — its other chemical components had been leached out, as sometimes happens in highly acid groundwater environments on Earth. For a variety of reasons, the waters that leached the Stimson sandstone could not be the same as the ones that put sulfate veins in Murray's mudstones. How many different times have these rocks been buried and wetted? How much time separated each wetting episode?

That last question can't really be answered with Curiosity's instruments; no dedicated age-dating instrument has yet been sent to Mars. One reason NASA's Mars 2020 rover will collect samples for eventual return to Earth is to permit geochronology experiments that will put numbers on these relative dates.

Curiosity finally turned toward the gap in the sand dunes on sol 1369 (June 12, 2016). Now the rover could head directly up the mountain, rather than skirting it. Through the summer of 2016, the rover drove among the spectacular landscapes of the Murray Buttes, knobs of Murray mudstone capped by Stimson sandstone. Martian wind whipping among the gaps between the buttes swept the ground free of dune sands, making a safe place for Curiosity to pass.

What's Next?

After four years of exploring, the science team has begun to understand elements of Gale's ancient history. Gale did host a lake for millions of years, one containing mostly neutral water, which occasionally dried and later refilled. Even after the surface became dry and inclement, percolating mineral-rich groundwater could have provided a persistent habitable environment for tens to hundreds of millions of years. While sometimes acidic, conditions still appear to have been hospitable to microbes — particularly those able to metabolize minerals' flow of electrons and survive deep in the cracked mudstone, away from sunlight. But searching for vestiges of life will have to wait for a future mission.

NASA / JPL / UNIVERSITY OF ARIZONA

▲ **PROTRUDING VEINS** This network of mineral veins juts up 6 cm (3 inches) above the surrounding rock. It formed when water moved through fractured rocks, depositing the minerals that now make up the veins. The surrounding rocks have eroded away to expose them.

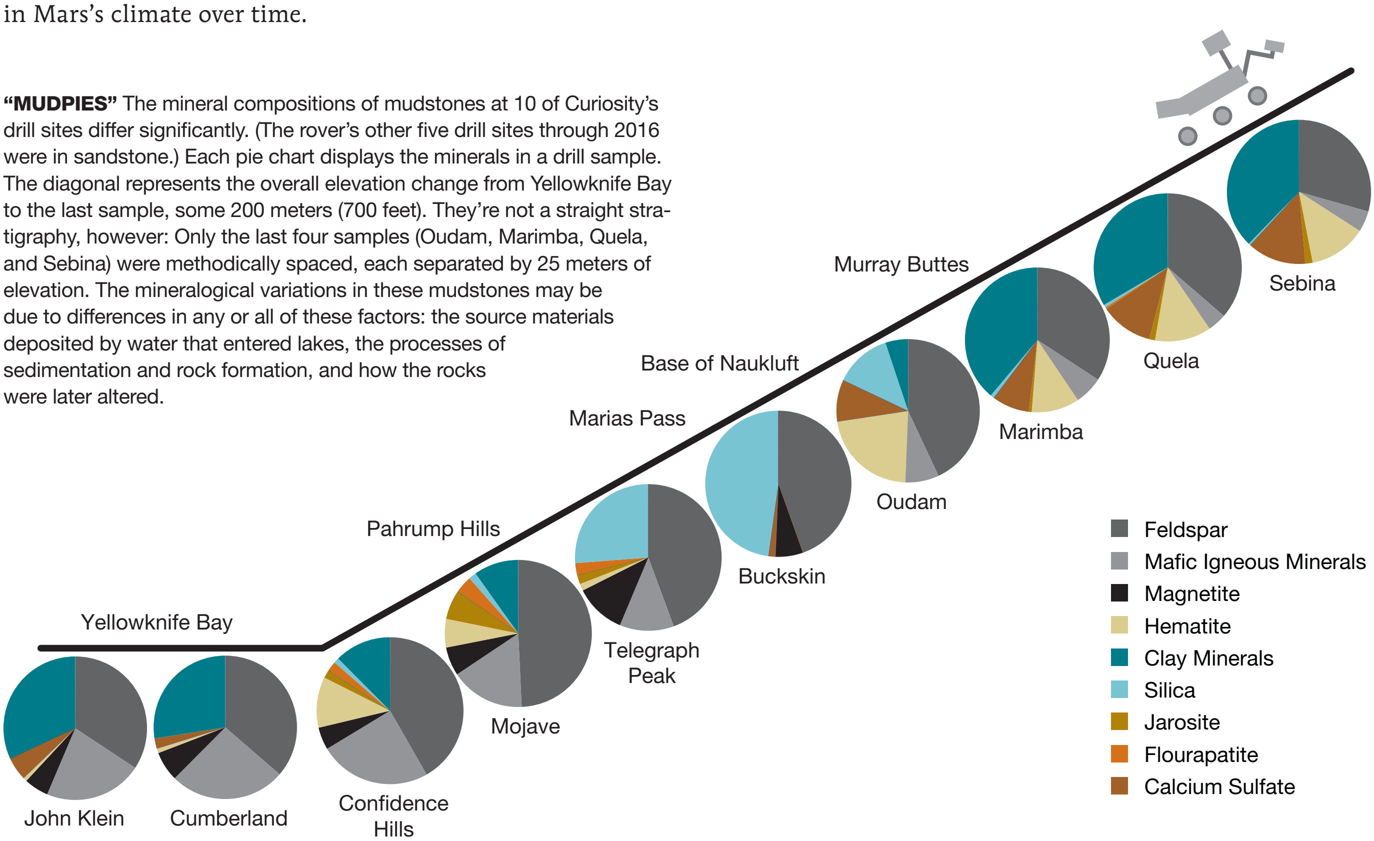
Curiosity will soon be across the Bagnold dune field, and then it will still have another kilometer or so of Murray rock to cross before it finally reaches the next major transition: the "hematite ridge," a break in both the topography and the mineralogy where the rock is rich in this water-made iron oxide. Crossing that ridge, Curiosity will move up into a rock whose clays are concentrated enough to be visible to orbiting spectrometers. The rover will likely spend the rest of its second 2-year-long extended mission within these three main rock types, as it traverses and drills from site to site to understand how the mineralogical differences record changes in Mars's climate over time.

If Curiosity gets a third mission extension in late 2018, it might continue studying those rocks, or it could continue upward. The next major boundary it could encounter is a place where a channel once cut through Mount Sharp and emptied into Gale's ancient lake, forming what looks like a spreading, fan-shaped delta. The sediments deposited within that delta and the channel that fed it turned into rocks that were more resistant to erosion than the rest of Mount Sharp, so after eons of weathering, the channel now stands *above* the surrounding rocks. Curiosity could use that channel as a ramp to drive upward into the mountain, transitioning from a time in Martian history where clay minerals drew from neutral waters to a period when water was scarcer and rocks ended up more sulfate-rich.

Or not. Several things could limit the rover's lifetime. Its wheels are the least of its problems; with care they should last as long as they need to. Some instruments are already showing signs of their age. And the radioisotope power source is, inexorably, decaying. Within 14 years of fueling — or about 4,700 sols into the mission, roughly the current age of the Opportunity rover — it will no longer provide enough power to keep the rover alive even through sleep, and the rover's driving days will be over. Who knows, Opportunity may yet outlast Curiosity.

■ Currently writing a book on Curiosity, **EMILY LAKDAWALLA** has penned a Planetary Society blog at **planetary.org** for a decade. She thanks mission members Ashwin Vasavada, Paul Mahaffy, and Kathryn Stack Morgan for help with this article.

"MUDPIES" The mineral compositions of mudstones at 10 of Curiosity's drill sites differ significantly. (The rover's other five drill sites through 2016 were in sandstone.) Each pie chart displays the minerals in a drill sample. The diagonal represents the overall elevation change from Yellowknife Bay to the last sample, some 200 meters (700 feet). They're not a straight stratigraphy, however: Only the last four samples (Oudam, Marimba, Quela, and Sebina) were methodically spaced, each separated by 25 meters of elevation. The mineralogical variations in these mudstones may be due to differences in any or all of these factors: the source materials deposited by water that entered lakes, the processes of sedimentation and rock formation, and how the rocks were later altered.



NASA / JPL-CALTECH / MSSS; DIAGRAM: *S&T* GREGG DINDERMAN, SOURCE NASA / JPL-CALTECH

Spirits of Our Galaxy's Past

Ephemeral streams of stars are helping astronomers probe our galaxy's dark matter halo, raising more questions than they answer about the Milky Way and its past.

In the late 19th century, new photographic techniques revealed "spirits" among us. First generated through an accidental trick of exposure, supposed ghosts soon became regular features in Victorian-era spirit photography.

Now, more than a century later, new photographs are once more revealing ghosts — but this time they're real. They're made of the stars in our galaxy's halo, which surrounds the disk in a diffuse sphere, and they have a great deal to say about the Milky Way and its past.

The halo glows dimly with the light of only a couple billion suns, a number that pales in comparison to the hundreds of billions of stars that shine in the galaxy's spiral disk and central bulge. Yet the halo contains about 20 times as much mass as all of those stars combined — it's just that we can't see most of it. The lion's share of the halo is in the form of dark matter, the mysterious invisible stuff that surrounds every galaxy and governs its growth and evolution, yet so far has avoided detection in physicists' labs.

Since we can't see dark matter, and would dearly like to, we must turn to what we can see. For more than a decade, ambitious all-sky surveys have revealed dozens of wraith-like stellar streams gliding through the halo of the Milky Way Galaxy; meanwhile, new techniques have revealed similar features around other nearby galaxies. These streams are mostly the stellar remains of dwarf galaxies torn apart during gravitational encounters with their bigger siblings.

When two large galaxies meet, they typically merge into a single object. However, when a dwarf encounters a far larger galaxy, it (counterintuitively) isn't entirely subsumed. The gravitational friction induced by the larger galaxy drags inefficiently on the dwarf's stars, which end up "remembering" their dwarf's initial orbit.

Because of this unique feature, stellar streams give voice to the past and present of the dark matter all around us. In addition to understanding the halo and what it says about our galaxy's ancient history, we also learn how the Milky Way fits in (or doesn't) with the universe at large.

ABDUL AZIS / GETTY IMAGES

Our Galaxy's Shadow

While the Milky Way's spiral disk spans some 100,000 light-years, its halo — mostly dark matter with faint, old stars here and there — may extend as much as 10 times farther, almost halfway to the Andromeda Galaxy. Yet the first indication that the Milky Way even had a halo of largely invisible material didn't come until 1970 — and it came not from our own galaxy but from its famous neighbor.

The late Vera Rubin and her colleague, Kent Ford (both then at the Carnegie Institution of Washington), had clocked the speed of hydrogen gas clouds whirling in the disk of Andromeda. If the galaxy's mass were largely concentrated at its center, where most of the light was coming from, then the farther out a cloud, the slower its speed ought to be. Instead, Rubin and Ford found that the clouds on the outskirts were all flying along at the same speed — without the galaxy whirling itself to pieces. Something was holding it all together.

Theorists, such as Jeremiah Ostriker and James Peebles (both at Princeton University), soon chimed in, agreeing that disk galaxies must be couched in spherical cushions of apparently invisible matter, or their fragile spiral patterns would become unstable and collapse.

But over the next decades, astronomers proved the halo to be far more complicated than it first appeared. In 1994 they first observed the strung-out stars of the disintegrating Sagittarius dwarf galaxy. Then, a few years later, the Sloan Digital Sky Survey (SDSS) began mapping very faint stars all across the northern hemisphere sky. An iconic image, dubbed the Field of Streams, showed that Sagittarius was far from alone in its destruction.

"The SDSS really changed the way we viewed the halo," explains Ana Bonaca (Harvard-Smithsonian Center for Astrophysics), who dived into SDSS data soon after the image was published in 2006.

The swoops of stars in the Field of Streams — some of them from the tidal tails of disrupted dwarf galaxies, others escaping from rent globular clusters — point to a halo that's still in the act of growing. Moreover, SDSS provides spectral information, which identifies stars' motion toward or away from Earth, and helps show which ones belong together. With the advent of such large spectral surveys, measuring the Milky Way halo became a whole new ball game.

Ghosts of Galaxies Past

Look at the Field of Streams image (page 24) and you'll see the ghosts that haunt the Milky Way today. The most obvious is the massive Sagittarius Stream: These broad tidal tails of what was once a dwarf spheroidal galaxy wrap around the poles of the Milky Way. Its stars lie between 20,000 and 300,000 light-years away from the Sun.

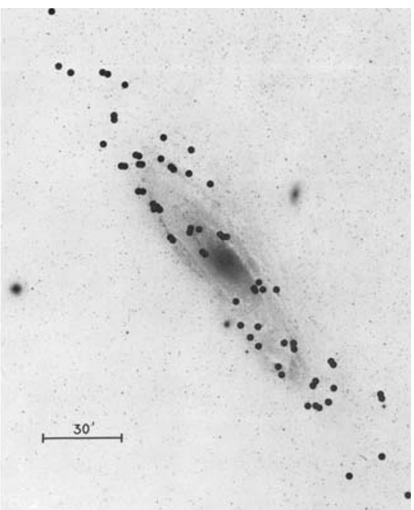
> "The Milky Way is the one place — and this is why I'm excited about it — where we can look at the halo in three dimensions."

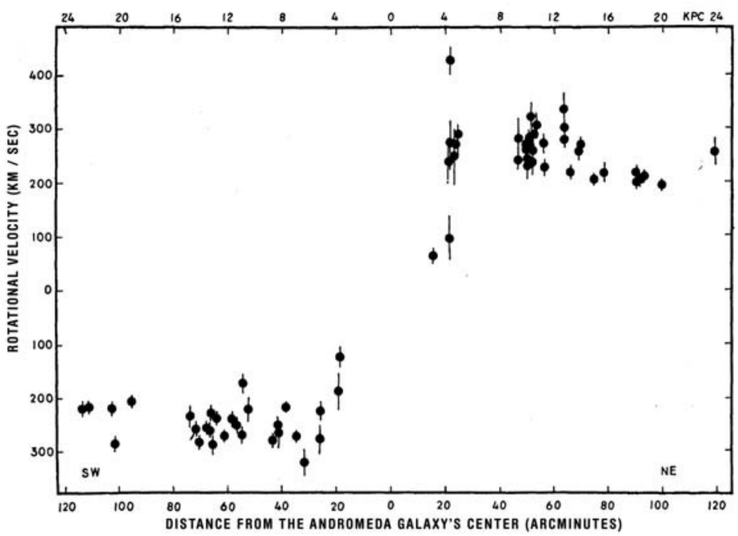
A smaller "orphan" stream crosses Sagittarius; its parent might be another torn-apart dwarf. (Except perhaps for Sagittarius, all the other digested galaxies now swimming in the halo were far less massive than the Milky Way's largest present-day dwarf, the Large Magellanic Cloud; *S&T:* Sept. 2015, p. 16). Tiny Palomar 5 is also clearly seen: a globular cluster in the act of dissolution about 75,000 light-years away. Another tidally destroyed globular is GD-1.

The list goes on, amounting to more than two dozen potential streams — a cosmologist's equivalent of a gold mine.

Each of these stars glides through the halo's gravity well like a marble rolling along the surface of a trampoline that's warped by a bowling ball resting in its center. Even if we know nothing about the bowling ball, the path a marble takes tells us about the ball's shape and weight.

Similarly, the streams orbiting the Milky Way help astronomers assess the mass and shape of our galaxy's dark matter halo. They can also help test standard cosmological





V. RUBIN & K. FORD / *ASTROPHYSICAL JOURNAL* FEBRUARY 1970 (2)

◀ SHE SPINS RIGHT ROUND Rubin and Ford clocked the velocities of gas clouds in the Andromeda Galaxy (marked by black dots, *left*), measuring from near the center to the galactic outskirts. To the astronomers' surprise, the clouds farthest from the center were whipping around much too fast (*right*) — yet the galaxy somehow still held together.

▲ **THE HALO'S EXTENT** The stellar halo reaches farther than the disk, out to 600,000 light-years or so, as shown here. The dark matter halo goes even farther — out to 1 million light-years — and outweighs the stars 20 to 1. For simplicity, stellar streams aren't shown.

theory, in which dark matter and dark energy dominate the nature and fate of our universe. In this framework, galaxies and clusters (and the dark matter halos they live in) grow largely by mergers. If that's the case, then past collisions with other galaxies might have shaped the Milky Way's halo into a slightly squashed football.

To understand how this shape develops, imagine balls of plasma within a lava lamp. When two balls merge, they don't form an instant sphere; first, they make a shape that's elongated like a football. Now watch another ball merge and the football looks a bit bigger along that direction. Dark matter simulations, no less mesmerizing than a lava lamp, show the same thing. Throw enough dark matter clumps together, and eventually the product of all those mergers is a flattened ellipsoid, a shape astronomers call *triaxial*.

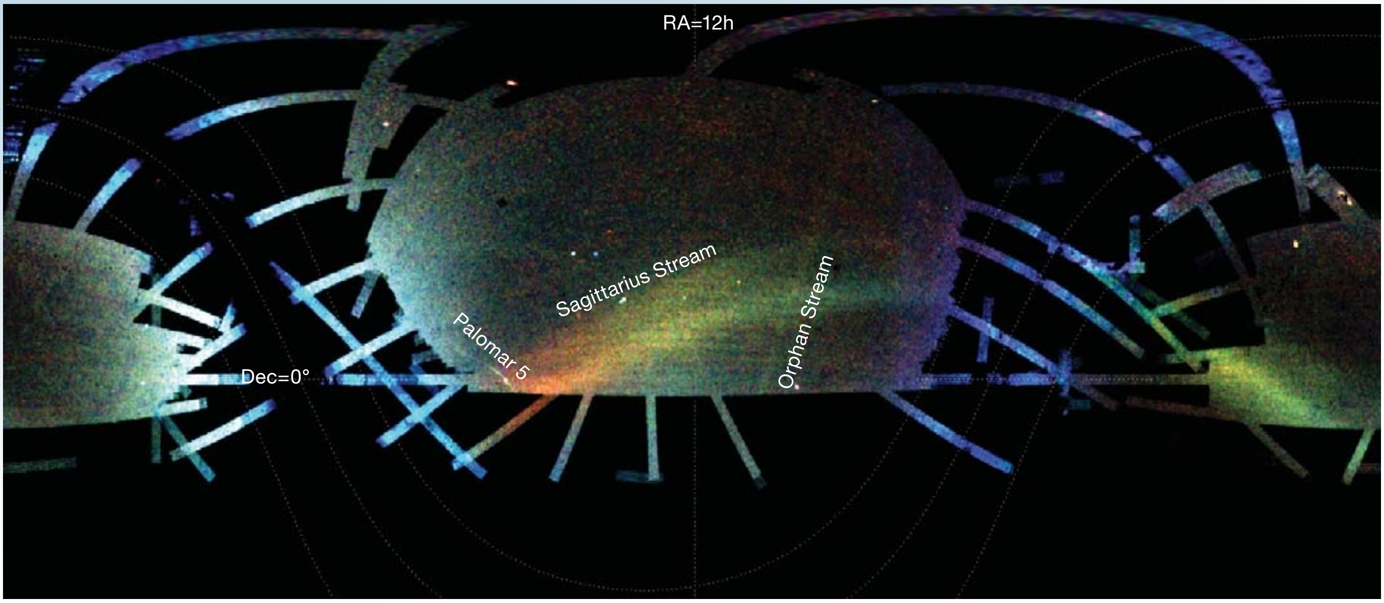
"The Milky Way is the one place — and this is why I'm excited about it — where we can look at the halo in three dimensions," says Kathryn Johnston (Columbia University).

Johnston and many others have tried again and again to estimate the mass and shape of the dark matter halo. At first, groups used the Sagittarius Stream that jumps out of all-sky surveys. However, this stream's numerous stars have fanned out across space. The very breadth that makes the feature easy to see also makes it difficult to model mathematically.

Astronomers have had better luck measuring the Milky Way's mass and shape using streams such as Palomar 5 and GD-1, which originated as globular clusters. The Milky Way's gravity has pulled their stars into long arcs that are much thinner than a pulled-apart dwarf galaxy. It's easier to calculate the path of stars streaming from a single compact object: Since the stars are all coming from a smaller point of origin, they're more or less on the same orbit.

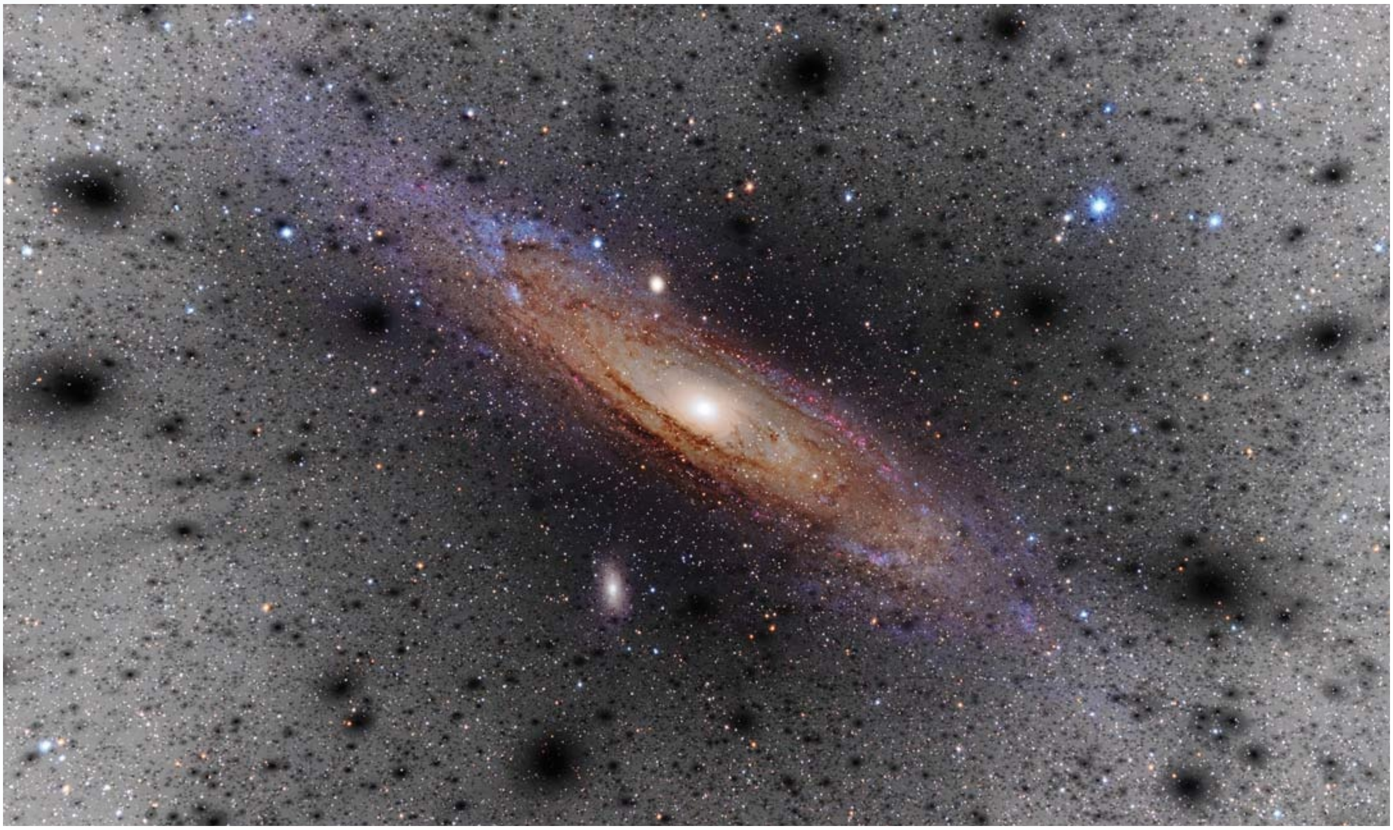
Still, Johnston says, "We don't know the mass of the Milky Way to better than a factor of two, which is pretty bad." Estimates put our galaxy's total mass around a trillion times the mass of the Sun, but the uncertainties are large enough that we're still not sure if the Milky Way reigns as heavyweight champion of the Local Group of galaxies, or if that honor instead goes to Andromeda.

The uncertainty stems in part from the nature of current simulations. The universe is large, long-lived, and hugely complex, so simulations that describe it accurately become computationally expensive. Theorists have to simplify their



▲ **FIELD OF STREAMS** This iconic image from the Sloan Digital Sky Survey maps individual stars across the Northern Hemisphere sky. The combination of unprecedented data collection and immense sky coverage reveals stars streaming from swallowed dwarf galaxies, as well as from globular clusters. (The title of the image is a pun on the 1989 ghost film, "Field of Dreams".)

DIAGRAM: GREGG DINDERMAN / S&T; FIELD OF STREAMS: V. BELOKUROV / SDSS



▲ **DARK LUMPS** While dark matter halos are sometimes thought of as smooth, featureless things, they're actually clumpy on small scales. This illustration, based on the Aquarius dark matter simulation, shows how dark matter might clump around a Milky Way-mass galaxy (represented by an image of the Andromeda Galaxy). Just how many clumps we'd expect depends on what goes into the simulation, such as the nature of dark matter.

COMPOSITE: V. BELOKUROV, D. ERKAL & S. E. KOPOSOV, DARK MATTER CLUMPS: VOLKER SPRINGEL, ANDROMEDA GALAXY: ADAM EVANS

mathematical models as much as possible, but such measures, Bonaca and others have found, can throw off mass estimates.

Uncertainty also plagues measurements of the dark matter halo's shape. While some studies have reported the expected squashed shape, more recent measurements have found the dark matter halo has a surprisingly spherical form. "I'd say there isn't much consensus at the moment," says Alis Deason (Durham University, UK), "but that's likely due to a lack of data rather than differences of opinion."

Black Gold

Still, there's more to our galaxy's dark matter halo than just its mass and shape. Zoom into any state-of-the-art cosmological simulation and the dark matter halos' lumpy interiors soon become apparent. Depending on the simulation, the Milky Way's halo might hold thousands of dark, starless nuggets. The number of nuggets itself holds clues to the nature of dark matter.

Though astronomers could never see these lumps directly, they might spot them by the holes they punch in stellar streams. Even a single firm detection of such a hole could tell us a lot about what dark matter is like. "That's the holy grail," says James Bullock (University of California, Irvine).

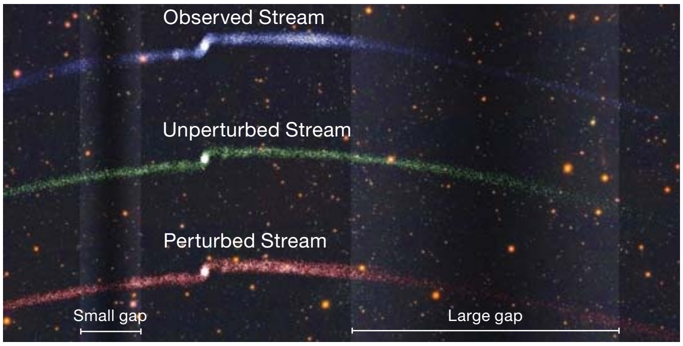
"I think we're right on the cusp of being able to say something about this," Johnston adds. "If you ask an astrophysicist what's the most exciting thing, I think they would say *this* is the most exciting thing."

One of the best-studied stellar streams — where researchers are making the most headway — is Palomar 5, whose stars wend across 20 degrees on the sky. Two tails, one leading and one trailing, come from a still-existing globular cluster that only recently (that is, about 3.5 billion years ago) began to disintegrate in the halo's gravitational well. It's a perfect place to look for evidence of dark matter clumps. Yet while initial studies were promising, debate has since ensued.

Picking out subtle variations along a barely visible stream seen against a foreground rich with galactic stars isn't easy. So Rodrigo Ibata (Astronomical Observatory of Strasbourg, France) led a team that collected the deepest data yet on the Palomar 5 stream, using the Canada France Hawaii Telescope (CFHT) to take sensitive images of Pal 5's stars.

> A definitive detection — the "holy grail" — still eludes astronomers.

Ibata's team found that, on scales of up to 1 degree on the sky, the stream appears surprisingly smooth. But new simulations reveal that dark matter clumps ought to disturb the stream on far larger scales — causing density variations



▲ **MIND THE GAP(S)** The top stream (colored blue) shows the Palomar 5 stellar stream as it's observed on the sky. The green stream is a simulated version of Palomar 5, in which the stream has not encountered any dark matter clumps. The red stream is likewise a simulation, this time one that has been struck by two dark matter clumps, one with the mass of 1 million Suns, which created the small gap at the left, and one with the mass of 50 million Suns that created the larger gap on the right. The observed stream appears to match the second, perturbed simulation, hinting at otherwise invisible clumps of dark matter in the halo.

up to several degrees long. Indeed, teams examining the same CFHT images on these larger scales argue that flybys of one kind or another have indeed had a profound impact.

The most recent result in this back-and-forth comes from Denis Erkal (University of Cambridge, UK) and colleagues, who detected two big "gaps" in the Pal 5 stream: One is 2 degrees across and plausibly generated by something other than dark matter — a run-in with a giant molecular gas cloud, perhaps. The other, at 9 degrees across, is harder to explain with ordinary interactions, but a dark matter clump roughly 10 million times the Sun's mass could be responsible. This result is exactly what theorists would expect, considering Pal 5's relatively short lifespan.

Not everybody's convinced, and a definitive detection — the "holy grail" — still eludes astronomers. Calculations of clump-stream interactions remain in early stages, says Andrew Wetzel (Caltech), who works on a simulation called Feedback in Realistic Environments (FIRE). "I still interpret any claimed detections with a grain of salt," he says. That's why he and colleagues are in the midst of modifying FIRE to test, for the first time, clump-stream interactions in a "live" dark matter halo that's still growing and spewing gas. "It will be interesting to see how all this comes together."

Stellar Archaeology: Digging Up the Past

Stellar motions that tell us about the current Milky Way dark matter halo also reveal its past: Each star in the galaxy's outskirts has its own unique history that informs its movement. Whether a star is moving toward or away from Earth is easy enough to determine from the Doppler shift of its spectrum. But to understand a star's 3D movement takes time — lots of it.

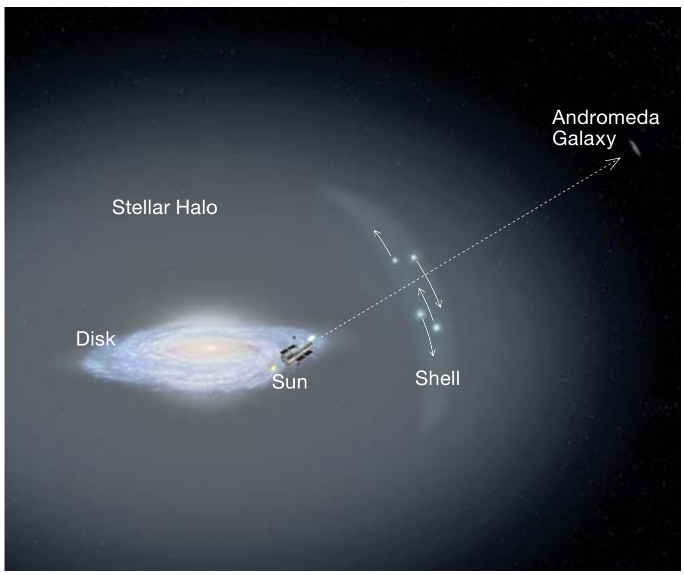
For several years, the Hubble Space Telescope has been watching distant halo stars' *proper motions* — their movement across the sky. "The motion of stars across the face of [background] galaxies is analogous to watching human hair grow on the surface of the Moon as seen from Earth," explains Puragra Guha Thakurta (University of California, Santa Cruz).

But it's worth the wait — that slow motion is key to understanding halo dynamics.

With a pilot project studying 13 faint halo stars, Emily Cunningham (University of California, Santa Cruz) and Deason combined Hubble proper motions with spectra to obtain 3D velocities for each halo star. Full knowledge of the stars' motions is crucial because, while stars in our part of galactic suburbia make orderly circles around the galaxy's center, halo stars don't follow the same rules.

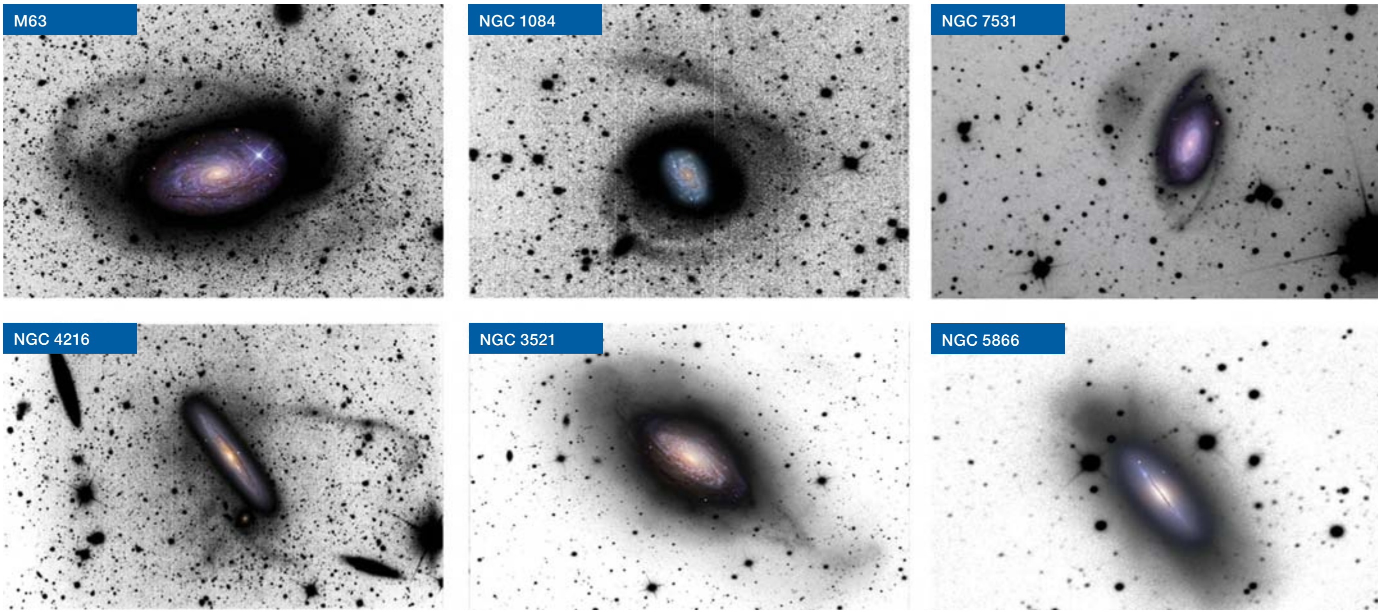
Most stars in the halo come from dwarf galaxies that fell into the Milky Way, so their orbits are typically radial — traveling toward or away from the galactic center. But, to Cunningham's surprise, the orbits of these 13 halo stars are more circular than radial. The stars, Cunningham argues, might be part of a pile-up roughly 80,000 light-years from the Milky Way's center. This pile-up could mark the point where stars from a single massive dwarf (or perhaps from several smaller dwarfs) accreted early in the Milky Way's history slow down and turn around in their radial orbits.

Even with impeccable data, though, 13 stars provide an extremely limited view into the Milky Way's halo. The team needs many more stars along other sight lines to confirm that the pile-up exists. Cunningham, Deason, and others are collaborating to measure the spectra of another 350 or so halo stars, while Hubble continues to observe those stars' proper motions from space. In addition to 3D velocities, the team will also measure and analyze spectra to measure each star's age and origin.



▲ **ANCIENT MERGER?** This diagram shows the Milky Way's blue disk of stars surrounded by a larger halo of faint, older stars. Hubble Space Telescope observations have revealed that 13 of these halo stars are traveling in a sideways motion, rather than in and out toward the galaxy's center as was expected. These stars could be part of a larger shell, a relic from the long-ago accretion of a massive dwarf galaxy.

PALOMAR STREAM: V. BELOKUROV, D. ERKAL, S. E. KOPOSOV (UNIV. OF CAMBRIDGE, UK); DIAGRAM: NASA / ESA / A. FEILD (STSCI)



▲ **ENDLESS VARIETY** These amateur images of nearby spiral galaxies show traces of devoured dwarfs, including wisps, plumes, stellar streams, and partially disrupted galaxies. In each composite image, the outer region shows the light in negative in order to allow better identification of the faint structures surrounding these galaxies.

D. MARTÍNEZ-DELGADO (MPIA AND IAC), R. JAY GABANY (BLACKBIRD OBS.), K. CRAWFORD (RANCHO DEL SOL OBS.) ET AL.

"I'm fascinated by the idea of piecing together the assembly of our galaxy star-by-star," Deason says. "I love the idea that by studying distant stars in the Milky Way halo, we can turn back the clock and reconstruct how these stars became a part of our galaxy billions of years ago."

Beyond the Milky Way

Reconstructing our past has shown the Milky Way's halo to be a surprisingly sedate place. Aside from the addition of one massive dwarf early on, life has been pretty uneventful for our galaxy until it only recently began accreting the monstrous Magellanic Clouds.

The halo around the Andromeda Galaxy, on the other hand, plays foil to our own. It's larger, more massive, and messier all around; its stars are younger, too. Andromeda has clearly been active from a young age, gobbling more and bigger dwarf galaxies than the Milky Way has.

In fact, the halos surrounding the two galaxies are so different, they actually span the full range that cosmological simulations predict for galaxies of similar mass — a fact that initially led theorists astray.

"We originally only had the Milky Way to compare with," says Roelof de Jong (Leibniz Institute for Astrophysics Potsdam, Germany). "All the modelers basically tried to model the Milky Way, because that's where the data were. They were sometimes frustrated that they missed it."

As astronomers began to see beyond Andromeda, they realized that the Milky Way might not make the best prototype. "If [the modelers] only had computing time for one or two galaxies . . . they wouldn't look like the Milky Way at all," de Jong explains. "Now we realize that if they'd had 20 models, maybe one or two would have hit the Milky Way."

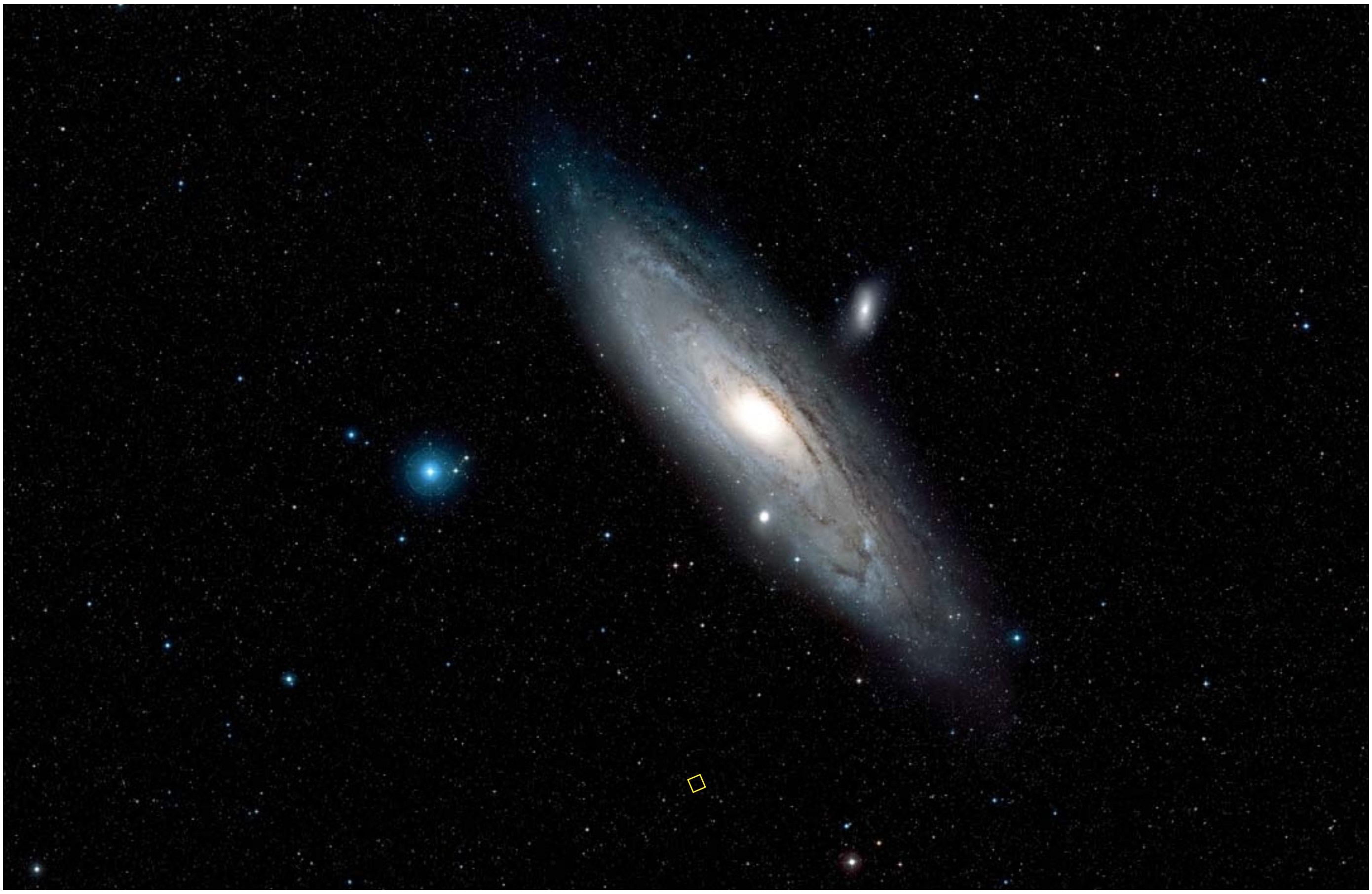
This realization is motivating several teams to look beyond our own galaxy. David Martínez-Delgado (University of Heidelberg, Germany) has been collaborating for almost a decade with a small team of amateurs (see box on page 29). Another team, led by Roberto Abraham (University of Toronto) and Pieter van Dokkum (Yale University), takes a slightly different approach: They're coupling multiple Canon telephoto lenses to CCD cameras, integrating them into a telescope that looks like a dragonfly's eye. Both amateurs' scopes and the Dragonfly Telephoto Array capture deep, wide-field images of stellar streams around nearby spiral galaxies.

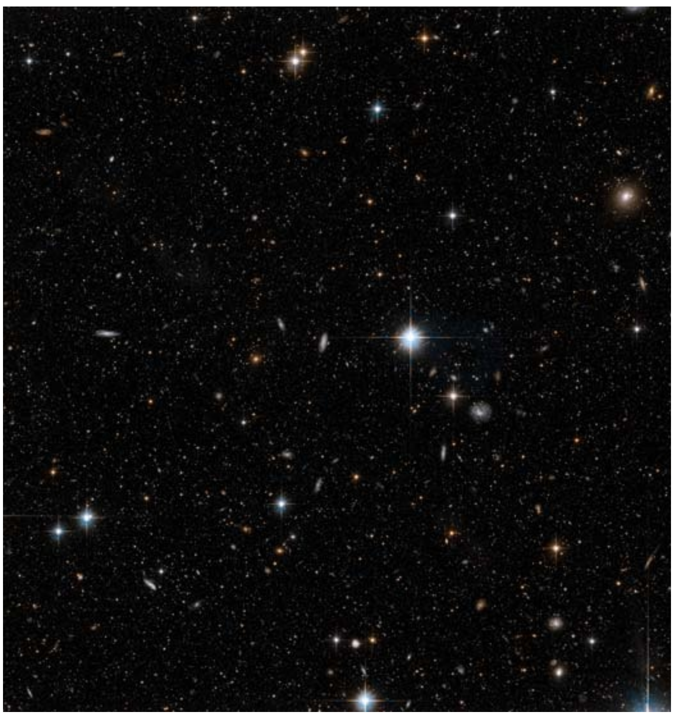
The variety is stunning. Around some galaxies, stars that were once part of dwarf galaxies have been swept into circles, shells, clouds, and even spikes. Surprisingly, other galaxies, such as the Pinwheel (M101), appear to have no stellar halos at all. These images are filling in the gap between lively Andromeda, the quiet Milky Way, and beyond.

> Questions about our halo and its past have been haunting astronomers. Now a second wave of astronomical data promises a deeper view, and perhaps some answers.

These observations appear to confirm that galaxy halos, where they exist, are largely dwarf galaxy graveyards. But the variety astronomers see as they image galaxy after galaxy doesn't have a clear explanation yet.

"It's still a bit early to say what a 'typical' stellar halo for Milky Way-mass galaxies looks like," says Allison Merritt (Yale University).





▲ **STARS IN THE STREAM** This Hubble image (*above*), which covers the area outlined by the yellow box (*top*), resolves a smattering of faint, red stars in Andromeda's halo that were once part of a companion galaxy. The stars' colors reveal their age and composition.

▲ **ANDROMEDA'S HALO** Though this groundbased image is too shallow to show the giant stellar stream that crosses over our sister galaxy, Hubble Space Telescope images of areas far off the stellar disk, such as the field marked by the yellow box, reveal individual stream members.

To complement holistic views of galaxy halos, another team, led by de Jong, employs the Hubble Space Telescope to zoom in on the streams around 18 galaxies for the "Galaxy Halos, Outer disks, Substructure, Thick disks, and Star clusters" (GHOSTS) survey.

Hubble's field of view is so small that even in its first proposals for telescope time, the team was already asking the telescope to point far off of a galaxy's disk to capture halo stars. "I remember getting the feedback from the Space Telescope Science Institute saying, 'Are you sure you want to put your field here? You'll miss the galaxy completely!'" de Jong recalls. "And I said, 'Yes, this is exactly the point.'"

Like the other teams, GHOSTS found a remarkable diversity of halo shapes and sizes. But the team also uncovered something entirely unexpected: middle-aged stars. Called asymptotic giant branch (AGB) stars for their stage of evolution, they're typically a couple billion years old and not exactly spring chickens anymore. But they're positively spry compared to halos' more typical ancient stellar populations.

Dwarf galaxies form most of their stars early in the universe's history (*S&T:* Mar. 2017, p. 16), so they're not the most obvious places to look for middle-aged AGB stars. Still,

ESA / HUBBLE & DIGITIZED SKY SURVEY 2 / DAVIDE DE MARTIN (ESA / HUBBLE); INSET: NASA / ESA / T. M. BROWN (STSCI) the gravitational forces that shred a dwarf during its accretion into a larger halo might press latent gas into new stars. Or young stars might instead have formed in — and then been cast out of — the larger galaxy's disk. Regardless, the stars' presence complicates our ideas about stellar halos and the dark matter around them.

Laying Ghosts to Rest

So let's sum up what we know — or rather what we don't — about the Milky Way's halo. We know the halo contains about a trillion Suns' worth of mass, but we only know that to within a gaping factor of two. Moreover, we still don't really know how clumpy this dark mass is, or even what general shape it has.

Meanwhile, observations of individual stars in the halo hint at a single long-ago encounter with one massive dwarf galaxy, or perhaps several smaller dwarfs, indicating an otherwise quiet past. But while our halo's sedate nature puts it on the opposite end of the spectrum from the dynamic Andromeda Galaxy, the variety of halos seen around other nearby galaxies makes it hard to tell whether the Milky Way's history is typical or far from it.

Since the SDSS and its iconic Field of Streams image first let us take a close look at the Milky Way's outermost stars, questions about our halo and its past have been haunting astronomers. Now, a second wave of astronomical data (*S&T:* Sept. 2016, p. 14) promises a deeper view, and perhaps some answers.

The European Space Agency's Gaia satellite, as well as the ground-based Large Synoptic Survey Telescope (LSST) that's set to begin observing in 2022, will enable astronomers to map halo stars from very near the Sun to far beyond the Milky Way's own halo. As computer simulations continue to advance at a rapid pace, these new surveys will rise to their predictive challenge. Finally, the ghosts are ready to speak — and we're ready to listen.

■ **MONICA YOUNG** is the web editor of *Sky & Telescope.*

• Visit https://is.gd/milkywayhalo to view additional illustrations of the Milky Way's stellar streams.

Amateur Astrophotographers Wanted

— David Martínez-Delgado

Is the Milky Way's history "typical"? We have to look at other galaxies to answer that question. Simulations predict that deep (long-exposure) observations should detect stellar streams in the outskirts of almost all nearby galaxies. But such features are extremely faint and difficult to find. Few were spotted until 1997, when astrophotographer David Malin used enhancement techniques on photographic plates to image structures around the spiral galaxies M83 and M104. I was inspired by his pioneering work and began observing other nearby spirals using professional telescopes — but without success.

By chance, years later, I stumbled upon some deep galaxy images that astrophotographer R. Jay GaBany had posted on his website. I invited him to join me. Within a couple of years, we had detected a wide assortment of giant tidal structures in the halos of several classic spiral galaxies. In 2010 the American Astronomical Society honored GaBany with the Chambliss Amateur Achievement Award, given annually to an American amateur who has helped advance scientific research.

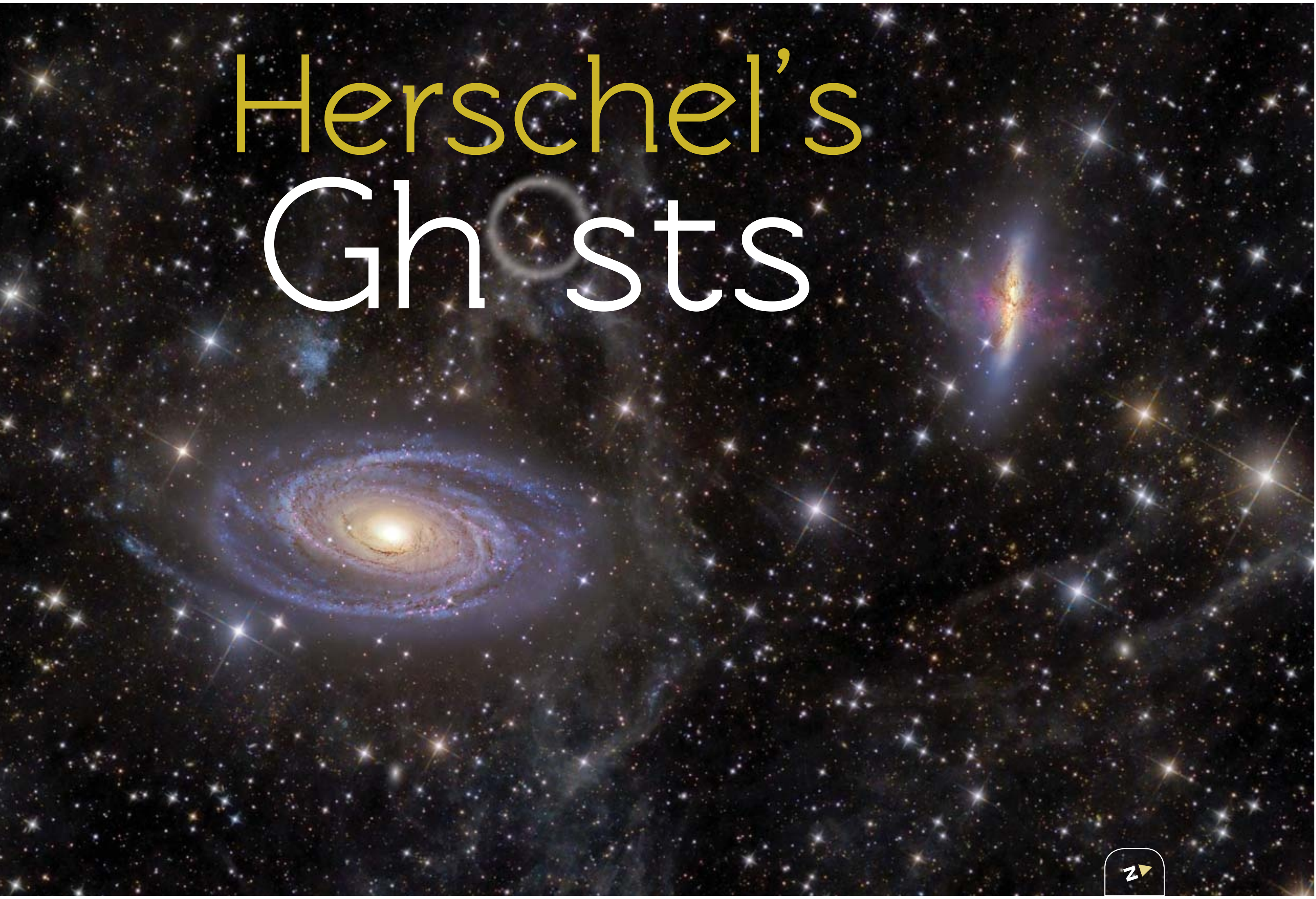
Today, our "stream team" includes a group of high-class astrophotographers interested in ultra-deep galaxy imaging, including Ken Crawford, Karel Teuwen, Adam Block, and Johannes Schedler. I also recently started a spin-off project that devotes amateur time to searching for whole dwarf satellites around nearby spirals. Both projects present unique opportunities for amateurs to contribute to the field of galaxy formation. The nearby universe abounds with faint galaxies ripe for exploration, so I am continuing to recruit talented astrophotographers to my team. Interested amateurs can contact me at **tidalstreamsurvey@gmail.com**.

• You can also keep up with new results on Twitter: @astro_delgado.

▲ **THE UMBRELLA** NGC 4641, a galaxy 35 million light-years away, shows an umbrella-like structure, the remains of a smaller dwarf companion that once orbited the larger galaxy.

R. JAY GABANY (BLACKBIRD OBS.) IN COLLABORATION WITH D. MARTÍNEZ-DELGADO (MPIA AND IAC) ET AL.

Herschel's Ghosts



With the right small scope, you can track down these dusty wraiths first observed in the late 18th century.

▲ **ROBES OF DUST** Galactic cirrus enshrouds the galaxies M81 (left) and M82 (right) in Ursa Major. It takes commitment to image these dim structures. This image represents nearly 25 hours of exposure time with a 12-inch f/4 reflector. Data was collected over three observing seasons: 2009, 2011, and 2012.

IVÁN ÉDER

WE SEE OUR GALAXY, the Milky Way, as a band of light stretching across the sky. There's a ghostly aspect to it; faint streamers of gas and dust extend far above and below the galactic plane, reaching the galactic pole. This *galactic cirrus* — twisted clouds of interstellar dust particles at high galactic latitudes first observed in the far infrared in 1983–84 by the Infrared Astronomy Satellite (IRAS) — glows in the dim red region of the spectrum. But the dust also reflects blue light from countless millions of stars, as shown by amateur astronomer Steve Mandel in 2004. Mandel noticed the subtle blue glow of the spooky dust tendrils associated with M81 and M82 and captured it in images. These images, which formed the basis of his Unexplored Nebula Project (**galaxyimages.com/UNP1.html**), demonstrated that the dusty interstellar medium could be seen not only in the far infrared, but in visible light as well.

Mandel called these clouds *Integrated Flux Nebulae* (IFN), and, taking their cue from his work, many amateur astronomers use this term whether referring to galactic cirrus or dusty *interstellar medium* (ISM) in the galactic plane. Professional astronomers distinguish more carefully between the two, though the boundary between them is somewhat, well, nebulous. ISM, the dust and gas between the stars, is distributed throughout our galaxy, but can be found relatively close by — say 200 light-years from us at its nearest — in the galactic plane. Galactic cirrus, on the other hand, technically lies at high galactic latitudes (above and below the zodiac) and thousands of light-years distant.

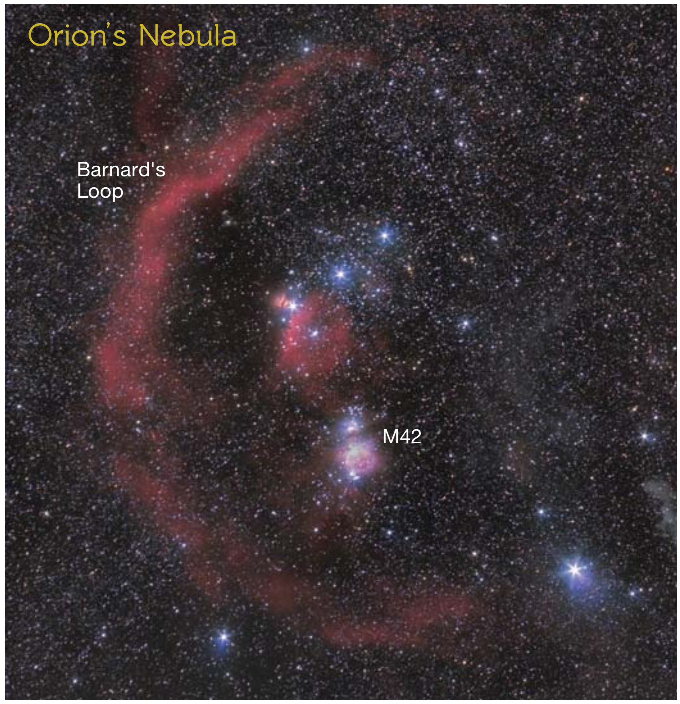
Whatever you choose to call it, you may be surprised to learn that you can see it with amateur observing equipment. For instance, I can detect faint glows tangling with well-known objects like the Pleiades and the Andromeda Galaxy with my improved richest-field (the widest possible view at lowest possible magnification) telescopes. My sketches at the eyepiece match deep digital images of the dark clouds, letting me know it's not just my eye playing tricks on me.

My first view of galactic cirrus was accidental and astonishing, and it made me wonder: Who else had spotted this ghostly dust? Turning to my library, my astonishment only grew as I uncovered a history of visual observations stretching back to William Herschel.

A Dusty Discovery

The typical discovery story you'll read for galactic cirrus goes something like this: It was first noticed on glass plates taken with the 48-inch Schmidt telescope at Palomar Observatory, one of the most productive telescopes of the modern age. Cataloged as dark clouds or nebulae in 1965 by Beverly T. Lynds, the dust's infrared emissions were discovered in the early 1970s and studied in detail by IRAS in the 1980s. In the 1970s, David Malin also found cirrus on images taken with the 1.2-meter UK Schmidt Telescope at Siding Spring Observatory, Australia, and Allan Sandage wrote about it and the scattering of optical light in 1975–76.

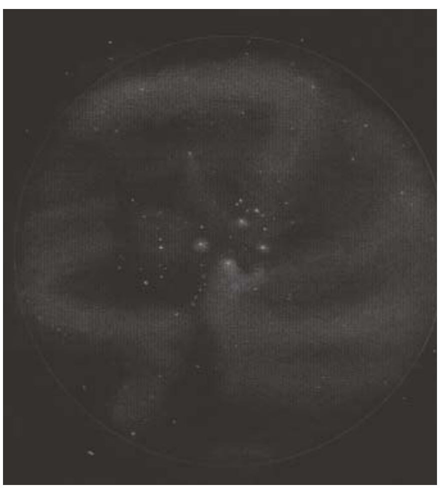
The discovery story you won't read goes back another 150 years, however, to one of the greatest visual astronomers of all time, William Herschel, who detected very faint nebulosity across large areas of the sky. What we call the sky background, Herschel called the sky "bottom" or "ground."



▲ **TRUE NEBULA** Even casual observers may be familiar with Orion's Nebula (M42), a naked-eye object in suburban skies. Less well-known is the nearby arc comprising Barnard's Loop, an emission nebula included by Herschel in his list of 52 nebulous regions.

From 1783 to 1811, Herschel cataloged 52 nebulous regions of the sky bottom, including the emission nebula behind the Horsehead Nebula in Orion (Williamina Fleming, a computer at Harvard College Observatory, discovered the Horsehead Nebula itself in 1888; E. E. Barnard's 1919 catalog of dark nebulae popularized it). Herschel's observations also included the North American Nebula and Barnard's Loop, as well as the nebulosity surrounding M81 and M82.

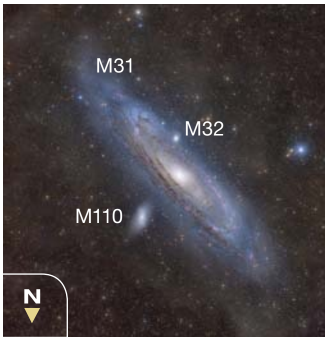
Herschel initially believed that even these faint, diffuse structures were resolvable; that is, the nebulosity could be explained as aggregations of stars too faint to be

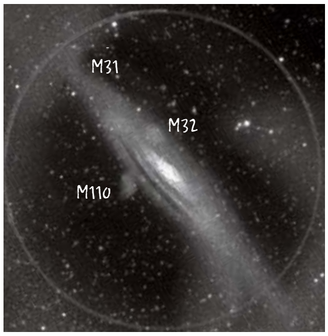


◀ **CAPTURING THE BUBBLE** A five-hour total exposure reveals not just the Merope reflection nebula, but also the dust through which the Pleiades cluster happens to be passing. The so-called Pleiades Bubble defines the margins of the galactic cirrus.

◀◀ **FINDING THE EDGE** The author sketched the Pleiades Bubble as seen through a 6-inch f/2.8 richest-field telescope with no filter.

BARNARD'S LOOP: SCOTT ROSEN; PLEIADES: VALERIE ROSEN; ALL SKETCHES: MEL BARTELS





▲ **SHIFTING VIEWS** The galactic cirrus surrounding M31, the Andromeda Galaxy, makes it difficult to measure the galaxy's dimensions visually. The shelf "below" M32 is subtle; use images and sketches to guide your search. **Right:** Dark, transparent skies are your best assistant when it comes to tracing dust structures. The author made this sketch at the Oregon Star Party, which is known for its dark skies and an observing field protected from white light.

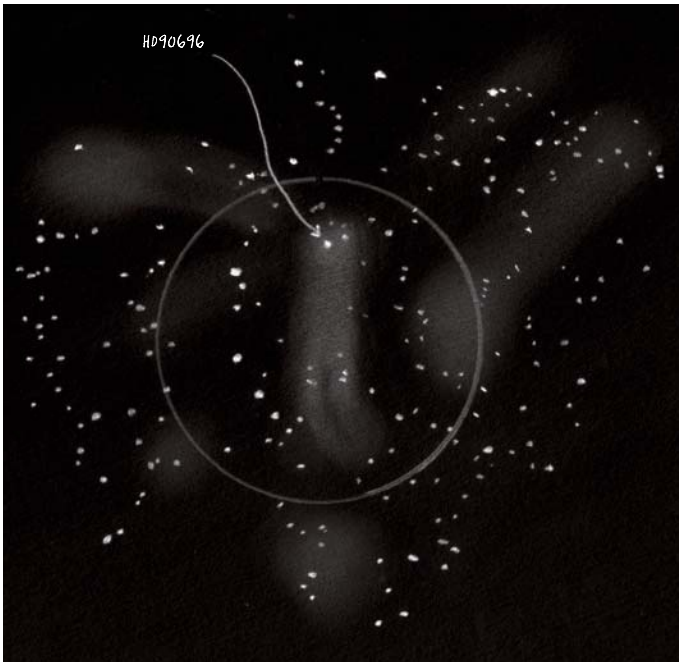
seen individually. He didn't consider brightness variations in sky ground important — after all, there were no stars to be counted in these fields. Frankly, these ghostly nebulous regions really didn't interest astronomers of the day, and Herschel himself acknowledged that they could "only be seen when the air [was] perfectly clear, and when the observer had been in the dark long enough for the eye to recover from the impression of having been in the light." This nebulosity was difficult to see even for him, and there were no telescopes equal to his for nearly a century.

So it's no surprise that his 52 diffuse nebulae never made it into his most popular catalogs of deep-sky objects. By the end of his career, however, Herschel came to believe that cloudy material was very common, so he published a catalog of extensive diffuse nebulosities in 1811. However, neither his son, astronomer John Herschel, nor John Dreyer, who compiled the *New General Catalogue*, included Herschel's nebulosities in their own catalogs. Herschel's diffuse areas became historical, mere observational ghosts.

In 1896 Isaac Roberts began systematically photographing Herschel's 52 nebulous regions using an exposure time of 90 minutes. The idea of using photographs to verify or correct Herschel's observations had been bouncing around in his head for several years. The results, obtained with a 20-inch reflector and 5-inch-aperture lens, were largely negative. Only four regions showed any hints of nebulosity. Roberts concluded that Herschel's observations were illusory. Reaction to Roberts' work was harsh: E. E. Barnard criticized him, saying

▼ **WINGS OF AN ANGEL** This uncataloged stretch of dust, crossing the far west region of Draco, was detected by Steve Mandel and designated the "Angel Integrated Flux Nebula" by his son.

M31: HYTHAM ABU-SAFIEH; DUST ANGEL: ROGELIO BERNAL ANDREO



▲ **BRIGHT EYES, DUSTY FEET** The spooky streak of dust known as the Angel Integrated Flux Nebula requires a very wide field of view. The brightest star in its "head," HD 90696, lies about 5° 08′ northeast of M81, 48′ south of star HD 92148, and 6° 13′ northwest of Lambda (λ) Draconis.

Targets in the Galactic Cirrus

Object	Size	RA	Dec.
Pleiades Bubble	4° × 12°	00h 10.0m	+22° 00′
Andromeda Shelf	5° × 3°	00h 45.0m	+41° 00′
Angel IFN	0.5° × 2°	10h 40.0m	+73° 30′
M33 Bridge	1° × 4°	01h 30.0m	+30° 10′
M15 Nebulosity	0.5° × 2°	21h 30.0m	+12° 15′
Leo Triplet	1° × 3°	11h 20.0m	+13° 00′
Markarian's Chain	2° × 4°	12h 20.0m	+13° 20′
M64	2° × 4°	13h 00.0m	+21° 20′
Volcano IFN	1° × 2°	09h 40.0m	+70° 20′

Angular sizes are from the author's observation logs and 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.

that 90-minute exposures weren't long enough, as he himself had photographed some of Herschel's regions (especially what we now call Barnard's Loop) — nebulosity that Roberts claimed didn't exist (*S&T:* June 2016, p. 36).

In the 1920s Herschel's observations were taken up by the Austrian-American astronomer Johann Hagen, the first Jesuit director of the Vatican Observatory in Rome. Hagen visually surveyed the sky for so-called "cosmic clouds" using a 6-inch f/15 refractor. He eventually claimed to have observed all 52 of Herschel's nebulae, results that were derided when presented to the Royal Astronomical Society in 1921 because the clouds weren't detectable photographically. Hagen continued to compile his list of faint clouds up until his death, coming to believe that they covered much of the night sky. Hagen was a true visual observer, favoring the visual record over photographs and arguing that many hours of long exposures couldn't match what he could see in minutes. He advised astronomers to put away their cameras and look through the telescope, lamenting that visual skills were a dying art.

In something of a plot twist, Isaac Roberts' widow, French astronomer Dorothea Klumpke Roberts, collaborated with Hagen that same decade, perhaps to rehabilitate her husband's reputation, which suffered after his criticism of Herschel. Despite Hagen's emphasis on visual observing, he joined Klumpke to publish Roberts' photographs as *Isaac Roberts' Atlas of 52 Regions, a Guide to Herschel's Fields* (1928). The photos received attention and applause; even Edward Hubble, a sharp critic of Hagen, suggested more images should be published.

The French amateur Marcel de Kérolyr, who has been called one of the greatest astrophotographers of all time, also worked to detect Herschel's specters during this time period. He successfully photographed some of Herschel's nebulosities, first with a 5-inch (130-mm) f/4.6 Derogy portrait lens from his "Astrophotographic Station" in Digne, Alpes-de-Haute-Provence, then with a 32-inch (800-mm) reflector from Forcalquier. In addition to the photos, which de Kérolyr published in 1931, the work at Forcalquier resulted in a list of visual observations of most of Herschel's original targets. However, de Kérolyr's 1931 paper didn't make much of an impact. Hagen had died a year earlier, and interest in his — and Herschel's — observations of nebulous fields had all but disappeared. The astronomical world lost this fascinating thread reaching back to Herschel.

At the Eyepiece

My own study of Herschel's fields started with first light through my 6-inch f/2.8 telescope. The 21-mm Ethos 100° apparent field-of-view (AFOV) eyepiece dominates the tiny scope; indeed, I offset the scope's center of gravity with the massive eyepiece in mind (*S&T:* Sept. 2014, p. 72). I aimed for the Pleiades, the Seven Sisters of mythology. The 4.3° true field of view swallowed the cluster. The Pleiades' stars shone brilliantly through the eyepiece; the Merope Nebula looked like a waterfall. I noticed a smudgy ring of grayness surrounding the cluster at the edge of the field. Was there something wrong with my baffling? Was there some sort of fog in the eyepiece or coma corrector? I moved the scope back and forth; the bubble stayed painted on the sky. Maybe the stars were casting some sort of glow? I followed the ring all the way around, keeping the cluster near the edge. No, it was real — a real mystery.

I shared the view through my scope with dozens of people. The nebulosity surrounding the Pleiades was visible in other scopes as well, albeit not as easily with narrower fields and higher magnifications. In fact, many have noted this so-called **Pleiades Bubble**: Walter Scott Houston described observations submitted by Stephen Knight of East Waterford, Maine, in his Deep-Sky Wonders column (*S&T:* Dec. 1985: p. 628). And Howard Banich points out that the German-French astronomer Hermann Goldschmidt, a painter and prolific discoverer of asteroids, observed the Bubble in 1863 (*S&T:* Jan. 2017, p. 60). Yet I'd never heard of it before spotting it through my scope!

From the Pleiades, I turned to M31, the Andromeda Galaxy. For many years amateurs have disagreed over the galaxy's extent, claiming widths from three to five degrees. Through my little telescope, the galaxy's edges merged with the Milky Way. When the ghostly Milky Way extensions are visible, the galaxy appears 5° wide; when not, it appears only 3° wide. Further, I discovered that the most prominent feature in my field of view is a "shelf" below M32, situated such that the companion galaxy appears to float on an ocean of faint gray-white nebulosity. Was the **Andromeda Shelf** part of M32 or its own entity? Familiar with images of galactic cirrus taken by Steve Mandel and Rogelio Bernal Andreo, I contemplated the unthinkable: Was I seeing parts of the galactic cirrus?

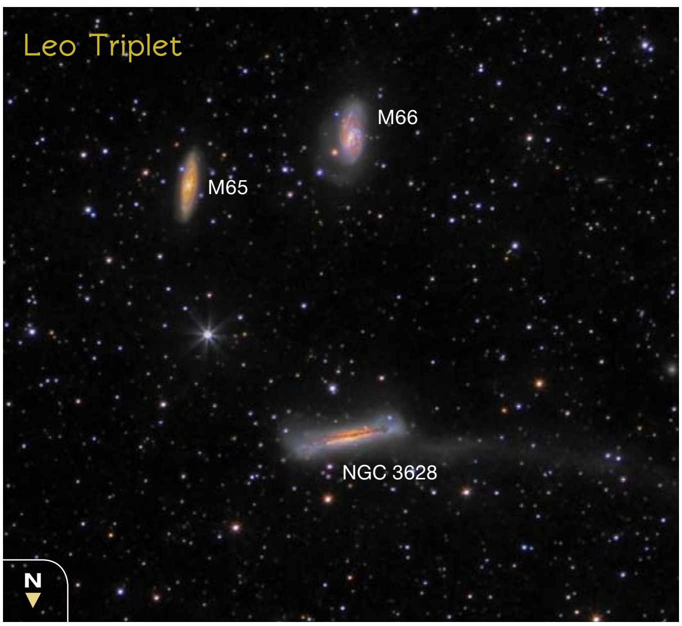
I decided to find out. I started with the brightest cirrus next to the galaxies M81 and M82 in Ursa Major. I selected my 10.5-inch f/2.7 richest-field telescope, aimed the red-dot finder at the area as I have so many times over the decades, and placed my eye at the eyepiece. My elation was unbounded — cirrus was clearly present. I sketched the **Angel Integrated Flux Nebula** (Mandel-Wilson 2), an area not associated with a deep-sky object. Beautiful, bright, subtle, deeply gratifying, an observation I'll never forget. I found myself agreeing with Father Hagen: The sky is awash in faint, dusty but surprisingly detailed cirrus.

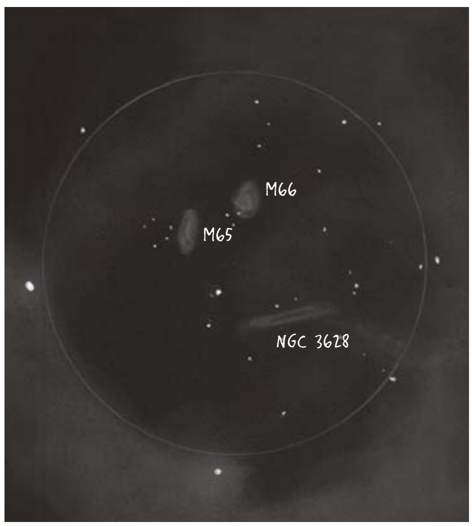
During one night out, I found a Milky Way extension that reached **M33**, the Triangulum Galaxy. How could I have missed it all these years? I found galactic cirrus in the fields of the globular cluster **M15**, M44 (the Beehive cluster), the galaxy trio **M65**, **M66**, and **NGC 3628** (the Leo Triplet), and **Markarian's Chain** in the Virgo Galaxy Cluster. Perhaps sketching 243 dark nebulae helped me tune into subtle variations in skyglow.

Maximize Your Potential

There are a few things you can do to prepare yourself for your own galactic ghost hunt. First, consider your equipment. Since cirrus structures are large, select telescopes and eyepieces with the widest possible true field of view, at least 2° across. Make dust more visible with lower magnifications and larger exit pupils; don't select for an exit pupil of 3–5 mm usually recommended for dark-sky observing — the background will be too dark. Filters won't help as much as they do with bright nebulae, but I've found broadband filters like DGM Optic's NPB and Orion's Skyglow modestly useful.

Herschel and others noticed that one field might be ever so slightly brighter than another field. In other words, they didn't see structure or form, just variations in brightness. The galactic cirrus adjacent to M81 and M82, for instance, has a brightness of 24.5 mag/arcsec^2 according to Sandage. On a good night with a Sky Quality Meter (SQM) reading of the sky background at 21.4 mag/arcsec^2, I estimate the faint-

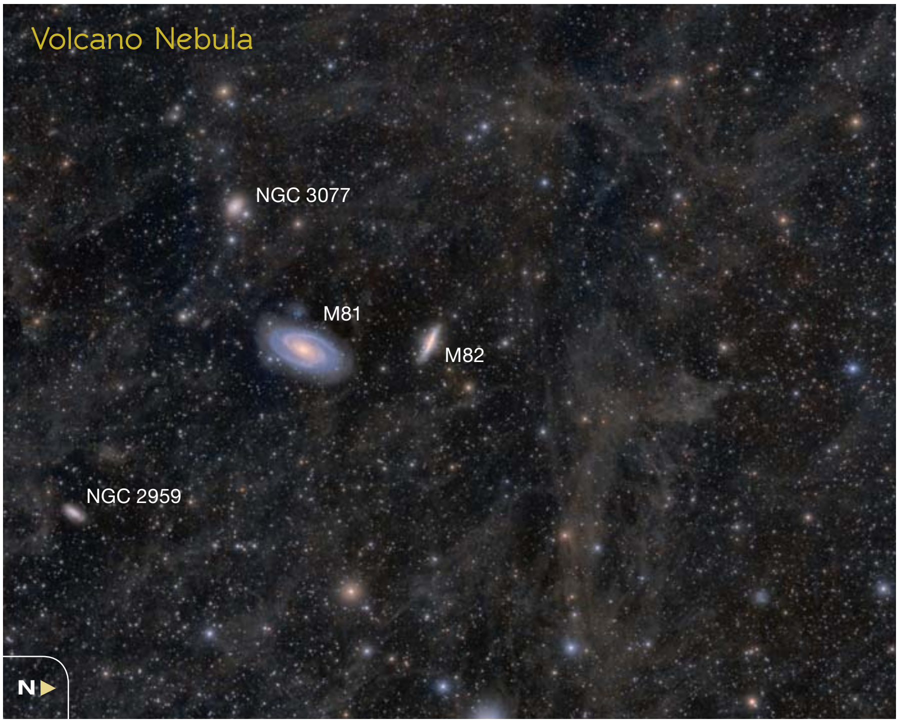


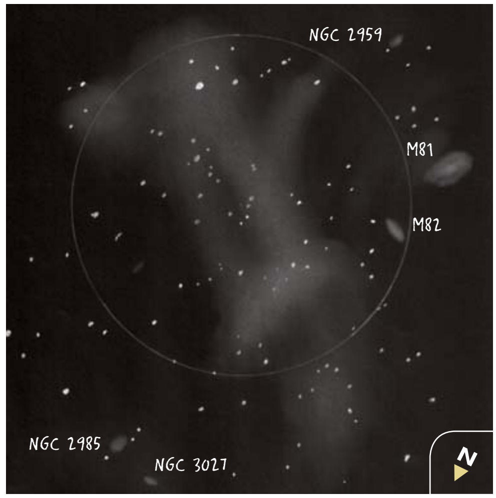


◀ **AS WIDE AS POSSIBLE** To see the dust encircling the Leo Triplet of galaxies, you need a wide field of view — the one here is 1.8°. Keep the magnifications low and meticulously protect your dark-adapted eyes from outside light sources. Try to spot the arc of dust that stretches from the surrounding cirrus to NGC 3628.

◀ **GALAXY TRIO** This composite image combines three sets of data, captured over the course of 43 hours, to reveal the faint galactic structures near the Leo Triplet of galaxies.

LEO TRIPLET: SCOTT ROSEN





▲ **AT THE EYEPIECE** Visually, the Volcano Integrated Flux Nebula appears as two parallel bands of dust capped by an equally bright, shorter band. The base of the volcano is broad and bright.

◀ **VOLCANIC ASH** The Volcano IFN "erupts" across the expanse between M82 and NGC 2985. Look southwest of M82 for the faint extension.

est visible portions of the M81/M82 cirrus are 25.5 mag/arcsec^2, offering a contrast of a scant several percent in terms of field brightness.

Once you have your equipment sorted, you can start by inspecting the field of view for subtle variations in the background glow — Herschel's sky bottom. Since the brightest cirrus glows at 24.5 mag/arcsec^2, the sky needs to be dark. A very dark sky, say a SQM reading of 21.5, means a three-magnitude difference between the background skyglow and the cirrus. That's a contrast difference of a meager 6%. If not for their large extended size, the dust structures would be invisible. Slightly less pristine skies that glow at 20.5 mag/arcsec^2 have a four-magnitude difference and a practically undetectable contrast of 3%.

I aim for high *etendue* (throughput, or the amount of light flowing through the system). More aperture and larger field means higher etendue. My 10.5-inch f/2.7 with coma corrector and 100° AFOV eyepiece produces an etendue of 4,400 cm^2 deg^2; a 10-inch f/5 coupled with an 82° AFOV eyepiece produces half the etendue of 2,400 cm^2 deg^2. Seeing subtle background variations takes time and practice — a lot of time and practice. Unlike tiny dark gray galaxies huddled in a cluster whose visibility comes and goes, the broad strokes of cirrus are more definitive: either you see them or you don't.

When planning my observing sessions, I use infrared all-sky maps like the Planck Thermal Dust map to scout out galactic cirrus. One arm of dust arcs through the eastern portion of Leo into Coma Berenices, just south of **M64**, the Black Eye galaxy. On a night under less than ideal conditions with a SQM reading of 21.1, I barely saw a bright patch to the southeast of M64. Two nights later in excellent conditions with a SQM reading of 21.4 I detected several patches. The patches don't perfectly match the dust; there must be an additional faint blue reflection component.

The easiest cirrus to spot is the **Volcano Nebula** (Mandel-Wilson 3), which lies north of M82. The Pleiades Bubble and Andromeda Shelf also offer good tests for burgeoning skills. Don't hesitate to try a variety of telescopes and filters under varying sky conditions; negative reports are useful, too.

Digital imagers tell me that they edit out variations in the background glow, aiming for dramatic and colorful objects floating against a black background. After all, noise needs to be suppressed and variations in illumination removed by flat-fielding. I encourage imagers to think of the background itself as an interesting object. Showing it at its best requires fast systems, wide fields, and very long exposure times.

Perhaps the illusive nature of these ephemeral "ghost nebulae" and their forgotten observations will capture your interest in sketching deep-sky objects. Until digital imagers increase their exposure times and search for dusty wraiths in the background, visual observers will lead the way.

■ During the day **MEL BARTELS** manages a software development team. On moonless clear evenings, he scans the skies with handcrafted richest-field telescopes. Mel's catalog of IFN observations can be read at **https://is.gd/bartels**.

FURTHER READING: To learn more about the observational history of Herschel's nebulous regions, read Arndt Latussek's 2008 paper "William Herschel's Fifty-Two Fields of Extensive Diffused Nebulosity — A Revision" in the *Journal of Astronomical History and Heritage* (**https://is.gd/Herschel52**).

VOLCANO NEBULA: SCOTT ROSEN

Narrowband Color in PixInsight

Create your own colorful nebulae images with this helpful technique.

▲ **DAZZLING COLOR** Shooting brilliant images of nebulae is within the reach of urban imagers using monochrome cameras equipped with narrowband emission-line filters. This composite image of the Pelican Nebula, IC 5070, was recorded by Michael Miller through a Stellarvue SV152T refractor and processed in *PixInsight* by Warren Keller.

SOME OF THE MOST DRAMATIC VIEWS of celestial objects seen today have been created using the technique of narrowband imaging. Instead of combining individual frames taken through red, green, and blue filters, photographers employ filters that isolate the wavelengths of light produced by ionized gases in emission nebulae. False-color photographs assembled from images taken through these filters are much more colorful than natural-color images.

Narrowband imaging also allows urban imagers to pursue deep-sky astrophotography in light-polluted settings. The extremely narrow passbands of emission-line filters block most of the wavelengths produced by streetlights and other artificial

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illumination (as well as by moonlight). This allows you to reveal ionized gases that permeate the Milky Way and other galaxies from even badly light-polluted areas.

It's no wonder that narrowband imaging has grown so popular, and there are tools to help get the most out of this technique. Here's how you can assemble your own in the popular software *PixInsight* (**pixinsight.com**).

While several narrowband filters exist, those isolating the wavelengths of hydrogen alpha (Hα), doubly ionized oxygen (O III), and singly ionized sulfur (S II) are most commonly used by amateur imagers. We'll use frames taken through these filters to create a three-color image by assigning each channel in a descending-wavelength order — an approach popularized by scientists using the Hubble Space Telescope and known today as the "Hubble palette."

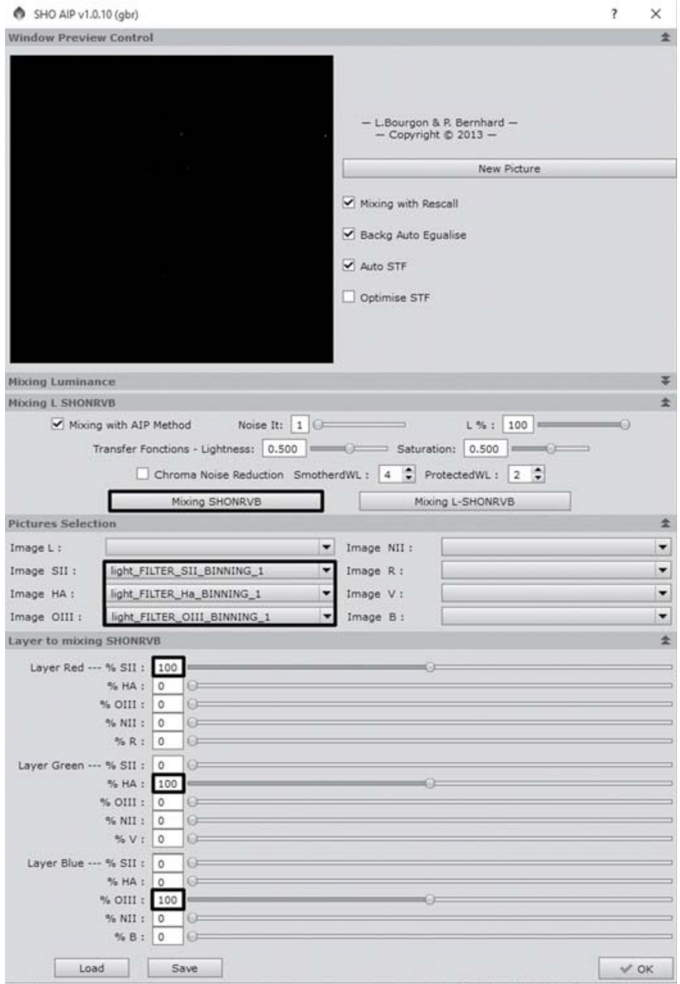
Scripting Color

As with most deep-sky CCD image processing, you should calibrate, align, and combine all your individual exposures into single master files for each filter used. Once completed, you can then begin to assemble them into a color image using *PixInsight*'s powerful Script functions. My preferred technique begins by opening the master Hα, S II, and O III images, then opening the SHO-AIP script found in the script pull-down menu (SCRIPT > Multichannel Synthesis > SHO-AIP). The letters SHO stand for sulfur, hydrogen, and oxygen, while AIP is the group that developed the script. This script uses the Hubble palette mentioned earlier as its default palette, in which S II is assigned to the red channel, Hα to the green channel, and O III to the blue channel.

Once the script is opened, assign your master files in the Pictures Selection section accordingly. The next stop is the Layer to Mixing SHONRVB section, an acronym for Sulfur, Hydrogen, Oxygen, Nitrogen, Rouge, Vert, Bleu. As the SHO palette is selected by default, note that 100% of the S II master is mapped to "Layer Red". Likewise, Hα is assigned to "Layer Green", and O III chosen for "Layer Blue". But you can easily create alternative narrowband palettes by moving the slider controls to change both the channel assignments and contribution amounts of the master files to your liking.

At this point, direct your attention to the check boxes at the top right of the script dialog. The most critical setting is to check the Auto STF box. Those having some familiarity with *PixInsight* know that when viewing linear data, the STF (Screen Transfer Function) AutoStretch must be turned on to see an unstretched, dark image. The other three options might require some experimentation, but for best results try checking Mixing with Rescall (meaning rescale), and Backg Auto Egualise (Background, Equalize), leaving the Optimise STF box unchecked.

Now you're ready to create a color image from the three grayscale masters. This is done in the "Mixing L SHONRVB" section — click on the line to expand its dialog. Leave all the default settings in this section, and click the Mixing SHONRVB button to produce the color image. Should you wish to try a different mix but keep the original result, click the New Picture button at the top of the window before clicking the Mixing SHONRVB button a second time.



▲ **COLOR SCRIPTING** *PixInsight*'s SHO-AIP script lets you blend monochromatic, narrowband master files into a color image.

◀ **RAPID RESULT** This view of IC 5070, the Pelican Nebula, exhibits a strong green bias and magenta stars — a typical result of using the Hubble palette combination before adjustment.

While the resulting image is a good start, you might notice two artifacts of the SHO palette. First, it appears predominantly green. This is because Hα is almost always the strongest wavelength generated by emission nebulae. Since the SHO palette assigns Hα to the green channel, green overwhelms the relatively weaker contributions of the red and

▲ **CORRECTED COLOR** The ColorMask script helps to correct the green bias that's typical in a color narrowband image.

blue channels. You can adjust this later. Second, the larger stars might have magenta-colored halos. This is because the red and blue channels have been overstretched in an effort to match the green channel's strength (red + blue = magenta). If this bothers you from an aesthetic point of view, you can adjust this later, too. Also, if you've acquired a few images of the star field with broadband red, green, and blue filters, you can replace the narrowband stars with the naturally colored ones. Before leaving SHO-AIP and addressing such matters, let's look at another ability of the script.

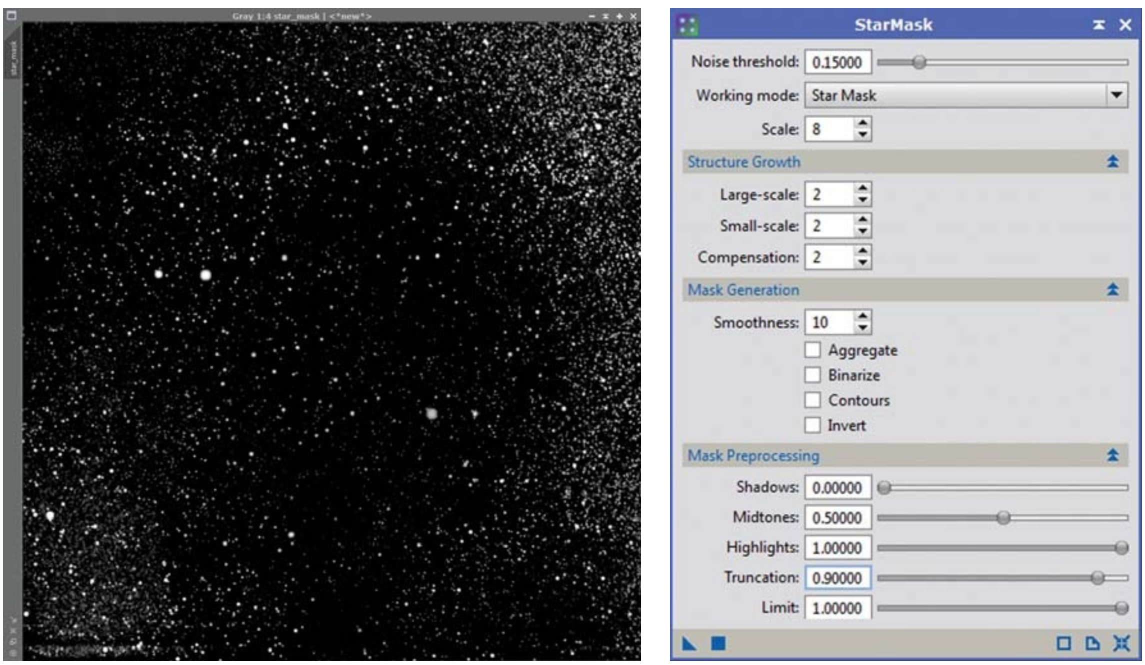
Synthetic Luminance

You might already be familiar with the concept of an image called "pseudo luminance," also known as *synthetic luminance*. This is a grayscale version created from the lightness properties of a color image. Comprised of the combined signal of all three color channels, a synthetic luminance is used to complement the color image, much in the way that a true luminance adds contrast and detail to an RGB image. The SHO-AIP script can produce a synthetic luminance from the color image, and you can do so immediately after creating the color image by first clicking the New Picture button.

To proceed, expand the Mixing Luminance section. Here you can order the masters of S II, Hα, O III, but the sequence doesn't matter since the percentage slider controls at right control the mix. If you want to create a synthetic luminance comprised of all three master channels, click "Create L With master 1+2+3." Or, if only two channels contain the majority of the desired signal, choose "Create L with master 1+2." The blend method can be either Lighten, or possibly Screen when a brighter result is desired. Once your luminance is generated, click OK at the bottom right. While the script is also capable of combining the synthetic luminance and color image, this is best done later after both have been non-linearly stretched.

From this point, linear post-processing of the image might involve using the BackgroundModelization process to eliminate uneven illumination across the field. You can also use deconvolution to sharpen detail and tighten the stars, and linear noise reduction before a nonlinear stretch is applied (*S&T:* Nov. 2013, p. 72).

Earlier, we noted the green bias of your image. While *PixInsight* offers several tools for adjusting color, another script is particularly useful for this task. The ColorMask script by Australia's Rick Stevenson is nothing short of



◀ **STAR MASKS** Using the StarMask process allows you to isolate the stars in your image (far left) to correct magenta halos often seen in color narrowband images.

terrific. Although not yet included in *PixInsight*'s standard release, you can download and install it from the PI Forum (**tinyurl.com/zfkuzgz**). Select your color image and open the script. Now simply choose the desired mask by clicking the appropriate color button — there's rarely any need to change the other default settings. Press the OK button, and the script will produce a mask with the selected color range. Once the mask is applied to the image, you can adjust that specific range of color using the CurvesTransformation process (PROCESS > IntensityTransformations > CurvesTransformation). In iterative applications, green, cyan, and yellow masks are produced and applied one at a time. Use the CurvesTransformation's individual color channels to adjust the image. The image at the top of page 38 shows the result of reducing the green bias while increasing magenta and cyan until I was satisfied with the overall appearance.

Focusing on Stars

Now let's address the magenta halos around the stars. These can be repaired in a couple of ways. As mentioned earlier, they could be replaced with natural color from a typical RGB image. For now, let's try taking a simpler tack using *PixInsight*'s adjustments. While a magenta mask produced with the ColorMask script might facilitate this, you'll get a more targeted result using the StarMask process (PROCESS > MaskGeneration > StarMask). In the process window, try increasing the Noise threshold slightly and increase the Scale value to 8, the Small-scale value to 2, then lower the Smoothness value to about 10 and the Truncation slider to about 0.9. Then press the Apply button at the bottom left of the window.

The resulting mask should appear black and white. You can apply it to your image by opening a context menu with a click of the right mouse button, then selecting Mask/Select Mask, and choosing the desired mask from the drop-down menu; only the stellar components are selected (indicated by the white circles). From there, you can reduce the saturation of the magenta star halos using the CurvesTransformation process's Saturation option. You could also alter the magenta hue using the finer control of the ColorSaturation process.

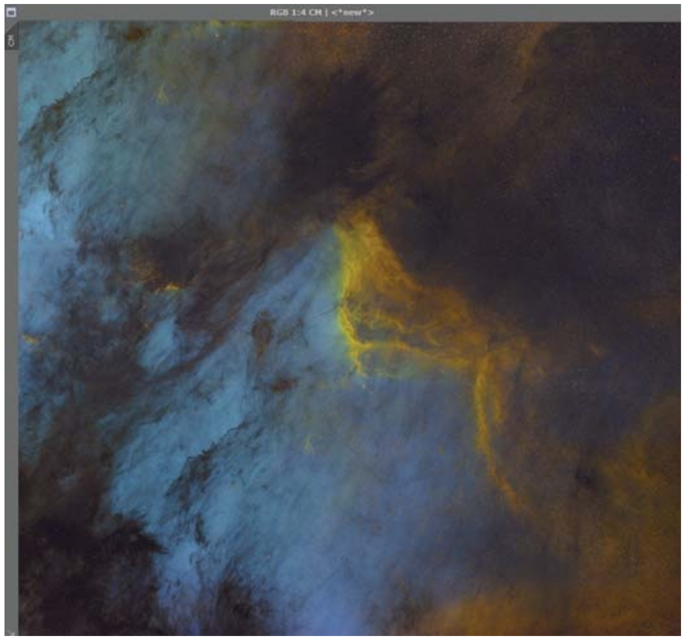
Another option is to alter the size and contribution of the stars. With the same star mask in place, use the Erosion setting in the MorphologicalTransformation process to reduce the stars' sizes — or even eliminate them completely.

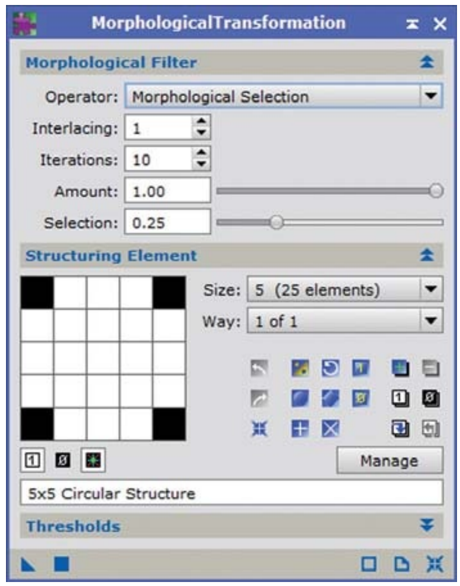
With color adjusted to your liking, you could enhance the synthetic luminance image further with a host of contrast and sharpness-enhancing processes. The LocalHistogramEqualization process can be applied for a subtle yet effective improvement in contrast. The wavelet-based MultiscaleLinearTransform and UnsharpMask processes would be more effective for sharpening small-scale details.

Bringing It All Together

To re-integrate the synthetic luminance with the color image, select your color image and open the LRGBCombination process (PROCESS > ColorSpaces > LRGBCombination). In this process window, select your stretched synthetic luminance in the L section, then uncheck the boxes to the left of the R, G, and B channels. You can perform some noise reduction by checking the Chrominance Noise Reduction box, and then click the Apply button at the bottom left. In a few moments, your new color image will appear, and you're all done.

In addition to tricolor (or even bicolor) narrowband images, narrowband data can also be combined with RGB data to produce hybrid results. In particular, hydrogen-alpha frames can be added to natural color images to enhance the H II regions of nearby galaxies such as M31 or M33. The possibilities of narrowband processing are endless.





◀ **STAR REMOVAL** You can use StarMask to virtually eliminate the stars in an image and thus reveal more small-scale structure within the nebula.

■ **WARREN A. KELLER** is author of the new book *Inside PixInsight,* available through Springer (**springer.com**).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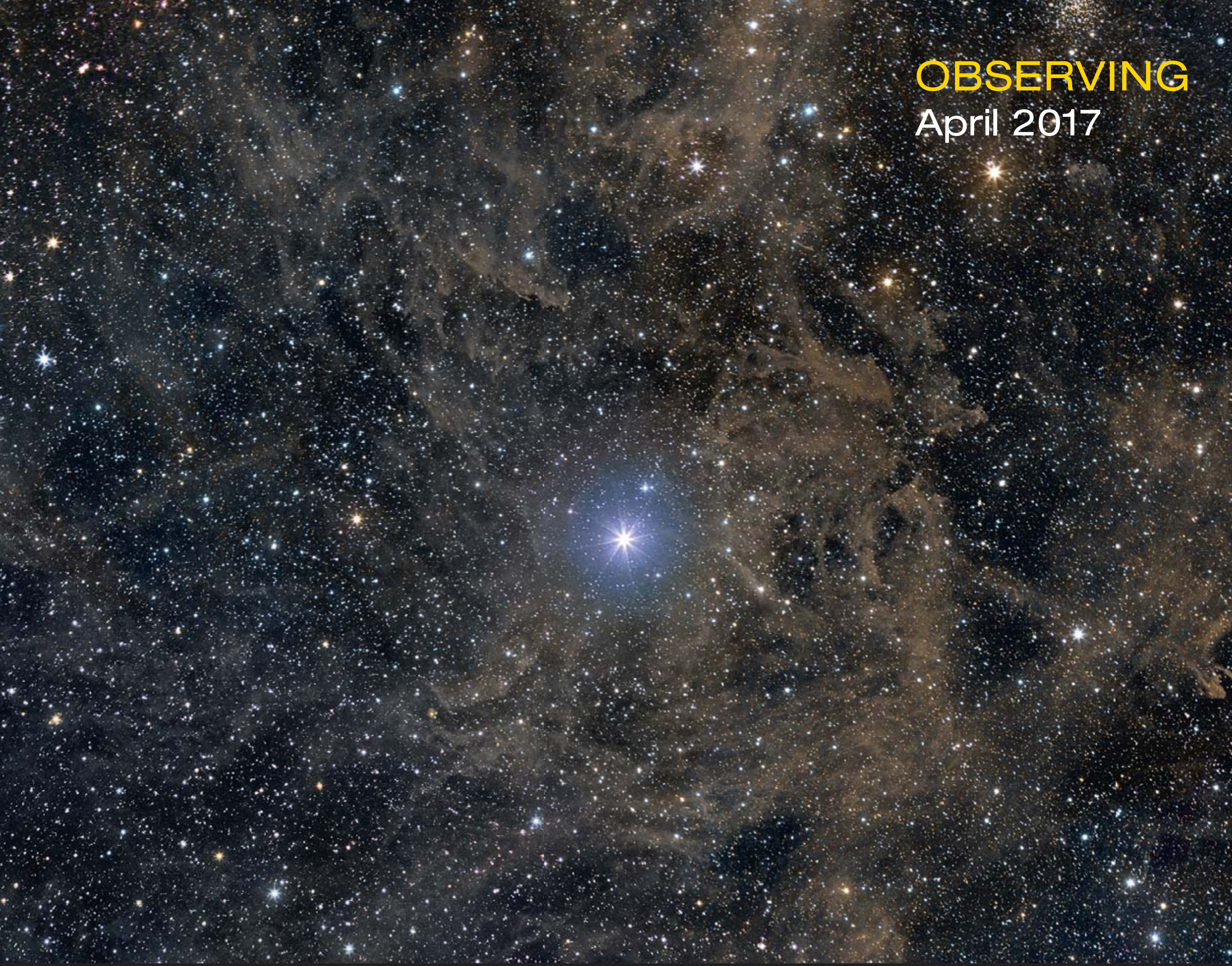


OBSERVING
April 2017

1 DUSK: Mercury reaches its highest altitude of the year. Look for the bright spark low in the west 30–45 minutes after sunset. Orange Mars will be 15° above it.

6 ALL NIGHT: The waxing gibbous Moon pairs with Regulus, the brightest star in Leo. Find them high in the southeast at nightfall and watch them travel together through the night.

7 ALL NIGHT: Jupiter is at opposition; see page 48.

STEFAN BINNEWIES / RAINER SPARENBERG

10 ALL NIGHT: The full Moon beams 2°–5° from Jupiter. The duo is highest about an hour past midnight.

16 MORNING: Look for Saturn about 5° below or lower left of the waning gibbous Moon. The golden planet is highest about an hour before sunrise.

18 EVENING: Look low in the west, where modest Mars shines less than 4° from the Pleiades for the next 5 nights.

22 PREDAWN: The weak Lyrid meteor shower peaks this morning; see page 50.

23 DAWN: The crescent Moon cuts the sky about 8° to the right of Venus, low in the east.

28 DAY: The thin waxing crescent Moon, about 30° from the Sun, occults Aldebaran in daylight for much of North and Central America; see page 51.

The yellow supergiant Alpha (α) Ursae Minoris, more commonly known as Polaris, shines through dense, cold clouds of dust and gas that astronomers refer to as "galactic cirrus."

See more on page 30.

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 \ 30	24	25	26	27	28	29

FIRST QUARTER
April 3
18:39 UT

FULL MOON
April 11
06:08 UT

LAST QUARTER
April 19
09:57 UT

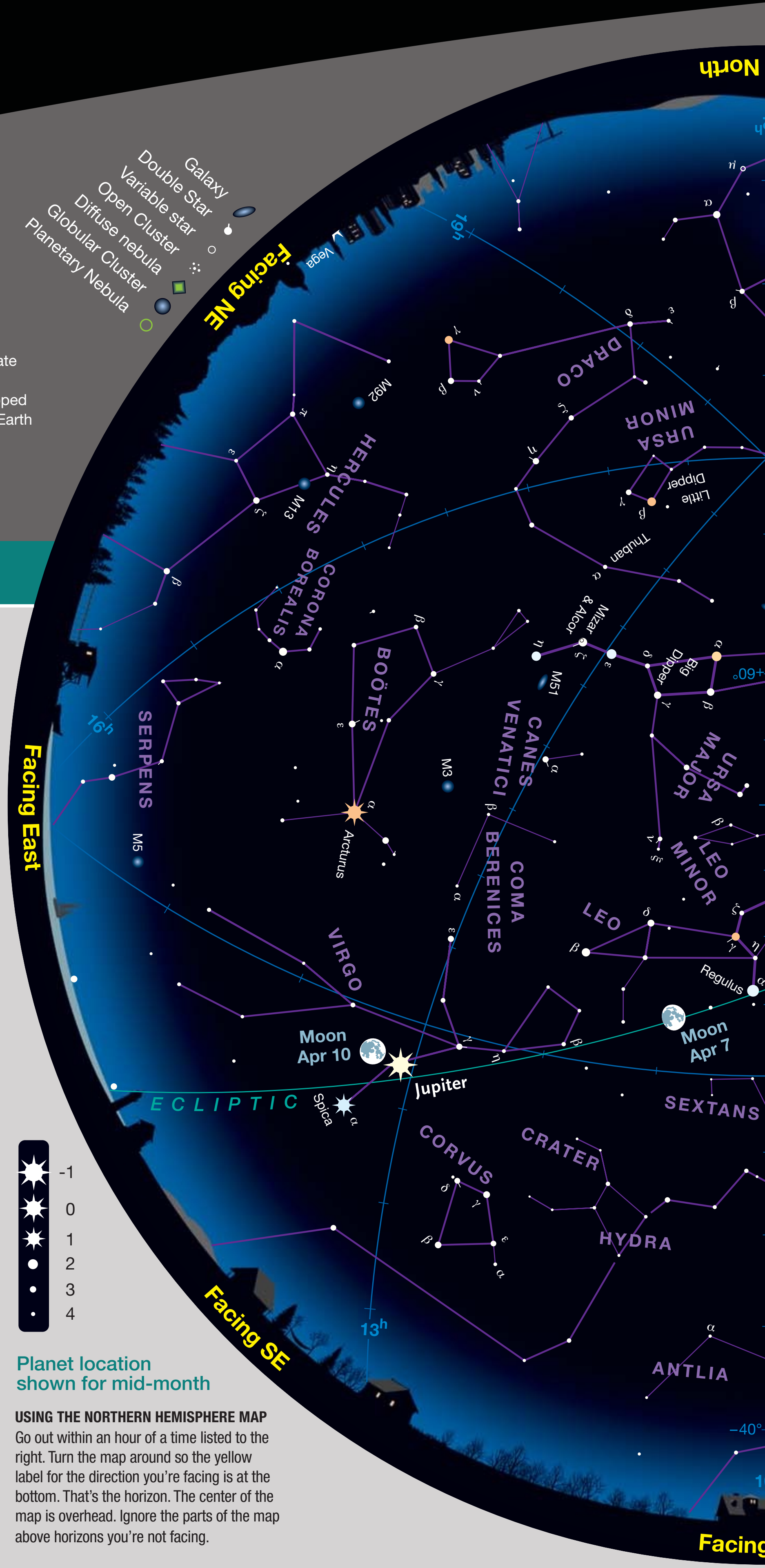
NEW MOON
April 26
12:16 UT

DISTANCES

Apogee 405,474 km	April 15, 10^h UT Diameter 29′ 28″
Perigee 359,329 km	April 27, 16^h UT Diameter 33′ 15″

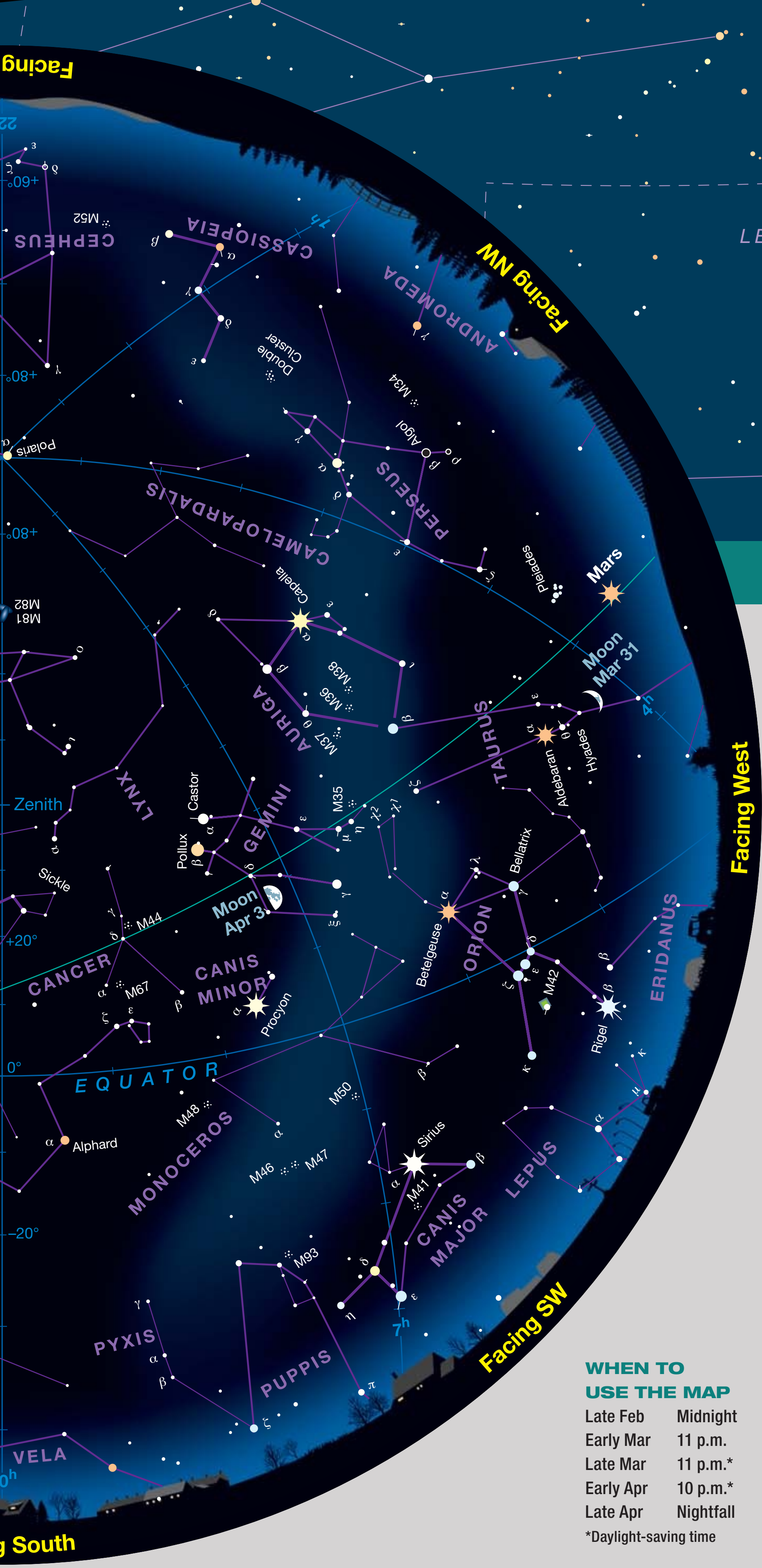
FAVORABLE LIBRATIONS

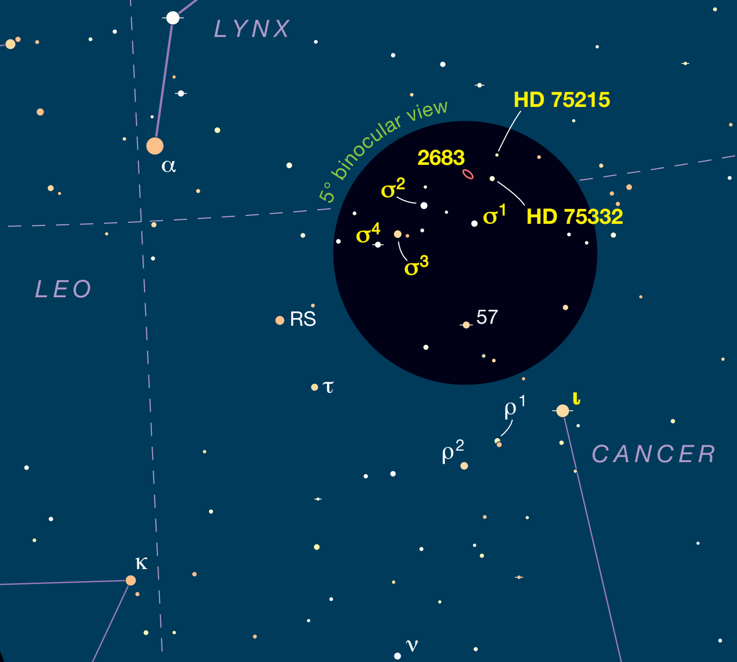
Hayn Crater	April 1
Riemann Crater	April 4
Helmholtz Crater	April 12
Balboa Crater	April 23



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

Better Than Expected

The phrase "northern Cancer" doesn't immediately stir the soul. Most people visit the cosmic Crab for its two Messier open clusters, M26 and M44. If you've been north of M44, it was probably to visit **Iota (ι) Cancri**, a lovely yellow and light blue double star. With a separation of 30.5″, Iota Cancri is a straightforward split in 15×70 binos, and a moderate challenge in 10×50s. Iota is also the jumping off point to an interesting binocular field on the border of Cancer and the neighboring constellation Lynx.

Scan 4° north of Iota Cancri to find a gaggle of 5th- and 6th-magnitude stars zigzagging like a miniature Cassiopeia. These are **HD 72515** and **HD 75332** at the northwestern end, and the four stars of **Sigma (σ) Cancri**. A few 7th- and 8th-magnitude stars fill out the background. Altogether, they make a rich group about 3° across. Several of the stars are doubles. You'll need a telescope to split Sigma^1 and Sigma^4 Cancri — both have separations of about 5″ — but Sigma^3 Cancri is a nice wide 90″, splittable even at 7×.

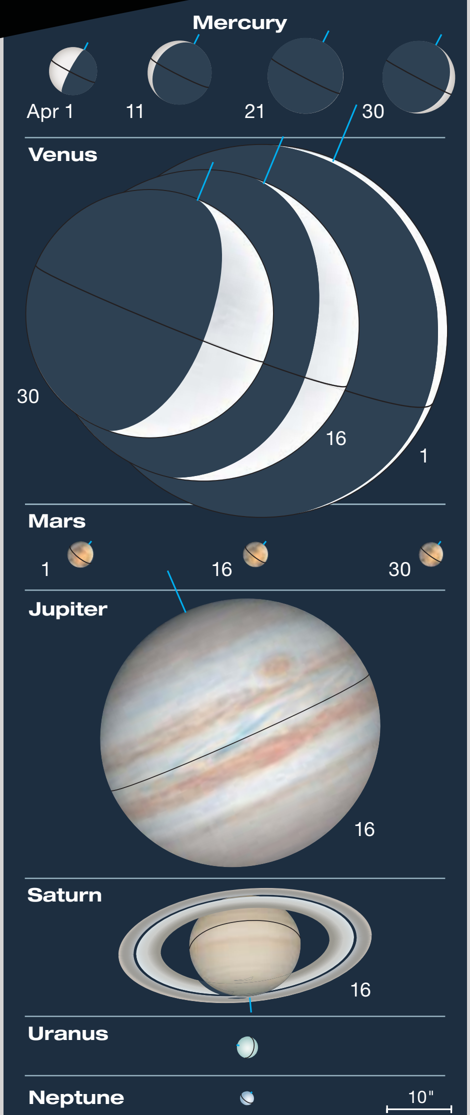
There's one more thing to look for in this field: **NGC 2683**, the UFO Galaxy, which lies on the line between HD 75215 and Sigma^2 Cancri. Like "northern Cancer," "Herschel 400 galaxy" doesn't immediately sound like a rewarding binocular target, but NGC 2683 has some advantages. At 9th magnitude, it's as bright as M84 and M86 in Virgo, and as a nearly-edge-on spiral, its light is concentrated along the galaxy's axis. The UFO Galaxy is also interesting from an astrophysical perspective. It's a field galaxy, meaning that it doesn't belong to any cluster. It wanders alone through a patch of sky that only seems empty — a pastime I highly recommend.

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

WHEN TO USE THE MAP

Late Feb	Midnight
Early Mar	11 p.m.
Late Mar	11 p.m.*
Early Apr	10 p.m.*
Late Apr	Nightfall

*Daylight-saving time



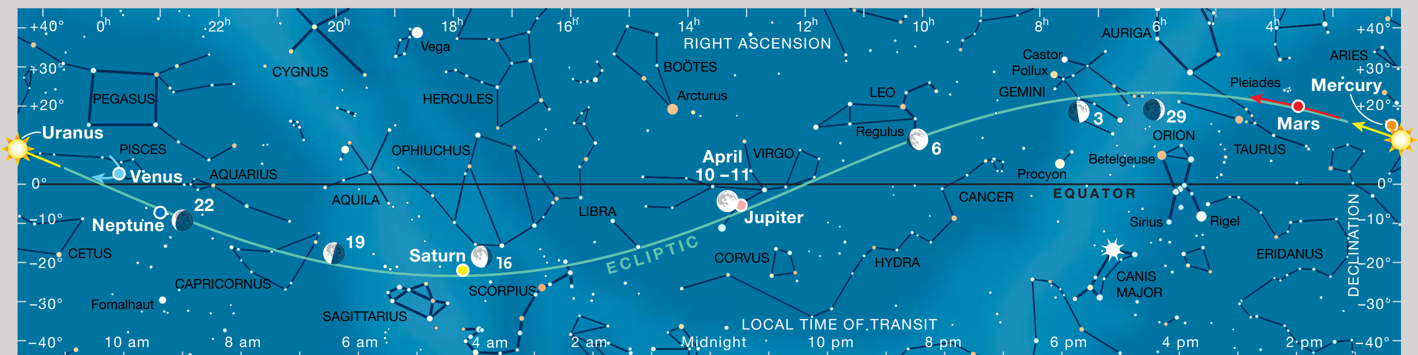
PLANET DISKS have south up, to match the view in many telescopes. Blue ticks indicate the pole currently tilted toward Earth.

PLANET VISIBILITY: Mercury: March 16 – April 9, dusk, low west • **Venus:** All April, dawn, low east • **Mars:** All April, dusk and after, west • **Jupiter:** All April, all night, east to west • **Saturn:** All April, early-morning hours, SE to south.

April Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	$0^h\ 41.3^m$	+4° 26′	—	–26.8	32′ 01″	—	0.999
	30	$2^h\ 28.8^m$	+14° 41′	—	–26.8	31′ 45″	—	1.007
Mercury	1	$1^h\ 48.2^m$	+13° 50′	19° Ev	–0.2	7.5″	43%	0.899
	11	$2^h\ 04.8^m$	+15° 59′	14° Ev	+2.3	10.0″	11%	0.674
	21	$1^h\ 47.9^m$	+12° 41′	2° Mo	—	11.7″	0%	0.572
	30	$1^h\ 32.6^m$	+8° 34′	15° Mo	+2.8	11.3″	9%	0.594
Venus	1	$23^h\ 51.0^m$	+7° 10′	13° Mo	–4.2	57.9″	2%	0.288
	11	$23^h\ 40.6^m$	+3° 49′	25° Mo	–4.6	51.9″	9%	0.321
	21	$23^h\ 44.9^m$	+1° 51′	34° Mo	–4.7	44.5″	18%	0.375
	30	$23^h\ 59.3^m$	+1° 30′	39° Mo	–4.7	38.5″	26%	0.434
Mars	1	$2^h\ 51.6^m$	+16° 50′	34° Ev	+1.5	4.2″	96%	2.231
	16	$3^h\ 34.1^m$	+19° 46′	30° Ev	+1.5	4.0″	97%	2.317
	30	$4^h\ 14.6^m$	+21° 53′	26° Ev	+1.6	3.9″	98%	2.391
Jupiter	1	$13^h\ 12.1^m$	–5° 56′	172° Mo	–2.5	44.2″	100%	4.464
	30	$12^h\ 58.8^m$	–4° 36′	156° Ev	–2.4	43.6″	100%	4.522
Saturn	1	$17^h\ 49.4^m$	–22° 05′	104° Mo	+0.4	17.0″	100%	9.771
	30	$17^h\ 47.5^m$	–22° 02′	132° Mo	+0.3	17.8″	100%	9.348
Uranus	16	$1^h\ 31.0^m$	+8° 55′	2° Mo	+5.9	3.4″	100%	20.933
Neptune	16	$22^h\ 58.9^m$	–7° 27′	43° Mo	+7.9	2.2″	100%	30.677

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-April; 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.

Winter Departs

Watch this month as the winter sky transitions into spring.

In the misty, tangled sky
Fast a wind is blowing
In a newborn rabbit's heart
River life is flowing

So begins another spring
Green leaves and of berries
Chiff-chaff eggs are painted by
Mother bird eating cherries

From the dark and whetted soil
Petals are unfolding
From the stony village kirk
Easter bells of old ring

So begins another spring
Green leaves and of berries
Chiff-chaff eggs are painted by
Mother bird eating cherries.

— Excerpt from "The Lullaby of Spring," Donovan

Spring inspires all of us to get outdoors more, by day or by night. You may still need a light coat on April evenings, but instead of shivering from the cold you can give all your attention to the beauties of the spring heavens.

Spring arrives when winter departs. You can't have spring without winter. Or, at least, spring skies are more intensely appreciated when they can be directly compared to the last, departing winter regions of the heavens.

A look at our all-sky map at the center of the magazine reveals that the winter Milky Way serves as a dividing line. It splits the bright stars that truly belong to winter — those that exit the night and even dusk sky during April — from the bright stars that, though prominent in winter, linger well on into spring. The true winter stars for mid-northern latitudes are Sirius, Rigel, Betelgeuse, and Aldebaran. The stars that remain above the west horizon into May and (in the case of the two Gemini luminaries) even into June are Procyon, Castor, Pollux, and Capella.

Cancer, Leo, Hydra, and the high, upside-down Great Bear (Ursa Major) lead the march of true springtime constellations across the sky. The winter constellations offer a bevy of beauteous open star clusters, and Cancer features an old, not-too-distant, and thus huge-looking open cluster of great repute — M44, the Beehive. But with Leo, Hydra, and Ursa Major, we're getting far enough from the band of the Milky Way to start seeing greater and greater swarms of galaxies far beyond our own.

I'll have much to say about the innumerable galaxies of spring in next month's column. But for now let's look at the constellations and stars that have connections — in legend or picturing — with spring.

Constellation creatures coming out of hibernation. The bees of spring are represented by the many individual stars of Cancer's Beehive cluster, but the birds of spring by just one bird — Corvus, the Crow. Corvus still flies rather low in the southeast at the time of our map. It is, however, a conspicuous and interesting constellation and, late on April nights, we can see it soar a bit higher, accompanying bright Spica.

On April evenings, we can study two constellations that represent creatures that emerge from hibernation in spring. The northern beast is the Big Dipper-bearing Great Bear, lumbering upside-down with giant paws, each marked with a pair of stars (one leg is supposedly hidden behind another, however, so we see just three paws and pairs). The southern creature is Hydra, who, if regarded as a common snake, also should be slithering from its winter burrow now. My favorite reptiles in the southern New Jersey pinelands are the box turtles that appear under our bird feeder in late April and get some bread from me when I see them.

Spring and the lion's leap. Boötes looks like a kite with Arcturus as a bow at its bottom — a kite lifting on spring winds. Virgo has been associated with (among other deities) Ceres, Roman goddess of agriculture and growing things — another spring topic. But surely lions, too, would become more active in spring. Leo, the Lion, is high in the south, now reaching the halfway point in his great leap — or spring — across the heavens.

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

Mercury Maxes Out

The tiny planet climbs to its highest altitude of the year in April, while Jupiter reaches opposition.

Nightfall brings majestic Jupiter into view low in the east, while far dimmer Mars descends in the west. Well below Mars, Mercury remains visible for about the first ten days of April, after which it fades into the solar glare. Saturn rises in the middle of the night, around the time Jupiter shines at its highest. Then, in early dawn, Saturn reaches its apex in the south while blazing Venus bursts above the east horizon.

EARLY EVENING

On April 1st, **Mercury** appears at its highest altitude of the year at nightfall for viewers around latitude 40° north. It's also at greatest eastern elongation, 19° from the Sun, and its magnitude –0.2 light doesn't set until more than 1½ hours after the Sun.

But this fine presentation doesn't last for long. By the evening of April 8th, Mercury's phase in telescopes decreases from 43% to 16% lit and its brightness fades by more than 1½ magnitudes.

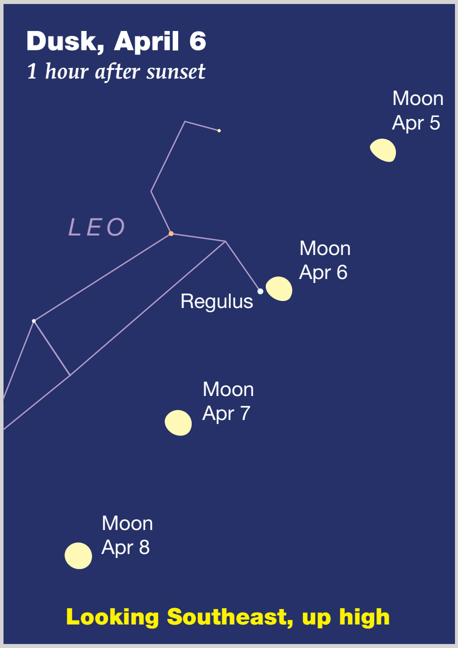
Mercury stands about 7° above the west-northwest horizon 45 minutes after sunset that day, with Mars 17° to its upper left. A few days later, the little planet is too dim to detect in the bright twilight sky. Mercury passes through inferior conjunction on April 20th before reappearing at dawn at the very end of the month.

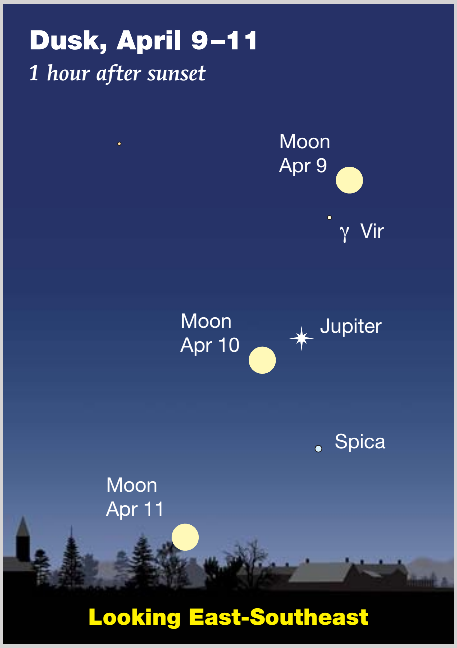
Mars stands about 20° high in the west one hour after sunset in early April, but only about 10°–12° high at a comparable time at the end of the month. Mars dims just a bit during April, dropping from magnitude +1.5 to +1.6. Already quite small in the eyepiece, its disk shrinks just a bit more, down to less than 4″ in apparent diameter.

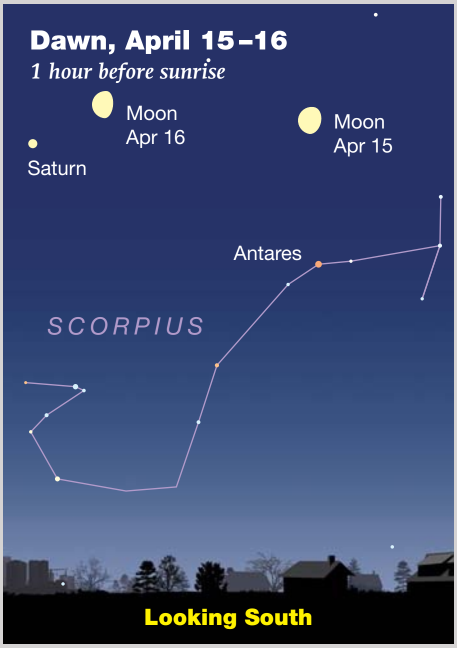
Mars does, however, make a pretty passage between the Pleiades and Hyades in the last week of the month. The Red Planet shines 10° directly below the Pleiades on April 7th. During the next two weeks it creeps upward and to the left of the star cluster, closing the gap between to about 3° on April 20–22. Mars ends April upper left of the Pleiades, right of the Hyades, and about 7° right of Aldebaran, which is similarly colored and distinctly brighter.

DUSK TO DAWN

Jupiter comes to opposition on April 7th and so is visible all night at its closest, brightest, and biggest of the year; see page 48. This opposition, however, occurs less than two months after Jupiter reaches aphelion (the gas giant's farthest point from the Sun in space) of its 12-year orbit. For only a few weeks







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

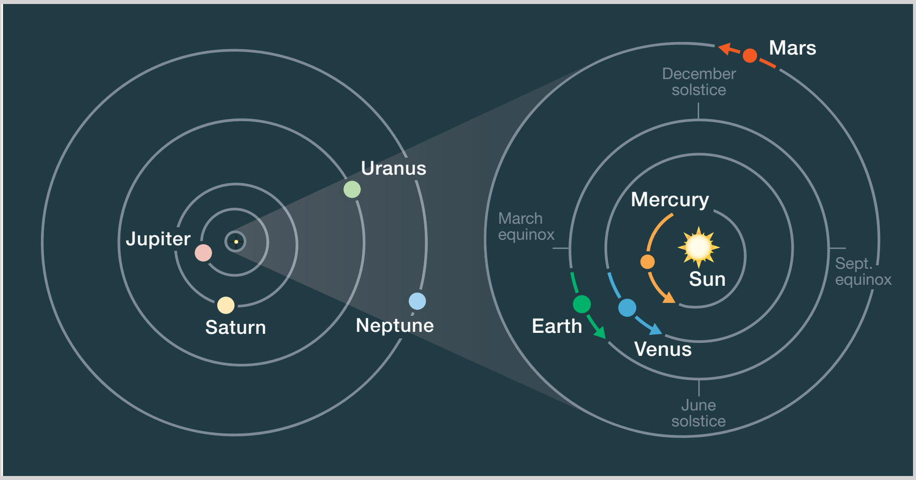
this month does Jupiter attain a magnitude of –2.5 and an apparent diameter of slightly over 44″.

Jupiter continues to move away from Spica, its separation from the bright star increasing from 6° to 9° during April.

On the American night of April 5–6, use binoculars or a telescope to see magnitude-4.4 Theta (θ) Virginis shining only a few times farther from Jupiter than the Galilean satellites. (The brightest of Jupiter's moons is Ganymede, which shines at magnitude +5.4. It's the farthest to Jupiter's east on the night of the 5th.)

LATE NIGHT TO DAWN

Saturn comes to a halt in western Sagittarius on April 6th and then slowly begins retrograde (westward) motion relative to the stars — setting Saturn on course for its opposition June 15th. Its magnitude improves during April from +0.4 to +0.3, making it markedly brighter than orange-red Antares 19° to its right. Saturn's equatorial diameter grows to almost 18″. Its rings tilt more than 26° from edgewise, nearly at their maximum. The golden world rises as early as 11:30 p.m. by the end of April and is highest during morning twilight.



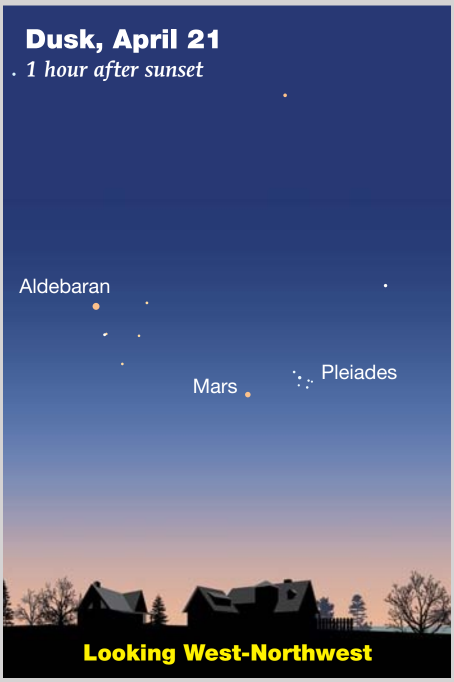
ORBITS OF THE PLANETS
The curved arrows show each planet's movement during April. The outer planets don't change position enough in a month to notice at this scale.

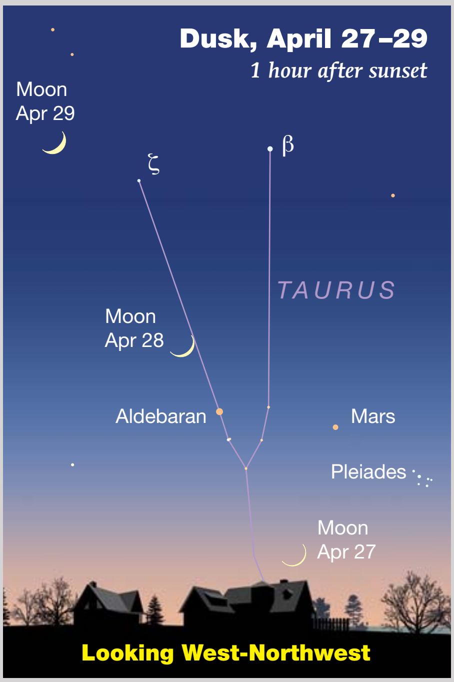
DAWN

Venus comes up in the east about an hour before sunrise on April 1st and climbs a little higher each morning all month. Telescopes or even steady binoculars will show the –4.2-magnitude planet only 2% lit on the 1st, its ultra-slender crescent 58″ tall. Venus kindles up dramatically to a maximum brilliance of –4.7 during April, as its illuminated fraction swells to 26% and shortens to 39″. April 30th marks the date of maximum illuminated extent (largest illuminated area in square arcseconds).

Venus's altitude improves from about 8° to 15° 20 minutes before sunrise during April for viewers near latitude 40° north, with the bright planet rising about 1¾ hours before the Sun by month's end.

Uranus and **Neptune** are not well placed for observation this month.





MOON PASSAGES

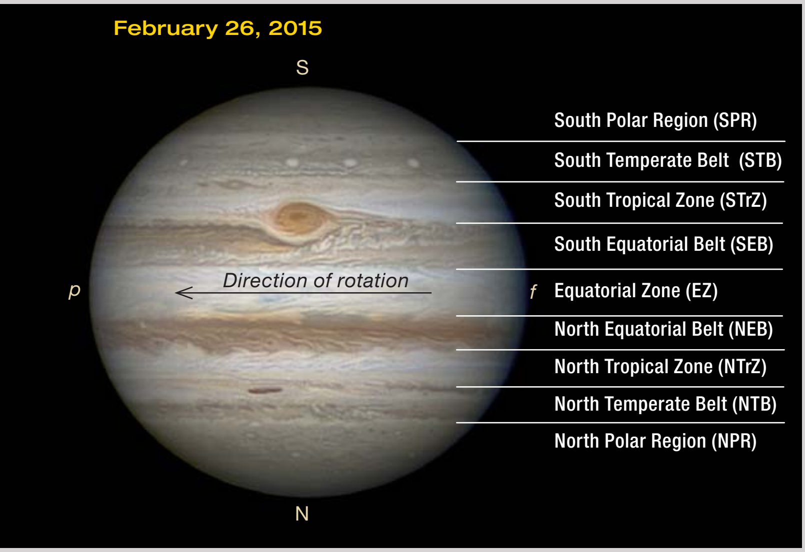
The **Moon** is a waxing crescent well to the right of Betelgeuse and upper left of Aldebaran on the evening of April 1st. On the night of April 6–7, the waxing gibbous Moon pairs nicely with Regulus. At nightfall on April 10th, the full Moon beams just 3° lower left of Jupiter, with Spica 7° below. The waning gibbous Moon shines 4°–5° upper right of Saturn at dawn on April 16th. The waning lunar crescent is about 8° right or lower right of brilliant Venus at dawn on April 23rd, and 10° lower left of it the next morning.

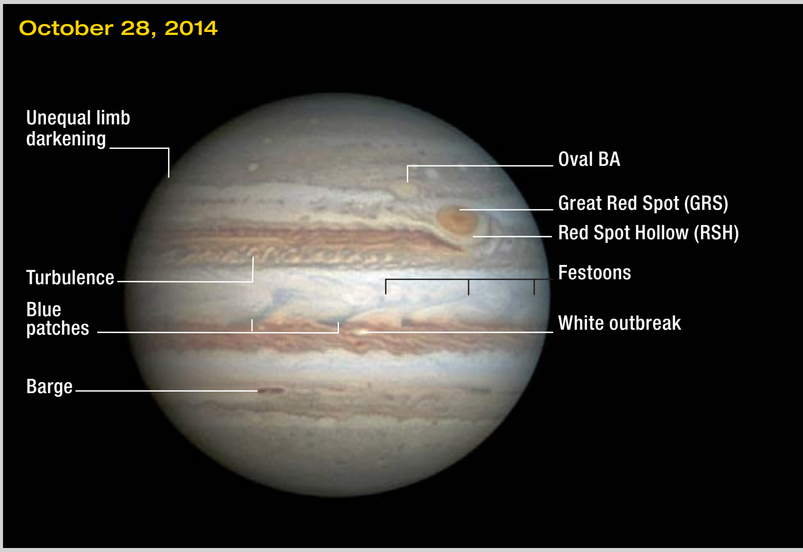
At nightfall on April 27th and 28th, the waxing crescent forms pretty patterns with Mars, the Pleiades, the Hyades, and Aldebaran low in the west.

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

Jupiter Enters the Evening Sky

What's up on "the amateur's planet"? March and April are Jupiter's best months.





DAMIAN PEACH (2)

To get an idea of how Jupiter looks in a telescope, stand far back from this page and squint your eyes. Gradually unsquint them to simulate larger apertures, steadier seeing, and the effect of practice and observing experience. How many of the planet's features can you spot?

SUPPORTING JUNO AT JUPITER: Amateur Jupiter imagers are coordinating with NASA's Juno mission to record the planet as continuously as possible, in order to provide context for what the spacecraft sees close-up.

• Read about this effort at is.gd/junoproam and at the additional links found there.

No planet in a telescope appears what you could really call "big," but Jupiter shows more illuminated surface area, measured in square arcseconds, than all the other planets combined. It comes to opposition on April 7th, so March and April are when it appears its biggest of 2017: 42 to 44 arcseconds wide.

If that doesn't sound like much for Jupiter, it's because this year Jupiter is near its aphelion (farthest from the Sun in space). Still, that's not much smaller than the 50 arcseconds it can attain at opposition around perihelion — a size it won't reach again until September 2022.

Jupiter has been called "the amateur's planet" for the amount and variety of changing detail it can display. Of course, everything depends on your scope's aperture, its optical quality, its temperature equilibrium with the surrounding air (put it outside early), and the atmospheric seeing (steadiness). Jupiter is in Virgo this year, never a super-high constellation for mid-northern observers, so plan to turn your scope on Big Jup when it's getting high near the meridian: after midnight in March, and around midnight in April. Opposition-time observing is like that, especially with the skywatcher's curse of daylight-saving time.

What's to See on Jupiter

Don't be spoiled by sharp, high-contrast images like the ones above, taken by skilled planetary imager Damian Peach with a 14-inch scope using selected, stacked video frames to beat the seeing. Jupiter's features are much more subtle and fleeting at the eyepiece. Instead of a computer grabbing the instants when the atmosphere is steadiest, you have to be alert to grab them with your eye and brain. But there's nothing like observing the real thing. Your skill in discerning planetary detail develops with time, so don't think you've reached your limit anytime soon.

Here are things to look for on Jupiter, in rough order of difficulty — depending, of course, on what the planet is actually displaying when you look.

Easiest: *Jupiter isn't round.* Its fast rotation period (9 hours 56 minutes, but 5 minutes shorter around its midsection) distorts it to be 9% wider across its equator than between the poles. Even the humblest telescope will show Jupiter's spun-up elliptical shape.

Belts and zones. Belts are dark, zones are bright. A small scope usually shows the North and South Equatorial Belts even if nothing else. Can you detect differences between the two — in width, darkness, color, or irregularities?

These and other belts and zones are labeled in the images at left. The naming is somewhat fluid; belts and zones not only come and go, but they can also move up and down a bit in latitude.

Limb darkening. Near Jupiter's edges, sunlight strikes the planet's cloudtops at a grazing angle, *and* both the sunlight and our own line of sight pass through more of Jupiter's atmosphere. So Jupiter always looks dimmer near its limb. This is especially obvious in photos, which are more sensitive to differing brightness levels than your eye is.

Around opposition, the limb darkening is uniform. At times away from opposition, the side of Jupiter farthest from the Sun in our sky is darkened more. This effect is strongest when Jupiter is at quadrature, 90° from the Sun, which will occur on July 7th.

Medium hard: *Belt irregularities.* Often, the finer details that you're most likely to see are irregularities in edges of the two broad equatorial belts.

Great Red Spot. This trademark of Jupiter has been colorful enough in recent years to actually live up to its name. It's more vivid now than the appearance most of us grew up with. Someday it will fade back to pale tan-white, so make the most of the opportunity now. The timetable on page 50 tells when the Red Spot faces Earth most directly during March and April.

Jupiter's rotation. If you can see discrete details, then you should notice the planet's rapid rotation within 10 minutes or so. Features rotate from celestial east ("following," *f*) to west ("preceding," *p*). It takes 50 minutes for a feature to rotate from Jupiter's central meridian halfway to the preceding limb.

Harder: *The Red Spot Hollow (RSH)* is the indentation in the South Equatorial Belt where the Great Red Spot lives. Sometimes it's white, sometimes gray, sometimes hardly visible.

White ovals. These are especially common in the South Temperate Belt (STB). About 11 of them currently reside there, spaced all around the planet.

Oval BA, "Red Spot Junior," is the long-lived product of the merger of three white ovals in the STB that had lasted for decades before. It's very pale tan-pink.

Blue patches often mark the edges of the dark equatorial belts against the lighter Equatorial Zone. They seem to be atmospheric clearings between clouds, blue for the same reason our daytime sky is blue. But the color is subtle.

Festoons extend from blue patches into the Equatorial Zone, where they're blown sideways like banners in the wind.

The *Equatorial Band* is a thin, subtle line sometimes seen along the equator, like the combined tails of many festoons.

Red ovals are small but often quite dark red.

Barges, just as narrow and dark, are elongated east-west into line segments.

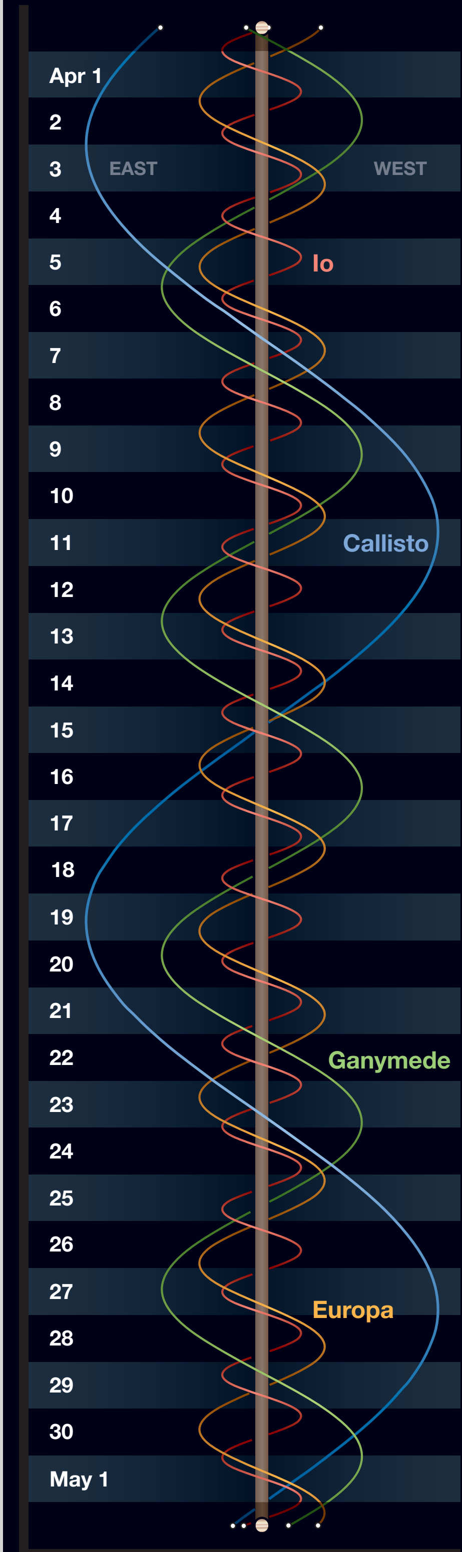
White outbreaks. Tiny, bright-white dots of fresh, upwelling clouds may evolve in days into thin white streaks; they occasionally morph into large, white, turbulent areas extending east and west far along a belt.

April's Jupiter Events

Of course, you can hardly miss Jupiter's ever-changing Big Four moons! Any telescope shows them. Spot Io, Europa, Ganymede, and Callisto at any date and time using the diagram at right.

With either luck or planning, you

Jupiter's Moons



The wavy lines represent Jupiter's four biggest 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.

can sometimes see the tiny black shadow cast by one of the moons onto Jupiter's face. The moons themselves are more difficult to see when they cross in front of Jupiter, because of their lower contrast. Callisto, with the darkest surface, is the easiest — and in fact it's easy to mistake for a shadow. See the timetable of satellite and shadow events on the facing page. Find events when Jupiter will be in good view for you.

And below are the times, in Universal Time, when the Great Red Spot should cross Jupiter's central meridian. The dates, also in UT, are in bold. (Eastern Standard Time is UT minus 5 hours. Eastern Daylight time is UT – 4 hours.)

March 1, 1:39, 11:35, 21:30; **2,** 7:26, 17:22; **3,** 3:17, 13:13, 23:08; **4,** 9:04, 18:59; **5,** 4:55, 14:51; **6,** 0:46, 10:42, 20:37; **7,** 6:33, 16:29; **8,** 2:24, 12:20, 22:15; **9,** 8:11, 18:07; **10,** 4:02, 13:58, 23:53; **11,** 9:49, 19:44; **12,** 5:40, 15:36; **13,** 1:31, 11:27, 21:22; **14,** 7:18, 17:13; **15,** 3:09, 13:05, 23:00; **16,** 8:56, 18:51; **17,** 4:47, 14:43; **18,** 0:38, 10:34, 20:29; **19,** 6:25, 16:20; **20,** 2:16, 12:12, 22:07; **21,** 8:03, 17:58; **22,** 3:54, 13:50, 23:45; **23,** 9:41, 19:36; **24,** 5:32, 15:27; **25,** 1:23, 11:19, 21:14; **26,** 7:10, 17:05; **27,** 3:01, 12:56, 22:52; **28,** 8:48, 18:43; **29,** 4:39, 14:34; **30,** 0:30, 10:26, 20:21; **31,** 6:17, 16:12.

April 1, 2:10, 12:05, 22:01; **2,** 7:56, 17:52; **3,** 3:47, 13:43, 23:39; **4,** 9:34, 19:30; **5,** 5:25, 15:21; **6,** 1:17, 11:12, 21:08; **7,** 7:03, 16:59; **8,** 2:54, 12:50, 22:46; **9,** 8:41, 18:37; **10,** 4:32, 14:28; **11,** 0:24, 10:19, 20:15; **12,** 6:10, 16:06; **13,** 2:02, 11:57, 21:53; **14,** 7:48, 17:44; **15,** 3:40, 13:35, 23:31; **16,** 9:26, 19:22; **17,** 5:18, 15:13; **18,** 1:09, 11:04, 21:00; **19,** 6:56, 16:51; **20,** 2:47, 12:42, 22:38; **21,** 8:34, 18:29; **22,** 4:25, 14:20; **23,** 0:16, 10:12, 20:07; **24,** 6:03, 15:58; **25,** 1:54, 11:50, 21:45; **26,** 7:41, 17:37; **27,** 3:32, 13:28, 23:23; **28,** 9:19, 19:15; **29,** 5:10, 15:06; **30,** 1:02, 10:57, 20:53.

These times assume the spot will be centered at System II longitude 264°. If it has moved elsewhere, it will transit 1⅔ minutes earlier for each degree less than 264°, or 1⅔ minutes later for each degree more than 264°.

Happy hunting! With Jupiter's great physical size — its equatorial diameter is 11.2 times that of Earth — the things you'll see there utterly dwarf anything going on in the atmosphere of Earth.

Minima of Algol

Mar.	UT	Apr.	UT
3	17:07	1	9:20
6	13:56	4	6:09
9	10:46	7	2:58
12	7:35	9	23:47
15	4:24	12	20:37
18	1:14	15	17:26
20	22:03	18	14:15
23	18:52	21	11:04
26	15:41	24	7:53
29	12:31	27	4:42
		30	1:31

Algol remains near minimum brightness for about 2 hours. These geocentric predictions are from the heliocentric elements Min. = JD 2445641.554 + 2.867324**E**, where **E** is any integer. For a naked-eye comparison-star chart and more information about Algol, see **skyandtelescope.com/algol.**

Will Comet 41P/T-G-K Reach 6th Magnitude?

High in the northern sky, the periodic comet 41P/Tuttle-Giacobini-Kresak should glow at 7th, 6th or even 5th magnitude from mid-March through mid-May as it crosses Ursa Major, then passes the Bowl of the Little Dipper, the Head of Draco, and Vega. Moreover, the comet has displayed frequent outbursts in the past.

This is one of three comets passing relatively near Earth this year for which researchers want high-quality amateur observations and images. The goal is continuous monitoring of fast-changing activity in the coma near the nucleus.

• **Read more — and get printable finder charts — at is.gd/4pcometcampaign.**

Two Good Asteroid Occultations

On the morning of April 10th before dawn, the 13th-magnitude asteroid 599 Luisa will occult an 8.5-magnitude star in the head of Scorpius for observers along the Eastern Seaboard: from Maine through Boston, then Connecticut, Long Island, the Carolinas, and finally across North Florida. The occultation could last up to 11 seconds. The star and asteroid will be fairly low in the southwest.

The next morning, April 11th, 11th-magnitude 105 Artemis should occult an 8.9-magnitude star in central Virgo lasting up to 10 seconds, along a track that grazes Phoenix, Las Vegas, and Salt Lake City before passing through eastern Idaho, Montana, and western Canada.

• For times, maps of the tracks, finder charts for the stars, and other information, see Steve Preston's comprehensive asteroid-occultation prediction site at **asteroidoccultation.com/indexall.htm**.

April Meteors

The Moon will be a thin waning crescent, no problem at all, when the annual Lyrid meteor shower should be at its peak on the morning of Saturday, April 22nd. The Lyrids are often elusive; their surge usually lasts just a few hours. But this year it's predicted to arrive sometime around 12^h UT, good timing for North America before dawn and particularly the West.

Under such circumstances, observers who have an ideal dark sky often count about 12 to 20 meteors per hour. Stronger outbursts have occasionally happened; in 1982, rates briefly reached 90 per hour.

A Super-Young Crescent Moon

▲ On February 19, 2015, Patricio Calderari imaged a very young Moon over mountains west of Varese, Italy. The Moon was only 18 hours 30 minutes past new.

Late winter and early spring offer your best chances to see a *very* thin young Moon. This is the time of year when the crescent stands most directly above the Sun after sunset for those of us at mid-northern latitudes, thus making it easiest to detect the Moon at small separations from the Sun (*S&T:* March 2016, p. 52). Not many people have seen a crescent that's less than 24 hours old. But such an opportunity is upon us.

On the evening of March 28th, East Coast observers have a shot at logging a 21-hour-old Moon. By the time twilight reaches the Pacific time zone, the Moon will be about 24 hours old and a little easier to see.

Use binoculars or a low-power telescope to start looking just above the due-west horizon 10 or 15 minutes after sunset. You want to catch the critical few minutes after the sky gets just dark enough for the Moon to be detectable — but before the Moon sinks too low into the horizon murk and sets.

If you succeed with a telescope or binoculars, then try with your unaided eyes.

Note the time of your first definite sighting. Calculate how long this is from when the Moon was new: this happened at 2:57 UT March 28th (10:57 p.m. EDT, or 7:57 p.m. PDT, on the 27th). The difference is your young Moon's age. Is this your lifetime record?

Phenomena of Jupiter's Moons, April 2017

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

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

The Curious Case of Concentric Craters

Why do some small lunar craters display a remarkable ring-and-rim structure? Researchers might finally have the answer.

Nearly all lunar craters formed by impact, but some have peculiarities that can't be explained as simply punching a hole in the Moon's surface. For example, *concentric craters* (CCs) contain circular rings or ridges, like a doughnut snuggled onto their inner walls and floors. The most famous of these, and one of the biggest, is 15-km-wide **Hesiodus A**, on the southern shore of Mare Nubium. You can spot its inner ring even in small telescopes using medium to high magnification.

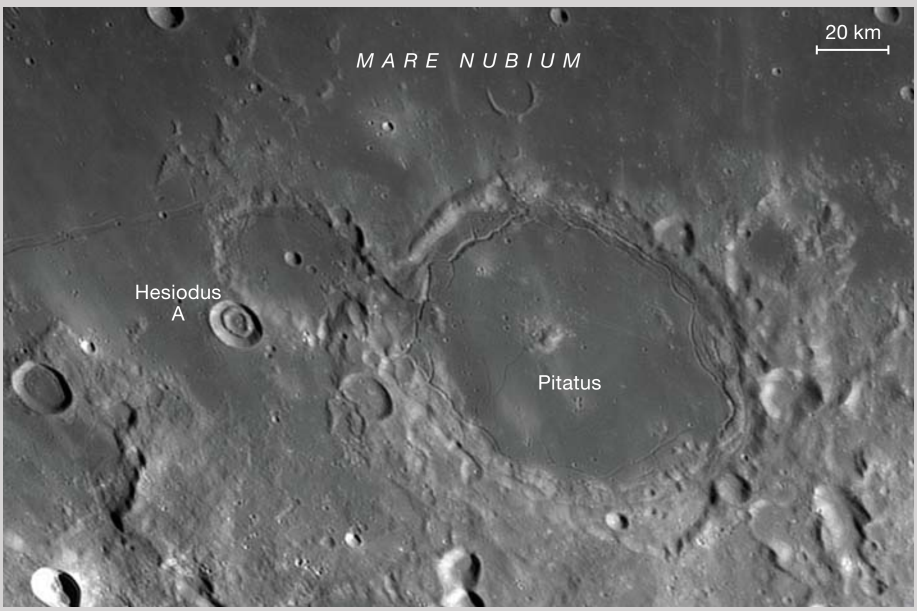
A few CCs have been known since at least the 1950s, but not until 1978 was a catalog published, by me, listing 51 of them. I found that these craters average 8 km in diameter and that the inner ring is about half as wide. Only a handful could be detected by telescopic observations or in photographs with the 1- to 2-km resolution of the day. Instead, I was able to find so many only by searching through photographs taken during NASA's Lunar Orbiter and Apollo programs, which typically show features as small as a few hundred meters across.

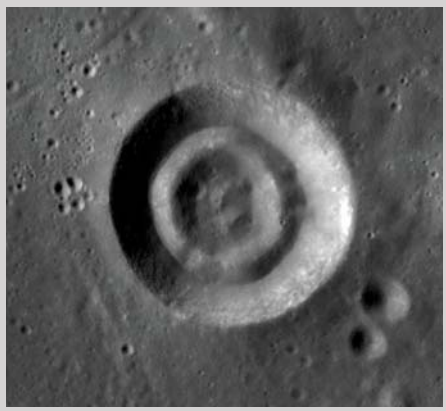
My most surprising discovery — and one that remains a key to understanding their origin — is that 70% of them lie near the edges of maria and 20% more occur on the lava-flooded floors of remarkable craters such as **Humboldt** (on the Moon's southeastern limb). Almost none occur in the highlands.

Their remarkable ring-within-rim structure led to some odd interpretations. One was that CCs resulted from two impacts at the same location. This unlikely occurrence *could* happen if an incoming asteroid had broken into two pieces, one traveling behind the other, before striking the Moon. But there is no logical reason why such double projectiles would only hit near the edges of maria.

A second hypothesis held that a single projectile, smashing into the edge of a mare plain (where presumably the lava is thin), would gouge out one crater in the lava and a second, smaller one in the underlying highlands material. In fact, that does happen for excavations a few hundred meters across, which yield small craters in a lava flow on a mare surface and in a separate flow just below.

But **Crozier H** and some other CCs occur in highlands terrain adjacent to maria, where the two-layer case does not exist. Another counterexample is an unnamed, 7-km-wide concentric crater on the lava-covered floor of Humboldt. Immediately next to it are two similar-size craters, one slightly larger and the

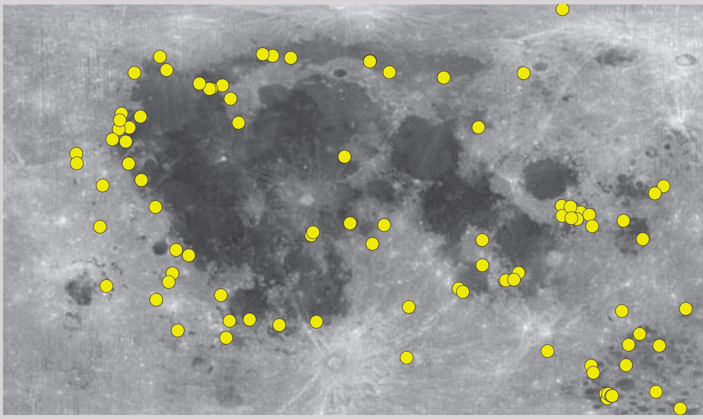




▲ The easiest concentric crater to spot telescopically is 15-km-wide Hesiodus A.

◀ The floor-fractured crater Pitatus displays many arc-shaped fractures just inside its rim. Nearby is Hesiodus A, which has a doughnut-shaped ridge concentric to its rim.

DAMIAN PEACH; CLOSEUP: NASA / LUNAR RECONNAISSANCE ORBITER



Concentric craters (yellow symbols) aren't randomly distributed around the Moon but instead are typically found on the nearside around the edges of maria. Floor-fractured craters (not shown here) have a similar distribution.

other somewhat smaller — and neither exhibits an inner ring.

What about volcanism? Might these odd little craters be volcanic calderas of some sort? It's highly unlikely, especially since the outer rim always looks like a perfectly normal impact crater.

An Answer Arising

In my now-ancient paper, I speculated that CCs were impact craters whose excavation near the edges of maria allowed magma to rise to the surface along preexisting fractures in the floors of the large basins that underlie the maria. Exactly why the lavas would make a ring, rather than flow smoothly across the floor — as occurred in **Plato** and **Archimedes** — was unclear. Perhaps these flows were more *viscous* (sluggish) and piled up in a ring.

David Trang, Jeffrey Gillis-Davis, and the late B. Ray Hawke (University of Hawai'i) now offer a better explanation. As they detail in the November 2016 issue of *Icarus*, concentric craters are apparently simple bowl craters that have been modified by goings-on below them. In this new model, the deep fracture system in a given basin's floor provided conduits for magma to well upward. This encroachment led to an increase in volume that pushed the crater floor upward to form a concentric ridge.

Key to their new interpretation is the much higher-resolution imagery available from Lunar Reconnaissance Orbiter and Kaguya. The researchers used these and other data to catalog 144 concentric craters, 75% of which are on the lunar nearside (where volcanism had been much more common). Their mean crater diameter and ring-to-rim diameter ratio match my older and more limited data.

Importantly, they found that the composition of a given CC's inner ring is very similar to that of its surroundings — it is not some unique material. Additionally, the ages of these craters coincide with the timing of most mare eruptions (3.8 to 2.8 billion years ago).

The Trang trio also realized that CCs occur in the same mare-edge locations as do much larger *floor-fractured craters* (FFCs) such as **Alphonsus**, **Posidonius**, **Taruntius**, **Petavius**, **Atlas**, and **Gassendi**. These are among the most observationally interesting craters on the Moon because their floors are cut by concentric fractures and ridges, and they often contain rilles, dark halo craters, and ponds of lava.

Interestingly, CCs have diameters that range from 3 or 4 km to about 15 km, whereas FFC diameters typically extend from 15 km to more than 100 km. As it turns out, 15 km is also the dividing diameter between simple and complex craters. Simple craters have steep walls and small, flat floors, looking like they were turned out by a lathe. Craters are considered complex if they have central peaks and if parts of their rims have collapsed onto their floors.

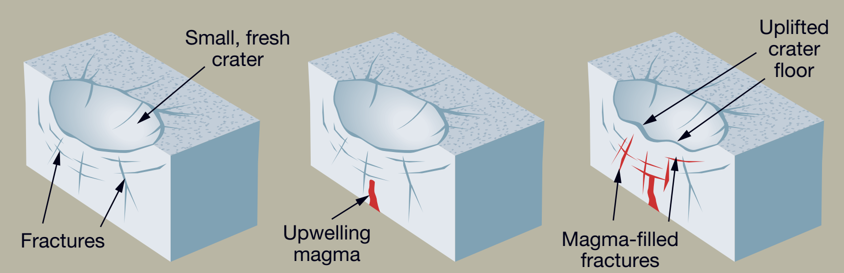
Trang, Gillis-Davis, and Hawke draw upon a model first proposed in 1976 by Peter Schultz (Brown University). They think floor-fractured craters formed when magma rose along basin fractures and lifted their entire floors — central peaks and all. Concentric cracks and ridges resulted as the floors' edges fractured, and magma "leaks" produced rilles, dark halos, and mare ponds.

Notice that this explanation neatly handles both simple and complex cases. The three researchers suggest that CCs form when magma rising along basin margins invades simple craters, and that FFCs form when larger amounts of rising magma colonize complex craters. So their differences are due to the size and the nature of the host crater.

This is a very satisfying solution, one that unites two types of craters previously considered as distinct. We still lack some specifics of how simple craters end up with doughnuts inside them — but we've got a better sense of the process.

■ Contributing Editor **CHUCK WOOD** used a typewriter to pound out his 1978 article on concentric craters. You can read it here: **https://is.gd/wood_cc**.

CONCENTRIC CRATERS: A PUSH FROM BELOW?



Concentric craters might have formed when deep-seated lava pushed upward through underlying fractures. The swelling volume then caused the craters' floors to bulge upward, forming distinctive rings inside the outer rim.

MAP: DAVID TRANG ET AL. / *ICARUS* 2016; DIAGRAM: *S&T* / LEAH TISCIONE (SOURCE: BARRY BAYS / DAVID TRANG)

The Lion-Guarded Gate

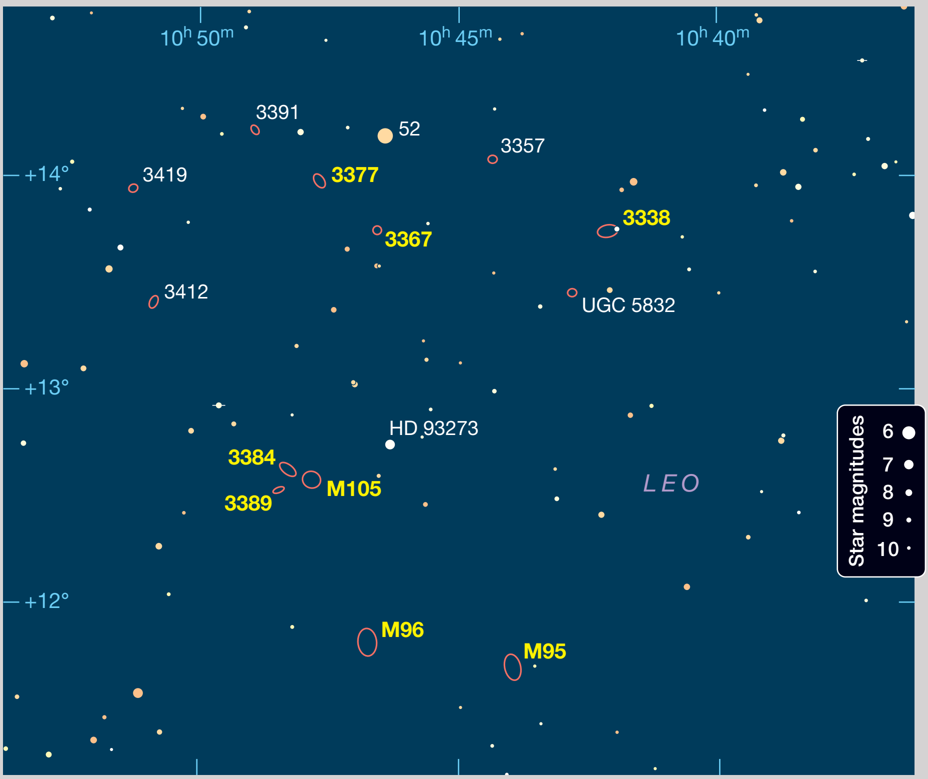
You'll need to brave a ferocious beast to find these deep-sky treasures in Leo.

As stone lions often flank the stairways to palaces and museums, so Leo watches over the grand entrance to the land of the galaxies.

— Leland S. Copeland,
Sky & Telescope, May 1942

Indeed, Leo leads a procession of springtime constellations greatly renowned for the teeming swarms of stars that we call galaxies. Leo itself harbors 809 galaxies from the *New General Catalogue* (NGC), five of them previously listed in Charles Messier's catalog. For this foray into the night sky, we're going to turn our gaze toward three of those bearing Messier designations and assorted NGC escorts.

The members of our Messier galaxy trio were discovered with a 3-inch refractor by Charles Messier's colleague, Pierre Méchain. Méchain found the first two, Messier 95 and Messier 96, on May 20, 1781. He spotted nearby Messier 105 shortly thereafter, yet too late for inclusion in the final version of Messier's catalog. However, Méchain sent a letter about his tardy catches to Johann Bernoulli III, and extracts were printed in two publications of the Berlin Royal Academy of Sciences and Arts. In part, the letter reads: "Mr. Messier reported . . . two nebulae that I discovered in Leo . . . but there is a third farther north; it is more beautiful than the other 2; I discovered it March 24, 1781."

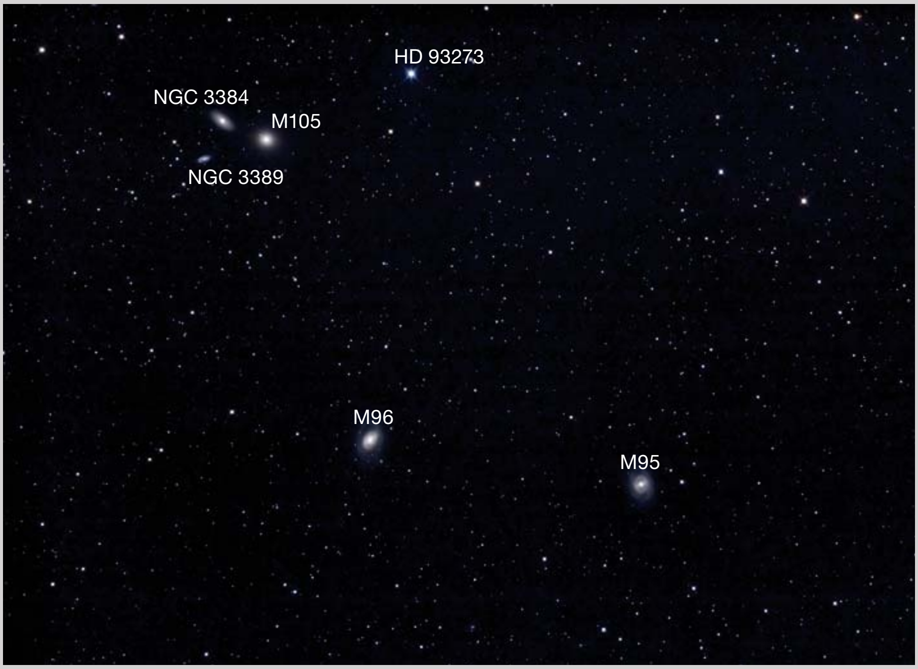


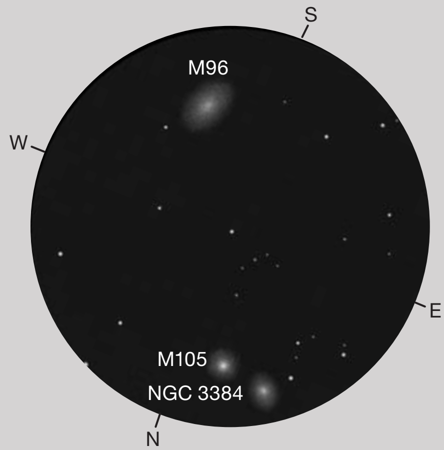
Examining Méchain's little-known letter in 1947, Helen Sawyer Hogg was able to identify this nebula as NGC 3379. She also recognized two of the others as NGC 4258 and NGC 6171. In the *Journal of the Royal Astronomical Society of Canada*, Sawyer Hogg wrote that in her opinion they should be added to the Messier list as M105, M106, and M107 — and they were. But what a difference a few days between discoveries made! M95 and M96 joined the ranks of the Messier objects in 1781, while M105 had to wait another 166 years to make the list.

All the galaxies in this tour are gathered into an area about 2¼° across, just south of 52 Leonis. When I aim my 18×50 image-stabilized binoculars that way, the trio of Messier galaxies is nicely visible. **M105** and **M96** are fairly obvious, each clutching a brighter center. **M95** is dimmer, with a distracting star close to its western side.

Through my 130-mm refractor at 37×, M105's roundish face grows much brighter toward the center. Just 7′ east-northeast of M105, **NGC 3384** joins the scene as an elongated oval pointed toward M105. This companion galaxy boasts a bright, round core and a tiny, vivid nucleus. M96 and M95 each appear oval. M96 rises markedly in brightness toward the center, while M95 hosts a fairly bright interior with a small, brighter core.

At a magnification of 63×, **NGC 3389** emerges 6′ south-southeast of NGC 3384 and is elongated toward M105. The smallest of the five galaxies, NGC 3389 displays a dim façade of uniform surface brightness, but at 91× the little galaxy does seem to have a slightly brighter central area.





▲ **SMALL-SCOPE SKETCH** A 6-inch f/8 reflector reveals the bright cores and dimmer halos of M96, M105, and NGC 3384.

◀ **THREE TO FIVE** The Messier galaxies M95, M96, and M105 are relatively easy targets for small scopes. Upping the power may reveal two dimmer galaxies east-northeast and east-southeast of M105: NGC 3384 and NGC 3389.

Studying the other galaxies at 91×, I see that M105 becomes slightly oval, pointed toward NGC 3384, and bears a small, radiant heart. NGC 3384 is comparable in apparent size and brightness to M105, and I'm a bit surprised that Méchain didn't note this galaxy along with M105. M96 shows three stages of brightness: a moderately faint halo; a bright, relatively large, oval interior; and roundish core that intensifies toward an indistinct nucleus. The galaxy also presents subtle mottling indicative of its spiral structure, although I see no suggestion of its arms. M95 reveals a starlike nucleus ensconced in its core, which sits at the center of a bar that's contained by the galaxy's bright, nearly round interior. The whole shebang is enfolded by a diaphanous halo that tilts north-northeast. M95's bar points nearly toward the fainter of the two stars (magnitudes 10 and 12) that rest off the galaxy's western flank.

I used a power of 117× to pin down some details. M105 appears about 3½′ long and nearly as wide, while nearby NGC 3384 is about 4′ × 2′. NGC 3389 is roughly 2′ long and one-third as wide. M96 bridges about 6′ and is accompanied by a dim star near its edge, west-northwest of the galaxy's center. The halo leans a tad west of north, but the bright, oval interior tips northwest. M95 covers about 5′ × 3′, and its pallid halo slants east of north.

Through my 10-inch scope at 192×, M105 gains a tiny but brilliant nucleus. The core of M96 now looks slightly oval,

Objects in the Lion's Den

Object	Type	Surface Brightness	Mag(v)	Size/Sep	RA	Dec.
M105	Elliptical	12.8	9.3	5.4′ × 4.8′	10^h 47.8^m	+12° 35′
M96	Spiral	13.1	9.3	7.6′ × 5.2′	10^h 46.8^m	+11° 49′
M95	Barred spiral	13.5	9.7	7.5′ × 5.0′	10^h 44.0^m	+11° 42′
NGC 3384	Barred lenticular	12.6	9.9	5.5′ × 2.5′	10^h 48.3^m	+12° 38′
NGC 3389	Spiral	13.2	11.9	2.8′ × 1.3′	10^h 48.5^m	+12° 32′
NGC 3377	Elliptical	13.3	10.4	5.2′ × 3.0′	10^h 47.7^m	+13° 59′
NGC 3367	Barred spiral	13.2	11.5	2.0′ × 1.6′	10^h 46.6^m	+13° 45′
NGC 3338	Spiral	14.2	11.1	5.9′ × 3.6′	10^h 42.1^m	+13° 45′

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.

MESSIER GALAXIES: FRED ESPENAK; SKETCH: JEREMY PEREZ

▲ **SPIRAL SPECTACULAR** Images taken with large-aperture scopes, like this one from the Schulman 32-inch Ritchey–Chrétien Telescope at the Mt. Lemmon SkyCenter, reveal the spiral arms of NGC 3338. The bright star to the west of the galaxy is 9th-magnitude HD 92622.

and it's skewed counter-clockwise with respect to the galaxy's bright interior, such that the halo is aligned north-northeast to south-southwest. Looking at M95, I can see that its bright interior is actually ring-like, with the ring's interior spanned by the bar, and its nucleus no longer resembles a star. The brightest region of NGC 3389 is offset west-northwest of the galaxy's visual center, and the galaxy as a whole is about 2′ × 1′.

The trio of Messier galaxies and NGC 3384 are members of the Leo I Group about 35 million light-years away from us, but NGC 3389 is a resident of the Leo II Group and approximately twice as distant. If we could somehow tug NGC 3389 into the Leo I Group, it would shine 1.6 magnitudes brighter in Earth's sky.

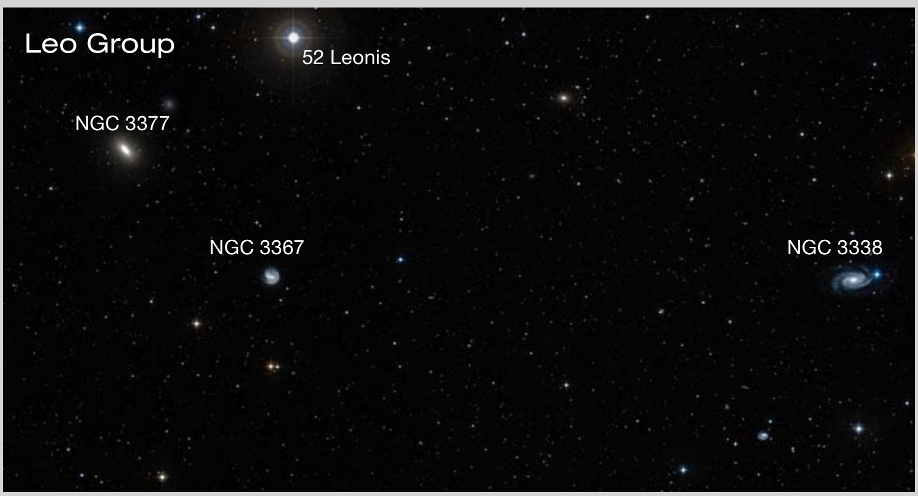
Closer to 52 Leonis, the galaxies **NGC 3377** and **NGC 3367** form an isosceles triangle with the star, and they share the field of view in each of the observations described below. Wide-angle eyepieces were used.

In the 130-mm scope at 37×, both galaxies are easily spotted. NGC 3377 is larger than its neighbor and holds a relatively large, bright, oval interior that intensifies toward the center. NGC 3367 is a misty, round glow with a slightly brighter center. At 91× NGC 3377 is swathed in a 3½′ × 2′ halo that tips northeast and gradually blends into the background sky. The galaxy's bright interior measures about 1½′ × ¾′ and a brightness pip pins its center. The entire face of NGC 3367 spans only 1½′.

NGC 3377 exposes a small, slightly elongated, bright nucleus when seen through the 10-inch scope at 115×, and NGC 3367 shows delicate variations in brightness. In their *Observing Handbook and Catalogue of Deep-Sky Objects*, authors Christian B. Luginbuhl and Brian A. Skiff describe their view of NGC 3367 through a 10-inch telescope. They saw "a very faint stellar nucleus in a bar-shaped core running east-west through the halo." Can you pick out these elusive details?

NGC 3377 is a member of the Leo I Group, but NGC 3367 is far in the background at 150 million light-years. If we could drag NGC 3367 into the Leo I Group, it would brighten by 3.2 magnitudes and outshine all the galaxies in that group.

Through my 130-mm scope at 37×, putting NGC 3377 and NGC 3367 in the eastern side of my view brings **NGC 3338** into the field. Although faint, the galaxy is readily visible, stretching eastward from a 9th-magnitude star. At 117× I see a 3′ × 1½′ oval with a fainter fringe. In my 10-inch scope at 213×, the galaxy appears gently mottled, with a brighter core and a faint, starlike nucleus. A few faint stars watch over the galaxy's periphery. Along with NGC 3389, this galaxy is also a member of the Leo II Group, and part of our lion-guarded gate.



▲ **EASILY SPOTTED** Elliptical galaxy NGC 3377 and barred spiral galaxy NGC 3367 lie close to 52 Leonis — use a wide-angle eyepiece to keep all three in the same field of view. If you move the pair of galaxies to the eastern side of your field, you may be able to bring spiral galaxy NGC 3338 into view on the western side.

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

Pure & Simple

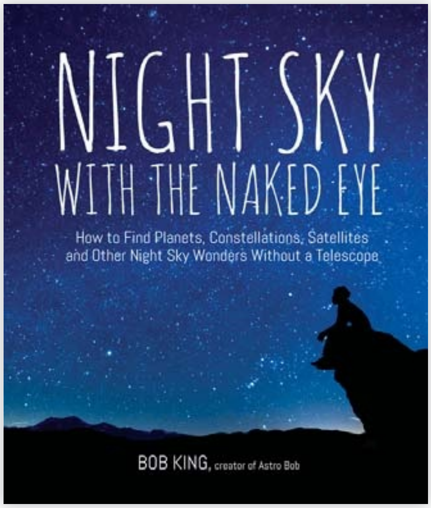
NIGHT SKY WITH THE NAKED EYE: *How to Find Planets, Constellations, Satellites and Other Night Sky Wonders Without a Telescope*

Bob King
Page Street Publishing, 2016
224 pages, ISBN 978-1624143090
$21.99, softcover.

HAVE A NEW STARGAZER in your family? Need some help explaining constellations, asterisms, or meteors to your neighbor? Looking for something new to jumpstart your own engagement with the night sky? Bob King's new book, *Night Sky with the Naked Eye: How to Find Planets, Constellations, Satellites and Other Night Sky Wonders without a Telescope* has you covered. A few (or several!) evenings in the backyard with this book will turn the novice into an expert and the expert into a rejuvenated enthusiast.

Night Sky with the Naked Eye is a well-conceived, well-written collection of topics and tasks organized around naked-eye observing. Each chapter opens with a list of activities and observing goals related to a particular type of night-sky target, starting with satellites and the International Space Station in Chapter 1 ("Wave 'Hi' to the Astronauts!") and finishing with celestial "oddities" like lunar halos and comet dust in Chapter 10 ("Curiosities of the Night"). Between beginning and end, King helps you prepare for a night out, sharing tips on how to check the weather, find a dark sky, and read a sky chart. You'll learn about the benefits of averted vision, the names of the Moon's most prominent features, and how to make your own comet (not kidding!).

Night Sky with the Naked Eye contains ten chapters, the longest of which ("Meet the Rabbit in the Moon") covers our nearest neighbor as well as the closest star, the Sun. The book is aimed



▲ An evening crescent moon is one of the most beautiful sights in nature and never fails to get our attention. Sunlight illuminates the bottom of the moon, while light reflected from the Earth—called earthshine—faintly lights the remainder. Photo credit: Bob King

Brew Up Some Earthshine

Earthshine offers us yet another interesting perspective on phases. Did you know that Earth goes through phases, too? When we see a thin crescent, an astronaut standing on the moon sees a nearly full Earth. A half moon here means a half-Earth there. Around the time of full moon, our astronaut sees a "new" Earth so close to the sun in the lunar sky that it's invisible in the same way we can't see a new moon. A full Earth reflects a lot of sunlight back at the moon, so earthshine is brightest when the crescent is thinnest. As the moon's phase waxes or increases to half and beyond, the Earth's phase wanes or decreases, going from full to half to crescent. With less Earth to reflect sunlight, earthshine grows fainter and fainter. You can follow its progress up to about 4–5 days after new phase. After that, you'll need binoculars or a telescope to see it. My personal earthshine record using a telescope is 10 days.

ACTIVITY: If you spend a few nights tracking the moon's movement, you'll see both its changing phase and increasing distance from the sun, a reflection of the moon's revolution around the Earth. The moon moves eastward from the sun at 12° or a little more than one fist per day. As it does, the crescent fills out to half as the changing angles between moon, Earth and sun expose more of its globe to sunlight.

at beginning skywatchers but offers challenges at every skill level. Some of the activities are easily accomplished (finding the Big Dipper, for example), while others require more effort and expertise (like monitoring the rise and fall of Algol's brightness). King offers some pointers on binocular and telescopic observing for those interested in taking their observations a bit deeper, but equipment is completely optional for this astronomical journey.

The depth (and breadth!) of observing experience and knowledge shown by King is impressive, but even more striking is how accessible he makes the subject for the reader. He sets the tone in the first chapter, where he relates our observing to the astronauts who orbit the Earth in the International Space Station. The book builds on that human connection, providing insights into the history and (sometimes tall) tales we tell each other about the sky. King's prose is friendly and engaging. In fact, *Night Sky with the Naked Eye* often reads like a series of short stories or a novel instead of an observing manual. There's a specificity and order to the activities, but members of my household found working through them more like a scouting adventure than a laborious slate of required tasks.

You'll find that the abundance of illustrative materials — photographs, finder charts, and diagrams, almost all of which King took or created — not only add color and style to the pages, but complement the book's educational purpose. Every caption contains useful information: Those accompanying the finder charts will help you plan your next star hop, and those attached to photos and diagrams will reinforce the concepts outlined in the main body of the chapter.

If you're looking for a friendly introduction to amateur observing, for yourself or your closest friend, consider picking up *Night Sky with the Naked Eye*. You may be surprised how far a single book can take you.

■ Observing Editor **S. N. JOHNSON-ROEHR** sometimes welcomes clouds because she can stay inside and read.

The ASI 1600MC Cooled Camera

This 16-megapixel camera is as effective shooting the Moon and planets as it is deep-sky targets, and at a price that's tough to beat.

◀ The ASI 1600MC-Cool from ZWOptical is a 16-megapixel cooled CMOS camera capable of operating in either high-speed video mode or as a long-exposure, deep-sky camera.

ASI 1600MC-Cool

U.S. Price: $999

Astronomy-imaging-camera.com

What We Like:

Affordable and versatile

Very low-noise images

What We Don't Like:

Poor documentation

Cooler power supply not included

ASTROPHOTOGRAPHERS today generally choose between two different types of cameras, depending on the objects they're interested in recording. The highest quality shots of the Sun, Moon, and planets come from the "lucky imaging" technique using high-speed digital video cameras to capture short video clips that are later processed into a finished still image by stacking and sharpening the highest-quality frames.

Deep-sky imagers in pursuit of the faintest objects usually turn to cooled CCD cameras that can capture long exposures often tens of minutes in duration. Like the lunar and planetary shots, multiple frames are stacked to improve the signal-to-noise ratio for better pictures.

But the line separating these two types of cameras is blurring. ZWOptical's ASI 1600MC-Cool camera is a versatile, 16-megapixel, one-shot-color camera that is as comfortable shooting the Moon as it is the faintest nebulae. Its Panasonic MN34230PLJ CMOS detector features a generous array of 4,656 × 3,520, 3.8-micron pixels forming an active imaging area measuring 17.6 × 13.3 mm. A monochrome version of the camera is also available for $1,280.

Housed in a compact, red-anodized cylinder, the camera has male T-threads (often called M42 threads) at the front and jacks for a USB cable, a 12-VDC power cable (that's only needed for the cooler), and an industry-standard autoguider port on the back end. Surprisingly, no AC adapter or even a power cord is supplied for the camera's regulated two-stage cooler. I contacted the manufacturer and was told that the 12-VDC input plug on the camera is center-positive and that the cooler draws about 2 amps of power. Suitable AC adapters are readily available online, and I was able to use one that I already had on hand.

The camera comes with 1¼- and 2-inch nosepieces as well as a short extension tube that has female T-threads on one end and slightly larger female M48 threads on the other end. This would come in handy for connecting the camera to telescopes and accessories that use M48 threads. The camera is light, weighing just 14.5 ounces.

When the cooler is operating, a small fan on the back circulates air through the camera body and out through two louvered vents on the side. Using the supplied software, you can enable a wide range of region-of-interest (ROI) sub-fields on the chip. The camera's tiny pixels produce high-resolution

ALL PHOTOS BY THE AUTHOR

lunar and planetary images with large-aperture telescopes, and work well on deep-sky objects using small-aperture instruments and camera lenses.

An optional camera-lens adapter is available, as is a mounting collar with a ¼-20 tripod socket that fits around the camera body. The camera's imaging chip is located just 6.5 mm back from the front face of the camera body. This allowed me to use a low-profile, off-axis guider while still maintaining the optimum distance between the sensor and the field flattener and coma correctors used when recording many of my deep-sky test exposures. The camera's detector chamber is sealed with an anti-reflection coated window that also blocks infrared light, and a 1¼-inch filter adapter is mounted just ahead of the window. This allows 1¼-inch filters to be used on the camera without vignetting the chip.

Although the ASI 1600MC-Cool is capable of capturing up to 23 full-resolution frames per second, the actual maximum frame rate may be lower depending on the speed of the USB port on your host computer and the write speed of your computer's hard drive. Although my relatively new laptop features USB 3.0 ports, the hard drive speed of 5,600 r.p.m. significantly limited the actual rate at which I could record frames when shooting lunar clips. Frame rates were much faster when I was using smaller ROIs for shooting the planets, since these didn't require the camera's entire 16-megapixel detector. Deep-sky exposures of several minutes were no problem using either the USB 3.0 on my laptop or the older USB 2.0 port on my desktop computer.

I tested the camera on several instruments ranging from a 12½-inch Newtonian/Classical Cassegrain reflector down to a telephoto camera lens.

Control Software

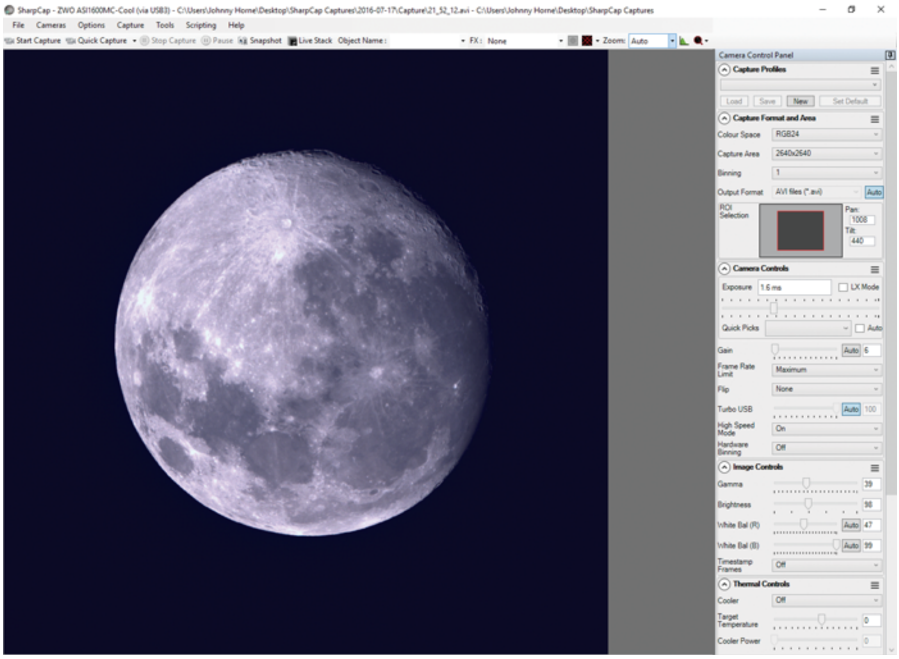
The ASI 1600MC-Cool camera includes three software programs on a CD that can control the camera. The simplest is titled *USB3_cameras*. The other two, named *SharpCap* and *FireCapture,* offer more features including control of the camera's two-stage thermoelectric cooling, which decreases noise in long-exposure images. Regulated cooling also allows you to record accurate dark and bias calibration frames in advance of an imaging session, which saves valuable shooting time under a dark sky. The popular planetary stacking program *Autostakkert!2* (*S&T:* Sept. 2016, p.68) and the autoguiding software *PHD2* are also included on the same CD, as are the camera and ASCOM drivers to allow control of the camera with other third-party programs. All of the software as well as the camera drivers were easily installed without issues.

▲ The rear of the camera's housing includes an autoguider port, the USB 3.0 port (which also powers the camera) and a 12VDC jack that powers the dual-stage cooling. New models also have a built-in, dual-port USB 2.0 hub to connect a filter wheel and electronic focuser.

▼ The camera comes with a 2-meter USB 3.0 cable, 6-pin autoguider cable, M42 extension adapter, and a CD-ROM disk containing the camera drivers and control software.

One feature of the camera that took me by surprise with all three of the included camera-control programs was that the camera starts exposing as soon as the control software detects it. A readout of the number of frames-per-second indicates the camera is active from the get-go. However, this doesn't mean that the frames are being saved. That only happens after you designate a folder for the images and enable the "start capture."

When the camera is capturing a series of images, it shows the actual frame rate recorded and displays the number of "dropped" frames, if any. The number of recorded frames depends on the set frame rate, the resolution of the frames, the gain setting and exposure duration, and the speed of the computer's hard drive. Both *SharpCap* and *FireCapture* include settings to monitor USB traffic on your computer and figure into how fast frames can be ultimately recorded. All of these factors can make the difference between having smooth video clips or a set of consecutive still frames, versus having many dropped frames or even having the camera lock up during an imaging session.



▲ *SharpCap*, one of the camera-control programs that comes with the ASI 1600MC-Cool, runs the camera in video mode while imaging the Moon and planets. It also provides live stacking of longer exposures when using the unit for public outreach.

Much of my initial time with the camera involved making sure these settings were optimized. If they weren't, camera hang-ups and many dropped frames were the rule rather than the exception. Downloading the latest beta version of *FireCapture* at **firecapture.de** helped with some hang-up issues I had when recording videos.

The manual warns against using any type of USB extension cable or connecting the camera through a USB hub. These could significantly decrease the frame rate. I made sure my computer was quite close to the camera at all times in order to use the supplied 2-meter-long USB 3.0 cable, though longer cables are available online.

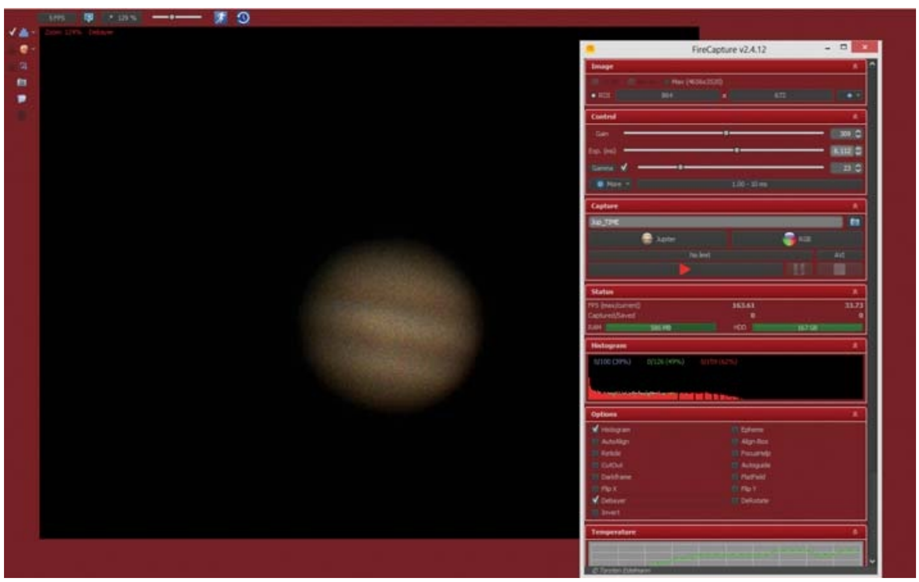
Additionally, the sparse documentation provided with the camera, especially the absence of any "quick start" guide, made my initial tests challenging. Both the camera user's guide and the trouble-shooting guide that are supplied as PDFs on the CD covered only earlier ASI camera models and not the ASI 1600MC-Cool specifically, though the manufacturer's website now offers a downloadable manual for the new ASI 1600 cameras.

High-speed Video

When using the ASI 1600MC-Cool for lunar imaging, the camera's large 16-megapixel chip allowed me to shoot the entire first quarter Moon at the native focus of my 12½-inch f/4 Newtonian reflector in a single video. However, the limited write speed of my laptop's hard drive resulted in a frame rate of 10 to 15 FPS — not terrible, but only around half of the full potential that the camera can achieve. Stacking the result was easy using *AutoStakkert!2*.

Both *SharpCap* and *FireCapture* enable the selection of various ROIs on the chip to achieve higher frame rates when shooting the planets at long focal lengths. These smaller ROIs eliminate the need to download the empty black sky in the field around the planets, which equates to unnecessary baggage in the video or image stream. The small ROIs result in less data that can be read off the chip quickly.

During my time with the camera, Saturn was well placed in the early-evening sky, so I used *FireCapture* to make several AVI video clips of the planet with my Celestron C11 at about f/20. Saturn has a low surface brightness and requires longer exposures than, say, Jupiter or Mars, but I was able to achieve a frame rate of 38 FPS with an ROI of 488 × 388 pixels. The software includes extensive exposure and gain settings that allow satisfactory results regardless of the optical system's effective f/ratio. In fact, *FireCapture* includes many useful features for planetary imagers that are worth exploring for owners of most high-speed planetary video cameras.



▲ Another program included with the camera is *FireCapture*, which provides extensive controls for imaging solar system objects as well as deep-sky targets, with additional support for filter wheels and autoguiding features.

▲ Images produced with the ASI 1600MC-Cool were smooth and noise-free; few hot pixels were noted on uncalibrated files. This colorful shot of M8, the Lagoon Nebula, consists of ten 5-minute exposures recorded through a 102-mm refractor.

Deep-sky Performance

Although *SharpCap* and *FireCapture* enable you to record exposures up to 20 minutes long, I used *MaximDL* via an ASCOM link to operate the camera for deep-sky exposures. In this configuration the ASI 1600MC-Cool performed like most CCD cameras I've used in the past. I also operated the camera successfully using *Nebulosity 4.0*, again through the ASCOM link. The camera has no mechanic shutter, so you'll need to cover the telescope's objective when shooting dark and bias calibration frames.

In spite of the camera's small pixels, it is very sensitive for long exposures. I often used 4 × 4 pixel binning to boost sensitivity further when aiming and composing deep-sky shots. This allowed fast readout of low-resolution images before switching to full resolution for the actual exposure sequence.

One limitation of the ASI 1600MC-Cool is its notably shallow dynamic range compared to other deep-sky cameras used by today's amateurs. The camera outputs 8-, 10-, and 12-bit capture modes, while 16-bit data is the standard for deep-sky imaging. The limited dynamic range was evident when shooting deep-sky objects with a wide range of brightness. One way around this is to record short exposures that capture detail in the brighter parts of an object and then shoot longer exposures that record fainter detail in a nebula or

▲ The CMOS detector in the ASI 1600MC-Cool is located just 6.5 mm from the front flange of the camera body, allowing users to include additional accessories between the unit and any field correctors while preserving any critical spacing requirements.

galaxy. The two sets of exposures can be combined in most astronomical image-processing programs.

Early in my testing, I experienced an intermittent-connection problem with the camera. I traced this to the USB connection at the camera. Fortunately, a shot of electronics cleaner on both the cable plug and into the USB socket on the camera solved the issue.

Among the most enjoyable evenings I spent with the camera involved no recorded images at all. Using the optional lens adapter, I installed an 85-mm f/1.4 lens on the camera and pointed it toward the Milky Way. Immediately, a near-real-time video experience began playing out on my laptop screen as the camera produced detailed, wide-field views of star fields and nebulae in full color with exposures of only a few seconds! Pinkish nebulosity as well as dark nebulae appeared against the rich, golden star fields of our home galaxy.

The camera's 16-megapixel detector with its small pixels easily fit large targets comfortably on the chip with moderate focal lengths. This image of the first-quarter Moon was recorded in video mode at the Newtonian focus through the author's 12½-inch telescope at f/4.

There were also occasional faint satellites passing through the field that were well below the naked-eye limit but easily seen on the computer screen. Besides the ASI 1600MC-Cool's considerable imaging capabilities, using the camera in such a configuration would be a great public outreach device, which can operate in HD quality or better with the appropriate computer monitor.

The Bottom Line

The ASI 1600MC-Cool camera is a solid competitor in the field of today's astro cameras, particularly for those of us who do a wide variety of astrophotography. The camera's ability to record high-resolution video of the Moon and planets, as well as its 16-megapixel detector capable of producing vivid color images of deep-sky objects at an extremely affordable price, make it an attractive option for beginners and experienced imagers alike.

Be aware that users looking at purchasing the camera and expecting it to perform at its best should also have a computer with USB 3.0 ports and a very large hard drive with fast write speeds (preferably a solid-state drive), or else they won't be able to achieve the camera's full video potential.

Deep-sky imagers aren't completely off the hook in computer power either. Given that the camera's 16-megapixel detector at full resolution produces a 32-megabyte image, a computer with considerable horsepower is necessary to process these files.

The sparse documentation may be frustrating to first-time users or for astrophotographers moving from a DSLR to a regulated, cooled camera with many settings and wide-ranging capabilities. But once you become familiar with the camera and software, the result will be high-quality images that can show fine lunar and planetary detail as well as dramatic color in nebulous fields throughout the Milky Way.

■ **JOHNNY HORNE**, a veteran newspaper photographer, has spent plenty of all-nighters in his backyard observatory since retiring in April 2016.

DIELECTRIC DIAGONALS ▶

Orion Telescopes & Binoculars now offers a pair of Dielectric Twist-Tight Mirror Star Diagonals. These 90° mirror diagonals feature highly efficient dielectric coatings that promise 99% reflectivity for maximum brightness and contrast in refractors or catadioptric telescopes. Eyepieces are secured with an innovative twist-tight mechanism that won't mar their barrels. The Dielectric Twist-Tight Mirror Star Diagonals are available in 1¼-inch and 2-inch versions, priced at $119.99 and $189.99, respectively.

Orion Telescopes & Binoculars
89 Hangar Way, Watsonville, CA 95076
800-447-1001; telescope.com

BUDGET ASTROGRAPH ▶

Another new product from Orion Telescopes & Binoculars is the 6" f/4 Newtonian Astrograph Reflector Telescope ($399.99). This photographically fast Newtonian reflector is built around a 150-mm parabolic primary mirror manufactured from B270 glass that reaches thermal equilibrium quickly. An oversize 63-mm (minor axis) secondary provides excellent field illumination for larger DSLR or CCD cameras. A 2-inch, dual-speed linear-bearing Crayford focuser is designed to hold heavy imaging accessories without slippage, and its steel reinforcing plate virtually eliminates flexure. The scope weighs a total of 12.7 pounds and comes complete with tube rings, a Vixen-style dovetail mounting plate, and an 8×50 finderscope.

Orion Telescopes & Binoculars
89 Hangar Way, Watsonville, CA 95076
800-447-1001; telescope.com

PLUTO GLOBE ▶

Sky & Telescope announces its new Pluto globe ($24.99). This 6-inch, semi-gloss-finished globe is assembled from more than 125 images acquired by cameras aboard NASA's New Horizons spacecraft during its historic 2015 flyby, resulting in a base map showing details as small as 1 mile across. Sixty features are labeled with the informal names chosen by the New Horizons team, as well as Latinized versions of topographical features. The globe comes with a freestanding base and a 4-by-6-inch information card. SKU #R5295.

Sky & Telescope
90 Sherman St., Cambridge, MA 02140
888-253-0230; shopatsky.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.

Amateurs Track a DISINTEGRATING Exoplanet

As we watch, a world that came too close to its dead star is falling to pieces.

If someone had told me 20 years ago that I, an amateur astronomer, would someday be on my roof watching the destruction of a small planet orbiting a 17th-magnitude star, I would have said they were nuts. Yet I and other amateur astronomers are now doing just that, and more.

WD1145+017, or "WD 1145" to its friends, is an obscure white dwarf star 570 light-years away in Virgo near the Leo border. It is pulling apart, grinding up, and devouring one or more of its planets as we watch. We are monitoring fast-changing clumps and streams of orbiting wreckage as they cross the star's face, dimming its light in ways both regular and irregular. Amid the debris is a solid object some 1,000 kilometers in diameter that continues shedding material.

We didn't discover this happening. For that, we can thank the ingenious and determined engineers who put together the K2 mission for the Kepler spacecraft after it lost its precision pointing ability in May 2013 (see box).

On March 21, 2015, Andrew Vanderburg, a graduate student at Harvard, was reviewing data from the K2 mission and noticed that faint little WD 1145, which happened to be in one of the K2 survey fields, showed some unusual brightness variations. He arranged to do follow-up spectroscopy with the 6.5-meter MMT telescope at Whipple Observatory in Arizona and to monitor the star's brightness with the 1.2-meter telescope at Whipple.

On April 11th, he found WD 1145 undergoing dimmings that looked similar to cases where a transiting planet sheds material if it orbits too close to a normal, much larger main-sequence star. Saul Rappaport (MIT) had been the first to report on those finds. Vanderburg wondered, could the same thing happen around a white dwarf? These stars are typically only a hundredth the diameter of the Sun. That's roughly the size of Earth, a smallish planet itself. How would that work?

Kepler's K2 Mission

Kepler detects worlds orbiting faraway stars by the tiny, periodic dimmings that a planet will cause if, by luck, it crosses the face of its star from our viewpoint. But after two of Kepler's four reaction wheels (gyroscopes) failed, leaving only two working, the spacecraft lost its ability to orient and point steadily. For that, it needs three different force vectors that it can twist itself around in 3-D space.

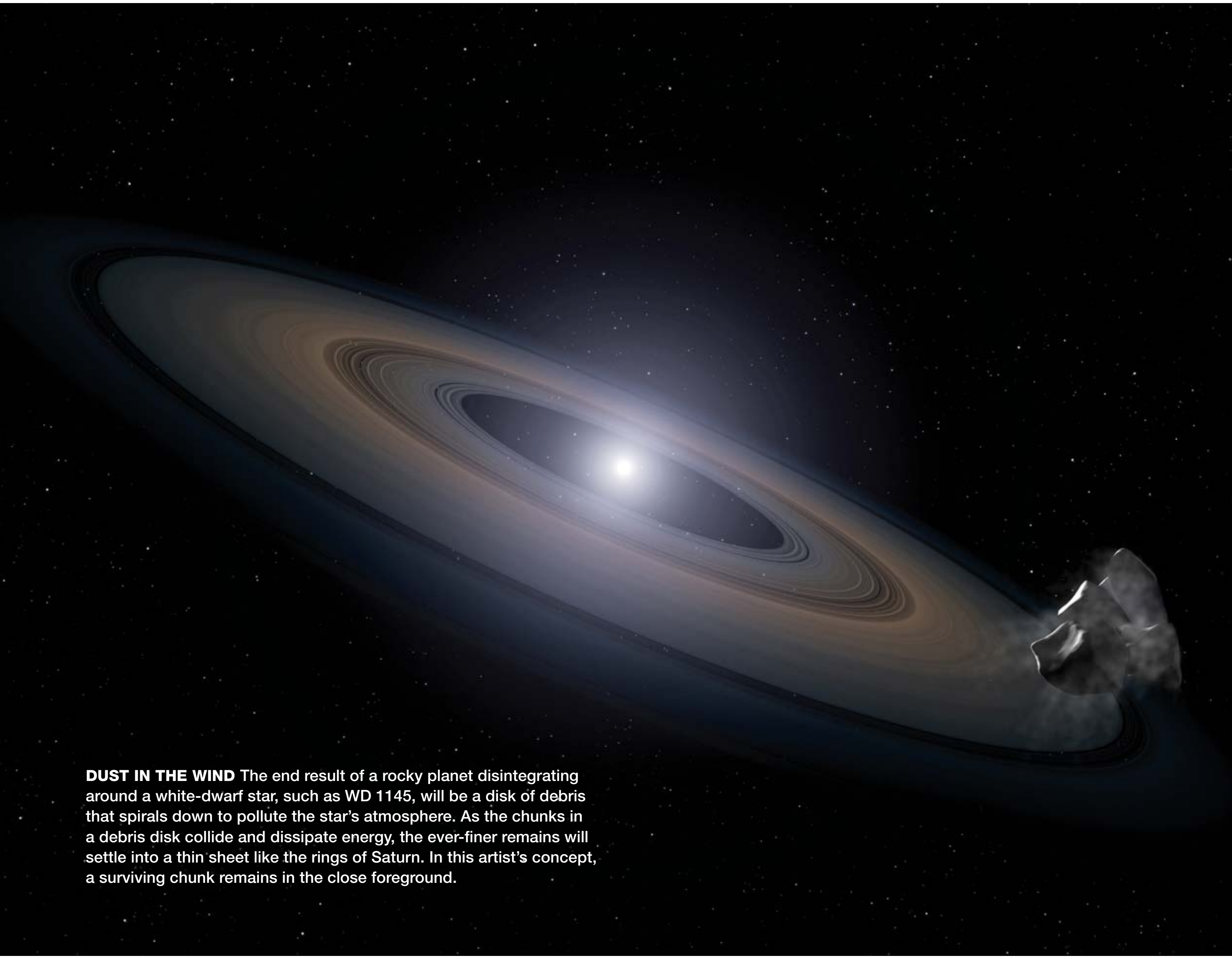
Kepler's handlers figured out how to balance the craft against the delicate radiation pressure of sunlight, so that it does not drift too far in its unconstrained third direction. Thus Kepler came back from the dead in November 2013. In its new role it is able to point to star fields along the ecliptic for a new, extended mission dubbed Kepler 2.

This mission continues today. Unavoidable slow drifts mean that Kepler cannot monitor stars' brightnesses with the same precision as it originally could. But even so, the K2 mission had found 178 new exoplanets as of January — some of them, like WD 1145, very interesting.

End-of-Life Drama

White dwarfs are the dense cores of dead stars that were once more or less Sun-like. They are what's left after a low- to medium-mass star comes to the end of its complex life of burning nuclear fuel. After evolving through a complex old age as a mass-losing red giant, the star goes through death spasms that throw off much more of its mass. The ejecta glow, for a relatively brief time, as an expanding planetary nebula. The star's exposed hot core, lacking any further source of energy, settles down to cool slowly forever.

The ejecta can amount to 30% to 75% of the star's mass. And that's bad news for any system of planets that may have



DUST IN THE WIND The end result of a rocky planet disintegrating around a white-dwarf star, such as WD 1145, will be a disk of debris that spirals down to pollute the star's atmosphere. As the chunks in a debris disk collide and dissipate energy, the ever-finer remains will settle into a thin sheet like the rings of Saturn. In this artist's concept, a surviving chunk remains in the close foreground.

NASA / ESA / GREG BACON (STSCI)

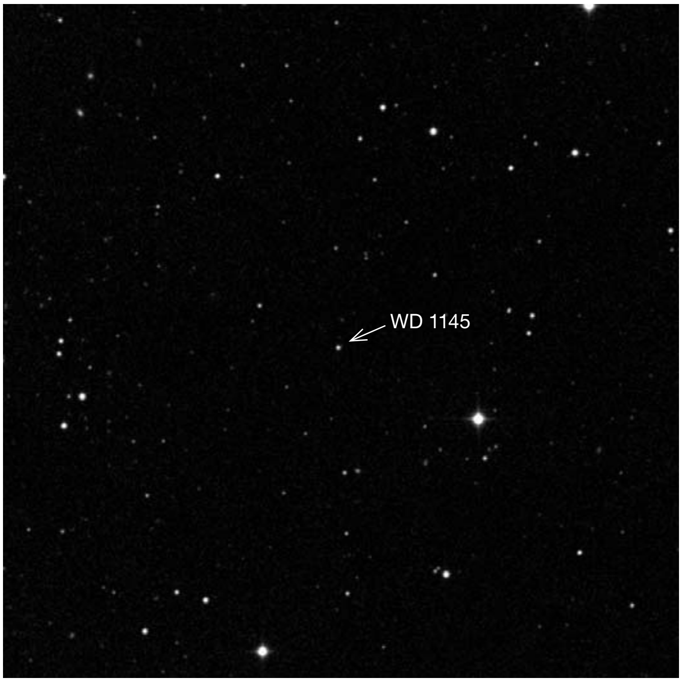
survived the previous stages of the star's late-life drama.

As a star loses mass, its gravity weakens, which means that any planets will migrate outward into larger, slower orbits. But the new planetary system will not just be a larger copy of the old one. The star's weaker gravity means that even though the planets orbit farther out, their influence on one another is more powerful. This spells trouble.

Our solar system, for instance, has remained stable for billions of years. That's because, early on, objects in unstable orbits were flung out by gravitational interactions or collided and merged. What was left were planets that don't seriously interfere with each other.

But the Sun will lose much of its mass in about 7 billion years, and when that happens the planets will drift outward from the Sun. The result can be a chaotic system where many strong gravitational interactions occur. At first, a planet may find itself gradually worked into a more elliptical orbit that eventually brings it close to another. Their first near miss is likely to throw at least one of the two into an even more elliptical orbit, setting it up to interfere with others. As the chaos spreads, some planets may be expelled

As an aging star loses mass, planets that orbited it stably for billions of years will drift outward and begin to interfere with each other. Chaos will grow.



▲ **PULLED FROM HIDING** Lurking ¼° from the ecliptic just behind the head of Virgo, the world-annihilating white dwarf WD1145+017 glimmers at an unassuming 17th magnitude. The events around it would have gone unnoticed were it not for the crippled Kepler spacecraft's K2 mission. This frame is ¼° square.

from the system, others may collide, and other encounters may send a planet inward toward the star. This last is what astronomers think happened in the case of WD 1145.

Astronomers already had evidence of the catastrophic end result. White dwarfs have intense surface gravities, so any heavy elements should sink below the hydrogen/helium surface in only a million years or so. Yet about a quarter to a half of white dwarfs show surfaces polluted with iron, silicon, magnesium, nickel, aluminum, calcium, and other rocky-planet material. The white dwarfs are old, but the heavy pollutants must be fresh.

And indeed, when Vanderburg's co-authors Warren Brown and Patrick Dufour took spectra of WD 1145 with the MMT telescope, it too showed such materials on its surface — despite estimates (from its temperature and expected rate of cooling) that it has been a white dwarf for 175 million years.

Now, with debris swarms apparently orbiting this star and obscuring its light, the Harvard group had found a "smoking gun" connecting polluted white dwarfs to a planet being destroyed in real time.

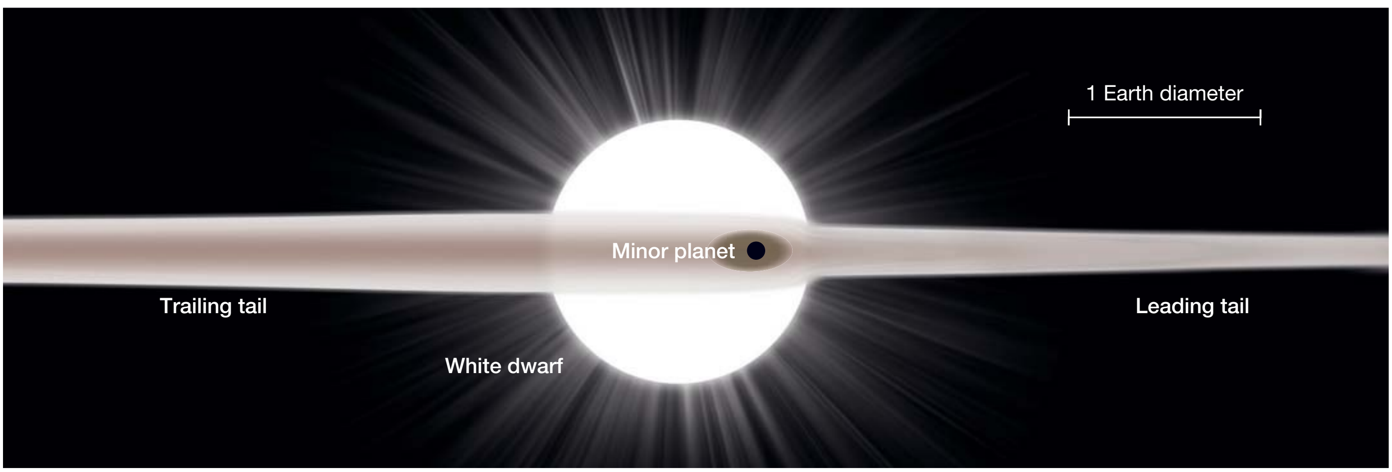
Fast Transits Nonstop

Again using Kepler and the MMT 1.2-meter, Vanderburg and the group found a distinct object whipping around WD 1145, transiting it every 4.5 hours. The star is 1.4 times the size of Earth, which makes the transiting object no larger than the dwarf planet Ceres. Wherever it originated, the object has worked its way down to orbit only 800,000 km above the star's surface: roughly twice the Earth-Moon separation, with one side roasting in the star's intense heat. At this distance the object has reached its expected Roche limit, where tides induced by the star should literally pull it apart.

Given the body's fast orbital speed and the star's small size, transits should last just a minute or so. What we see, however, are a great many transits happening continuously all around the orbit, differing in depth and duration. And they change from week to week! This implies that many clumps and clouds of debris are expanding like the coma around a comet nucleus. The fact that we see obscurations throughout the 4.5-hour "year" indicates a clumpy ring of debris all around the star.

A Network of Observers

Vanderburg realized early on that, if he wanted to properly study this unusual and scientifically interesting system, he



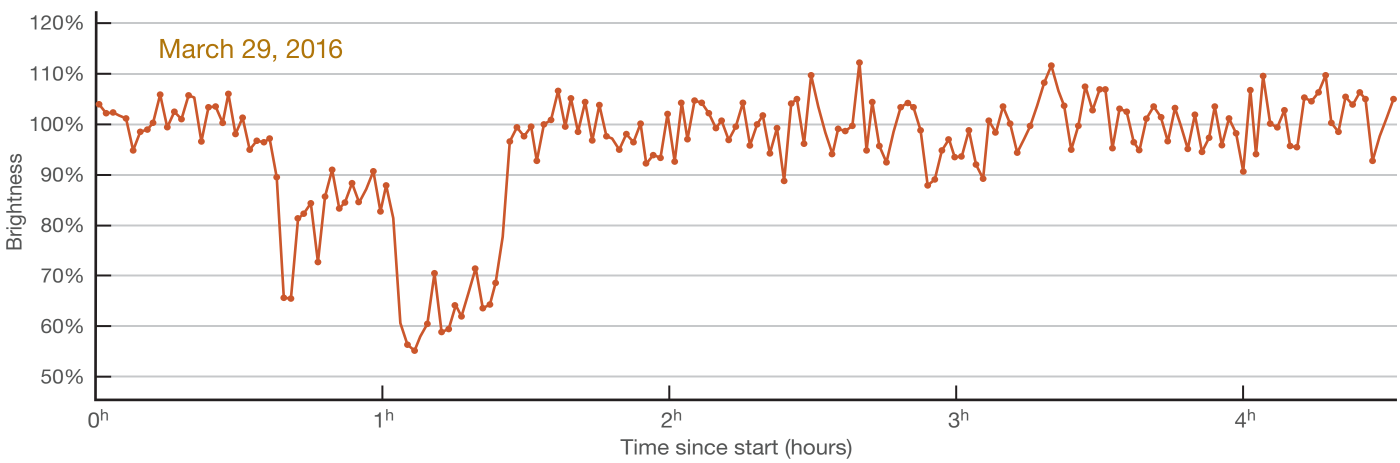
▲ **STREAMER OF OBSCURATION** In this smoothed reconstruction from 5 minutes of data around a "primary" transit, the planetoid speeding around WD 1145 (black disk, drawn to scale) is surrounded by an opaque dust cloud with a thick extension orbiting behind it and a sparser, narrower extension ahead of it. The star itself is very typical for a white dwarf, with 1.4 times the diameter of Earth and 0.6 solar mass.

IMAGE: DIGITIZED SKY SURVEY. DIAGRAM: *S&T*: LEAH TISCIONE / DATA: ANDREW VANDERBURG ET AL. / *NATURE*

▲ **TROUBLE AHEAD** The Helix planetary nebula in Aquarius, as imaged by the author with his scope at right. The central star is a newborn white dwarf, the core of an expired star that recently expelled its outer layers. The reduction in its mass is bad news for any planetary system that may remain around it. **Right:** The author and his homebuilt 32-inch reflector. The observatory is on the roof of his house; the scope rests on a pier that goes down to bedrock. Faint stars beware; your secrets shall be revealed.

would need to enlist many observers to track its events as continuously as possible. Among those he recruited were Bryce Croll at Boston University and a few advanced amateurs such as Bruce Gary, Tom Kaye, and myself. He contacted me in the summer of 2015, then visited my home in Gloucester, Massachusetts, where I have a 32-inch (0.8-meter) homemade telescope in a rooftop observatory, seen above. We tested the capabilities of the telescope and its systems on some other stars with transiting exoplanets.

Considering the speed expected of objects circling WD 1145 at the Roche limit, Vanderburg wanted a fast, 1-minute cadence of brightness measurements to capture the details of the orbiting debris field. So, no long exposures! But with the star only 17th magnitude, would my scope and camera be up to that task? Although Kepler boasts a 1-meter telescope, it images on a 30-minute cadence, more appropriate for its work of looking for small planets around much larger main-sequence stars. The longer exposures allow the extremely

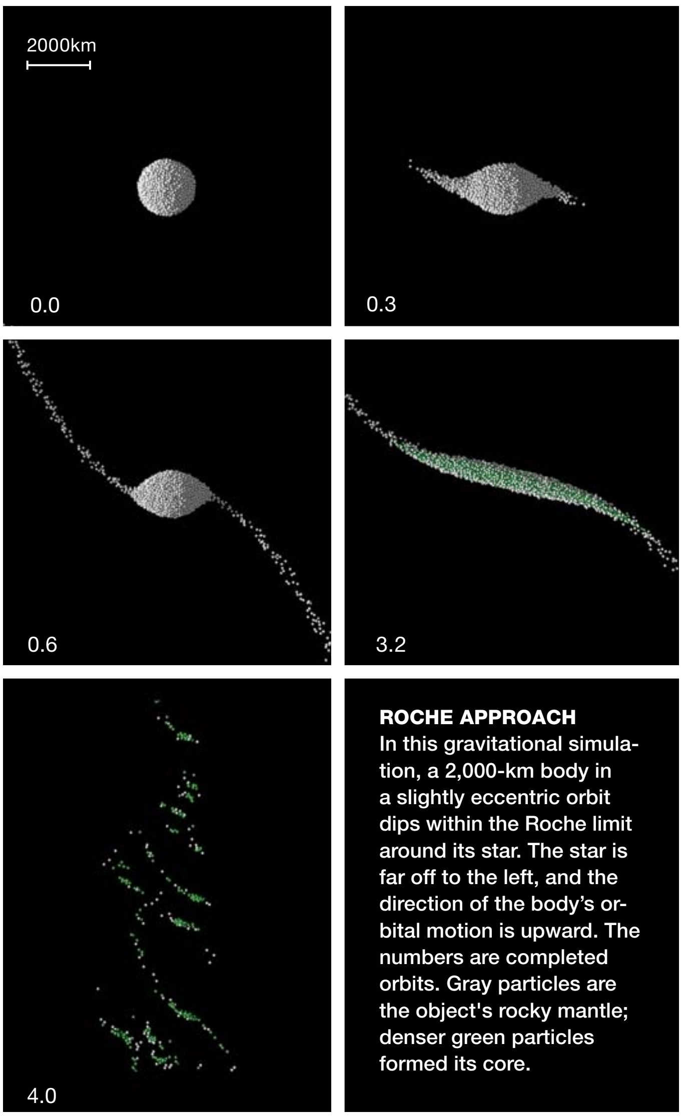


▲ **ONE ORBIT, SCORES OF TRANSITS!** Once a minute, the author's system shown above measured the brightness of WD 1145 against comparison stars in the same field. The comparison stars held steady in brightness to within 1%, but the white dwarf dimmed and recovered wildly from minute to minute as clumpy orbiting material crossed its face. This 4½-hour run spanned almost one complete orbit of the debris ring. The solid planet with its opaque surrounding cloud, which transited about 40 minutes into the run, has a smaller profile than the dusty swarms of stuff it has shed.

PHOTOS: MARIO MOTTA (2), LIGHT CURVE: *S&T* LEAH TISCIONE / SOURCE: MARIO MOTTA precise brightness measurements that are required for this.

Virgo wasn't observable from New England until winter, and as luck would have it, the winter of 2015-16 was so cloudy that I could not start collecting data until March. Fortunately, advanced amateurs in other parts of the world started taking data in December. One was Bruce Gary, a leader in the amateur exoplanet-transit world. His early and influential book *Exoplanet Observing for Amateurs* had inspired me to get started in this exciting field.

In December 2015 Gary and Tom Kaye confirmed that the star is undergoing multiple chaotic transits. I took the light curve on the previous page on March 29, 2016. It showed that by then the system had evolved into a new state. The brief, initial sharp fade for 1 or 2 minutes likely corresponds to the planet itself, but it was much deeper than expected for such a small body. Apparently an opaque or semi-opaque cloud of material surrounded it. Following this "primary" transit came a clearer spell and then an even deeper dimming lasting some 25 minutes: a large cloud of debris, which later expanded in size and thinned out. The rest of the orbit showed smaller rapid obscurations, indicating that an irregular, dusty debris field completely rings WD 1145. Broken-off chunks of the main body seem to be shedding debris and dust of their own, in a cascading process. Some of the objects seem to have slightly longer orbital periods of up to 4.9 hours.



ROCHE APPROACH
In this gravitational simulation, a 2,000-km body in a slightly eccentric orbit dips within the Roche limit around its star. The star is far off to the left, and the direction of the body's orbital motion is upward. The numbers are completed orbits. Gray particles are the object's rocky mantle; denser green particles formed its core.

DIMITRI VERAS *ET AL.* / *MONTHLY NOTICES OF THE RAS*, OCT. 25, 2016

> Next year the TESS satellite should start revealing a flood of nearby exoplanets. Some will be especially ripe for pro-am followups.

Meanwhile, the comparison stars in my imaging field held very steady: to about 0.01 magnitude from frame to frame, or 1% of their brightnesses. So the seemingly "noisy" fluctuations you see from minute to minute in the light curves are mostly real — not instrumental noise or atmospheric effects.

By comparison, in a recording I made of a normal exoplanet crossing the star HAT-P-26 last April, the smooth, steady dimming of only 7 millimagnitudes (a 0.7% percent brightness change) stands out clearly from my system's noise. That planet is roughly Neptune-size and crosses a main-sequence star of spectral type *K*1. This was one of the observations that Dennis Conti of the American Association of Variable Star Observers (AAVSO) is coordinating among amateurs to support a major Hubble study of 15 exoplanets.

Compare that to the wild fluctuations of WD 1145 and you see what drew Andrew's initial attention to this object. Instead of the typical transit drop of just a few millimagnitudes, we have seen WD 1145 being obscured by up to 40%!

The light curves at right show five more of my observing runs from the following two months. Most span a large part of the system's 4.5-hour "year." No two are alike, indicating the debris field's fast evolution. We are watching the end of a world in real time.

Given the planet's small size, this situation is not likely to continue much longer. Eventually everything should grind itself down to small particles, settle into flat rings like Saturn's, and gradually spiral into the star via "friction" with the star's brilliant radiation, as in the artist's portrayal on page 67. Indeed, the last observation on May 31st showed reduced activity. Was the show winding down?

Nope! When Virgo came back into view in December 2016, Bruce Gary was the first to find that new debris was causing big dips again, which I subsequently confirmed.

We will collect many more observations over time to follow the continuing evolution of the WD 1145 system. It's possible that more than one initial body has broken up, or is breaking up, or is about to.

Join Us!

Scientists like Vanderburg, Croll, and Rappaport depend on close professional-amateur collaborations. Pro-am partnerships are proving essential as astronomers find ever more exoplanets and need followup observations. As of January, 3,440 planets of other stars were considered "confirmed," and more than 2,000 additional "candidates" awaited verification. This is an area where diligent, well-equipped amateurs can contribute greatly to science.

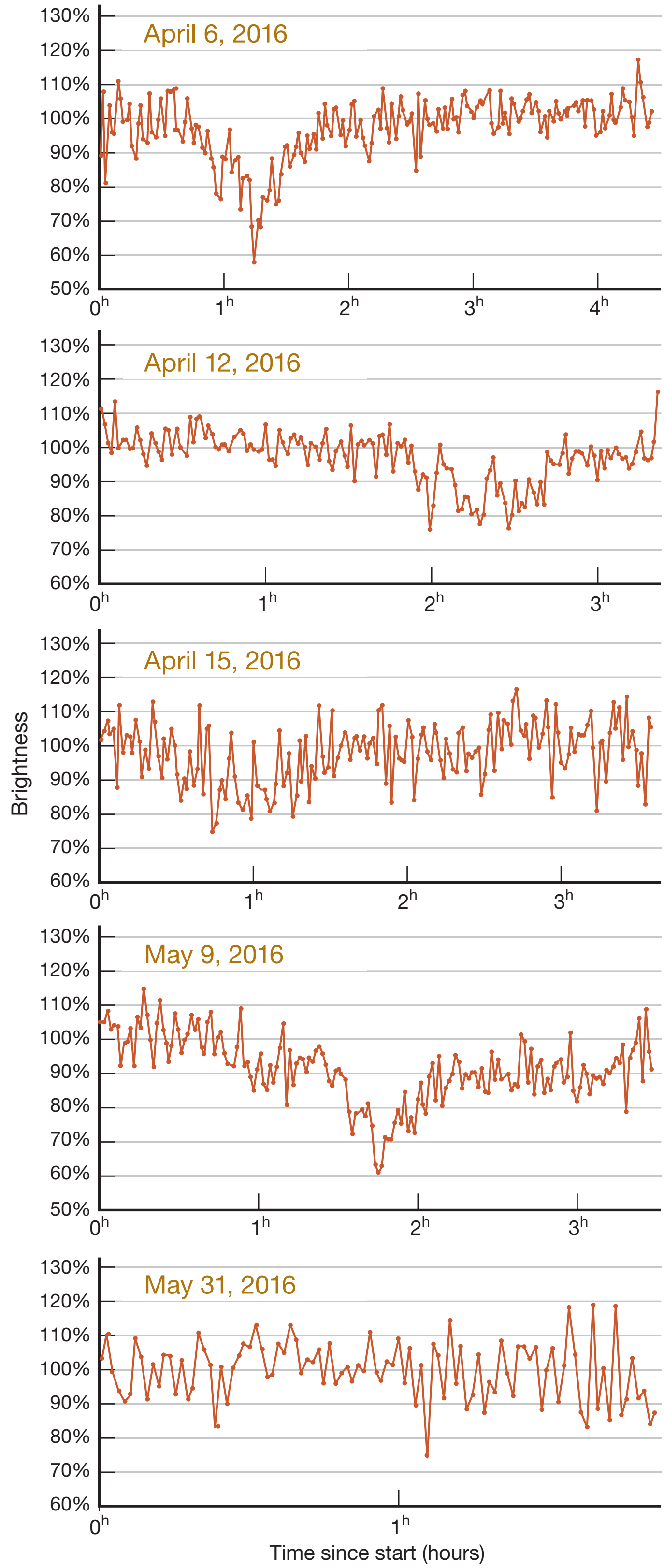
A useful way to start is to join the AAVSO's exoplanet section, headed by Dennis Conti. Find it at **aavso.org/exoplanet-section**. You can download the current edition of his *Practical Guide to Exoplanet Observing* from **astrodennis.com**. See also Bruce Gary's book mentioned earlier. Finally, get the powerful, free data-reduction program *AstroimageJ* at **astro.louisville.edu/software/astroimagej**. Karen Collins designed it with amateurs in mind for following up transit discoveries made by the KELT survey. It reduces the large volumes of data that your camera acquires, organizes it into a scientifically useful Excel spreadsheet, and can draw light curves like the ones on these pages.

Any amateur with imaging and variable-star experience has the skillset to contribute incredibly useful data. And you don't need access to a 32-inch scope! Many stars of interest are much brighter than my 17th-magnitude pet project. For instance, high-school student Alana Gudinas, a beginner at Phillips Academy in Andover, Massachusetts, obtained useful data on WASP–39 b using the school's 16-inch scope and high-end CCD camera. That planet is a puffed-up Jupiter closely orbiting a G8 star of magnitude 12.1. Much smaller scopes can be appropriate for selected systems. In particular, long-term monitoring can reveal slight *transit timing variations* (TTVs). These reveal the gravitational influence of additional bodies or other interesting things happening.

The K2 mission continues searching, and so do ground-based professional and amateur transit hunts. And in the spring of 2018 the TESS satellite should launch. It will watch 200,000 relatively bright stars all around the sky, most of them much closer to us than the bulk of Kepler's targets. TESS will be the first all-sky transit survey conducted from space. Its principal goal is to find small planets around relatively nearby main-sequence stars, so that astronomers will have prime Earth-size worlds for further study. But TESS will also identify planets of all sizes up to the largest gas giants, orbiting stars of a wide variety of types. Many in the expected flood of discoveries will be ripe for extended followups by pro-am collaborations.

It's an exciting new field. You may not find something as bizarre as a planet that's disintegrating, but you will be in on many new discoveries and the satisfaction of helping to find and characterize new worlds. Happy hunting.

■ **MARIO MOTTA**, MD, FACC, is a cardiologist, a clinical professor at Tufts Medical School, past president of the Massachusetts Medical Society, past president of the AAVSO, and telescope maker extraordinaire. He has received several national awards for his years of work in advanced amateur astronomy.



▲ **NO TWO ALIKE** The author took these further observing runs on WD 1145 over the course of two months. Again, typical comparison-star noise was only about 1%, much less than the rapid changes being recorded. The activity seemed to quiet down a bit by the end of May, but as of December 2016 the long, deep dips had picked back up.

S&T: LEAH TISCIONE / SOURCE: MARIO MOTTA (5)

The Dethloff Eyepiece Shade

How to block practically any light from your eyepiece.

THE FIRST TIME I met Howard Banich, he was face-deep in a salad bowl. No, he wasn't passed out drunk, he was intoxicated by the view through the eyepiece with absolutely no distracting light glow whatsoever. He was using a salad bowl as a light shield, and you can too.

Last month I wrote about shielding porch lights. That's a good start, but even if you shield every light around you there's still one enormous source of stray illumination: the sky full of stars! Most of us don't think of that as a problem, but if you're trying to tease out the finer details of a distant galaxy, every stray photon that's not part of your target becomes a contrast-reducing part of the general background. The shiny chrome thumbscrew on your eyepiece holder, the barrel of your telescope itself, and the glow of the Milky Way all add distracting light where you don't want it. Fortunately ATMs Tom Osypowski, Howard Banich, and Chuck Dethloff have come up with the perfect solution.

Tom first saw the idea at the Riverside Telescope Makers Conference back

▲ Make a generous cutout in the side of the bowl that will face the ground, and add felt wings if necessary to block light from the sides.

in 1985. Someone had glued two slabs of Styrofoam to the top of his scope, making a tent that shielded the eyepiece from overhead light. Tom says, "My own take was to make one out of foam board that Velcroed onto the scope's upper cage area. Then Howard and Chuck took the original idea and perfected it."

Perfection took some fiddling. Howard remembers: "I came up with a much more complicated version made from a mix of materials that could rotate around the focuser, which worked but was rather flimsy and didn't rotate easily. Then Chuck came up with his salad bowl version, which solved all the problems of my version, plus it was easy to make. Mel Bartels dubbed it the Dethloff Eyepiece Shade."

To make one, start with a lightweight plastic salad bowl. It has to be big enough for your head, but small enough to fit next to your finderscope. Chuck says "Most of them won't have tall enough sides. That's okay though, as felt wings can easily be attached to the sides of the bowl to provide extra height."

Once you've got your bowl, Chuck says, "You'll want to cut out a good part of the plastic bowl as a first step, especially the bottom half (as it sits in your telescope's focuser) almost all the way down to the base of the bowl, so it's easier for reaching in to change eyepieces and also to allow a path for moist air to escape when you exhale. I also like to have a gap at the top between the two felt wings. This allows another path for warm moist air to escape."

The plastic can be brittle, so be careful cutting it. Use a Dremel tool with a cutting bit, or try a fine-tooth coping saw or hacksaw blade and go very slowly. You can dress up the edges with sandpaper afterward.

Chuck also advises, "If the bottom of the salad bowl has a reinforcement ring, you might need to grind it off with the Dremel so that it doesn't get in the way of your focuser's set screws."

After shaping the bowl, cut a two-inch hole in the bottom. Use a hole saw with a backing board and drill slowly.

After you've made your cutouts and glued your felt wings on, spray-paint the whole works flat black, using a paint that's designed for plastic, and mount it on your focuser. The shield is held in

▲ Chuck Dethloff with his eyepiece shade. It also works well for solar viewing and in humid observing conditions.

BOTTOM: JUDY DETHLOFF, TOP: CHUCK DETHLOFF

• For more information about the details of this project, contact Chuck Dethloff at cd2015@dethloffhome.net.

place by the 2- to 1¼" adapter, or by a 2" eyepiece itself (or a Paracorr if you use one.) You will need to replace the set screws with longer ones that extend outward far enough to be accessible behind the bowl. The shield can easily be rotated as you raise or lower the scope, so you can remain upright while observing.

Both Chuck and Howard observe with these light shields even in the dark skies of the Oregon Star Party. Tom reports, "I have used both of their scopes with salad bowls attached, and the effect is quite remarkable. All you see is the field of view as presented to you by the eyepiece. It's a pleasure to observe that way."

■ Contributing Editor **JERRY OLTION** still considers his wife's potato salad the best use for a salad bowl, but this eyepiece shade is a close second.


JUDY DETHLOFF

▲ The shield mounted on the focuser. Note that you can access the eyepiece set screw through the gap in the shield.

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

▷▷GOBBLING GALAXY

Steve Mazlin & Warren Keller

The giant elliptical galaxy NGC 1316 (a strong radio source called Fornax A) has begun to ingest the smaller spiral galaxy NGC 1317 to its north.
DETAILS: *RCOS 16-inch Ritchey-Chrétien astrograph, FLI ProLine PL16803 CCD camera, and LRGB filters. Total exposure: 66 hours.*

▷THE CONE AGLOW

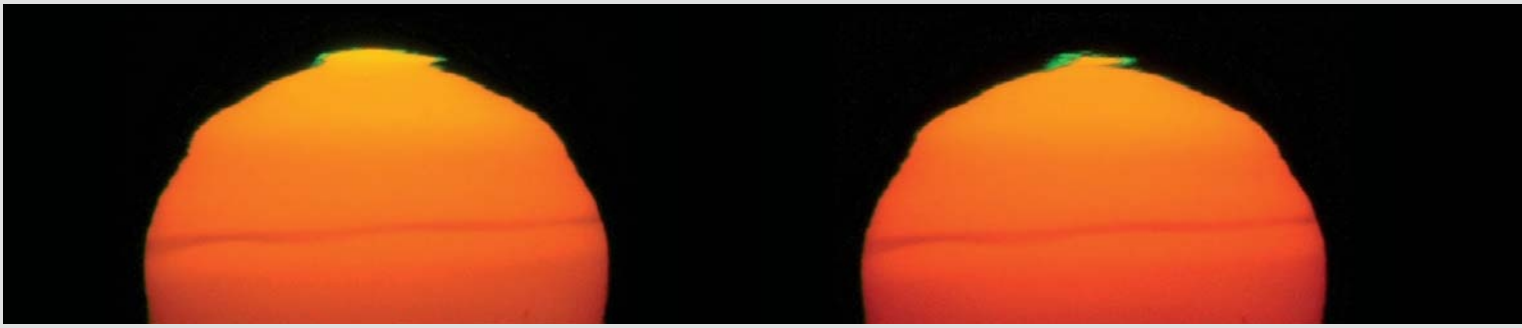
Jim Renard

The Cone Nebula, part of NGC 2264, is a cold cloud of molecular hydrogen in Monoceros.
DETAILS: *24-inch Ritchey-Chrétien astrograph, SBIG STL-11000M CCD camera used with Baader Hα and LRGB filters. Total exposure: 14½ hours.*

▽DOUBLE STAR TRAILS

Dario Gianobile

No trickery here — time-lapse star trails, a simple mirror, and light painted on a rural Italian farmhouse create a surreal view of the nighttime sky.
DETAILS: *Canon EOS 7D DSLR camera at ISO 800 and a 11-to-16-mm zoom lens used at 11 mm. Foreground exposure: 30 seconds; star trails: 6⅓ hours.*

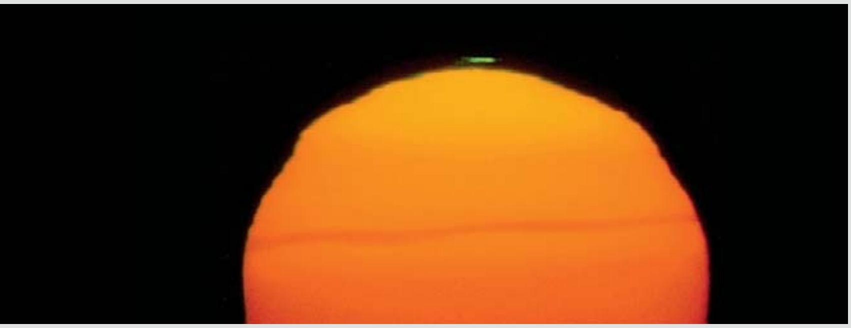


A TREASURE IN ARA

Gerald Rhemann

Deep in the southern sky lies NGC 6188, an emission nebula set aglow by the hot stars of NGC 6193. Near the bottom (toward east) is the small, curious bipolar nebula NGC 6164.

DETAILS: ***Astrosysteme Austria 8-inch H astrograph and ProLine 16803 CCD camera with Hα and LRGB filters. Total exposure: 2.1 hours.***



◁ GREEN FLASH SEQUENCE
Leo Aerts
An undulating fleck of green appeared atop the Sun before sunset on October 15, 2016.
DETAILS: *Nikon D90 DSLR camera at ISO 200 and 180-mm lens with 2× teleconverter. Exposure: 1⁄4,000 second.*

◁ THE TADPOLES (TAKE 1)
Dan VanDerZanden
The IC 410 nebula in Auriga features two twisted knots of gas and dust called "the Tadpoles." This version uses a trio of narrowband-filtered images dubbed the Hubble palette.
DETAILS: *Takahashi TOA-130 apochromatic refractor and SBIG STF-8300M CCD camera with hydrogen alpha (Hα) assigned to the red channel, ionized sulfur (S II) to green, and ionized oxygen (O III) to blue. Total exposure: 16 hours.*

◁▽ THE TADPOLES (TAKE 2)
Dan VanDerZanden
The same image set, combined differently.
DETAILS: *Identical specifications as above, with Hα assigned to red and O III to green and blue.*

▽ CRYSTAL BALL NEBULA
Kfir Simon
Look for this bauble (NGC 1514) in Taurus.
DETAILS: *Celestron C14 Schmidt-Cassegrain telescope, Moravian Instruments G3-16200 CCD camera, and LRGB filters. Total exposure: 7½ hours.*

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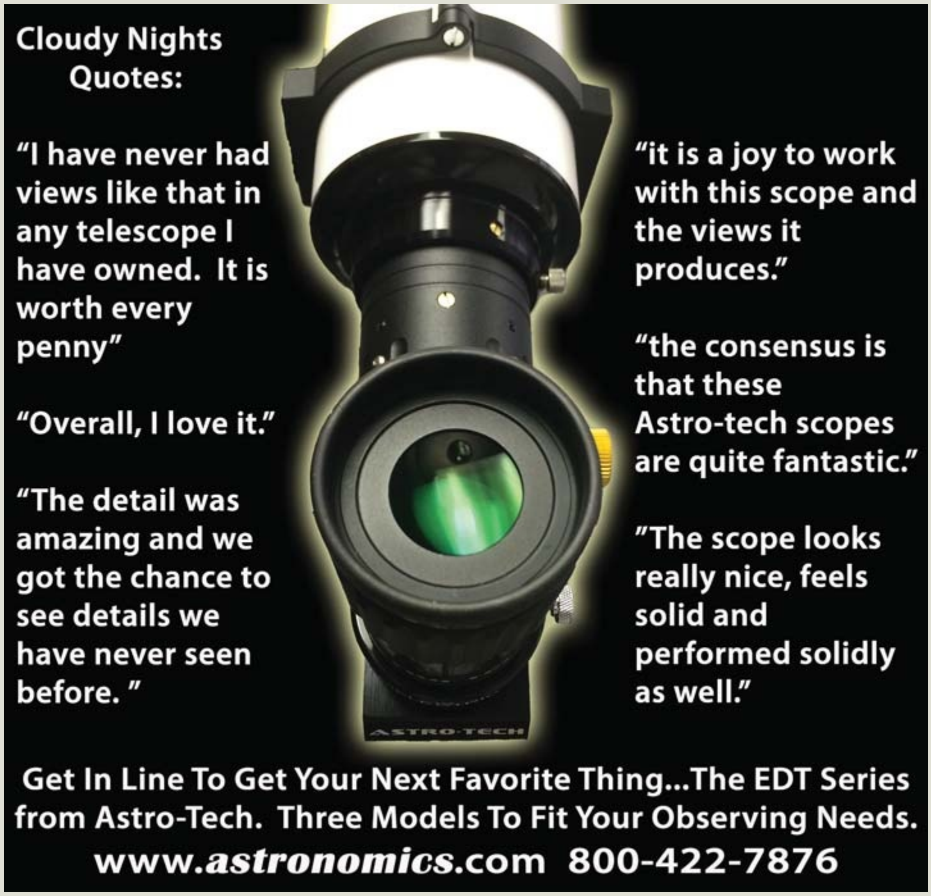

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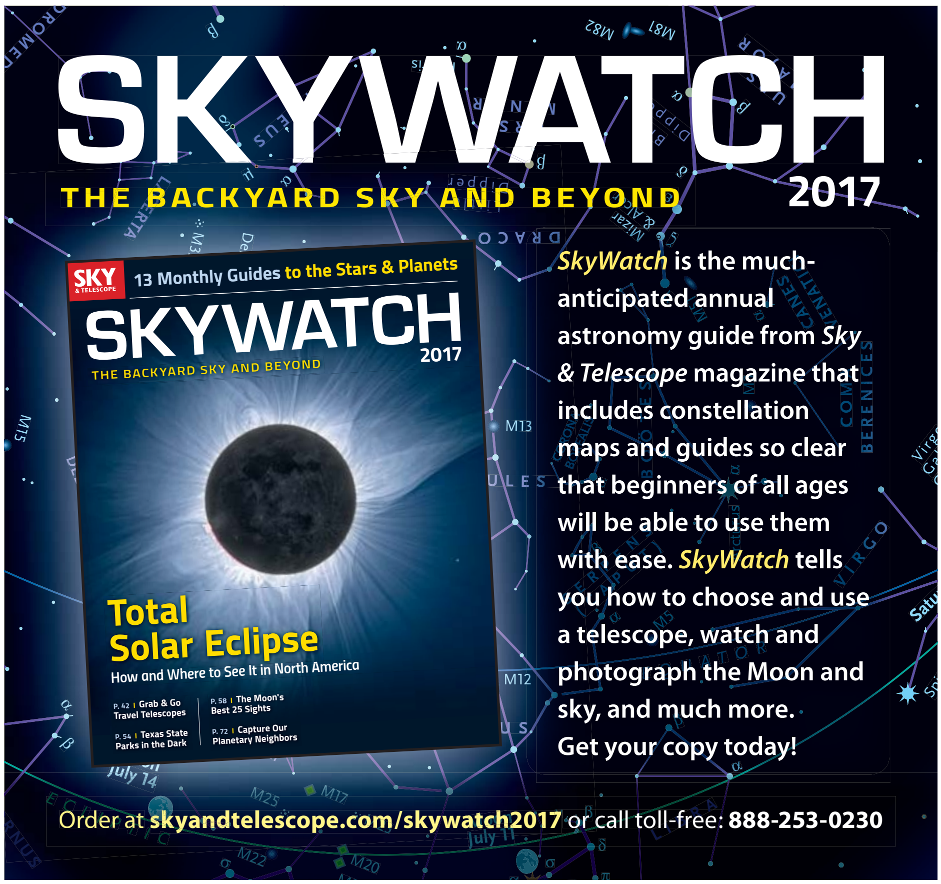
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Let the Stones Stand Again

A Colorado astronomy club builds a Neolithic-style solar observatory.

THE LAST PREHISTORIC standing stone circle was erected in the British Isles thousands of years ago. So why would I, an amateur astronomer, want to build one now? For that's what I did recently with the support of fellow members of the Southern Colorado Astronomical Society.

One of our club's goals is to help anyone interested in gaining a better understanding of the universe we live in. Why not start with the closest star to Earth, our very own Sun? What better way to introduce young people to astronomy than to show them firsthand how some ancient peoples used the Sun as a calendar?

Three years ago our society received a gift of 35 acres near the towering Spanish Peaks in southern Colorado, just west of the town of La Veta. With its dark skies, flat terrain, and easy access, the site is ideal for use as an astronomy park. When complete, the park will host several astronomy domes, camping and picnicking facilities, and the standing-stone calendar.

Sunset over the winter solstice perimeter stone, with the center stone in foreground.

> How long will this modern-day version of an archaic stone calendar stand?

When I first explored on-site the feasibility of building the calendar — it was a cold, gusty fall morning before sunrise — my mind drifted back to distant ancestors from the British Isles who perhaps made use of a standing-stone observatory much like the one I planned to construct. Who were those people? How did they live? What mythology did they create around what they saw in the sky? Only their stones remain to suggest answers.

The stone calendar took two years to design, plan, and build. In keeping with the low-tech nature of construction in Neolithic times, we made all astronomical observations with the unaided eye, and we measured distances with a simple tape measure and roll of twine. Would this calendar be as accurate as one made using modern technology? No. But in its simplicity and flaws lie its authenticity.

We broke ground in 2015. After verifying the solar alignments, we began excavating holes and manhandling 13 donated limestone markers, each weighing up to 400 pounds, into place. Last summer we installed the final stone, and the site became a functional solar observatory. The calendar is approximately 72 feet in diameter and oriented to true north (aligned on Polaris). In its center rises a standing stone surrounded by 12 marker stones placed roughly 36 feet away from it around the circle's perimeter.

By visually aligning the center stone with the appropriate marker along the perimeter, an observer can determine the equinoxes as well as the winter and summer solstices. For example, if you imagine the stone calendar as a clock seen from above, with 12 o'clock pointing north, on the winter solstice the Sun, as viewed from the center stone, will rise directly over the "4 o'clock" marker and set directly behind the "8 o'clock" marker.

• To see a diagram and learn more about the standing-stone calendar, go to https://is.gd/stonecalendar.

How long will this modern-day version of an archaic stone calendar stand in that grassy plain and passively measure out the changing seasons? A century? A millennium? Only time holds the answer to that question. But if just one young person becomes enriched and motivated by what he or she observes there, it will have been worth all the effort.

■ **RUSS ERGANBRIGHT**, a retired engineer, is the newly appointed Director of Ancient Astronomy for the Southern Colorado Astronomical Society. Reach him at **erganbright@yahoo.com**.

RUSS ERGANBRIGHT