MIND THE GAP: How Planets Are Built
PAGE 34

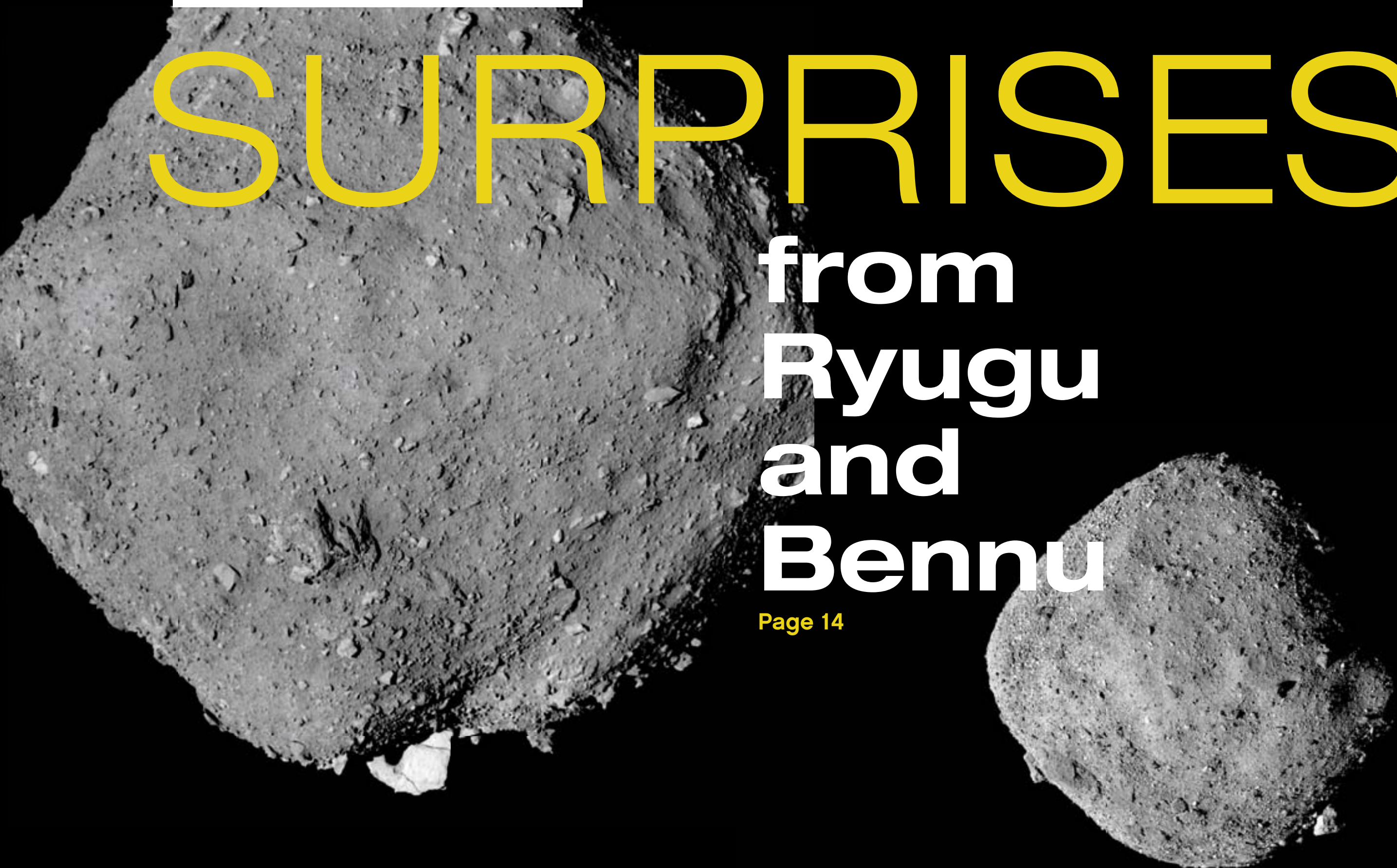
GALACTIC HULA-HOOP: Hoag's Object
PAGE 57

OBSERVING: A Cascade of Galaxies
PAGE 22

SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

MAY 2020



ASTEROID RECON

SURPRISES from Ryugu and Bennu

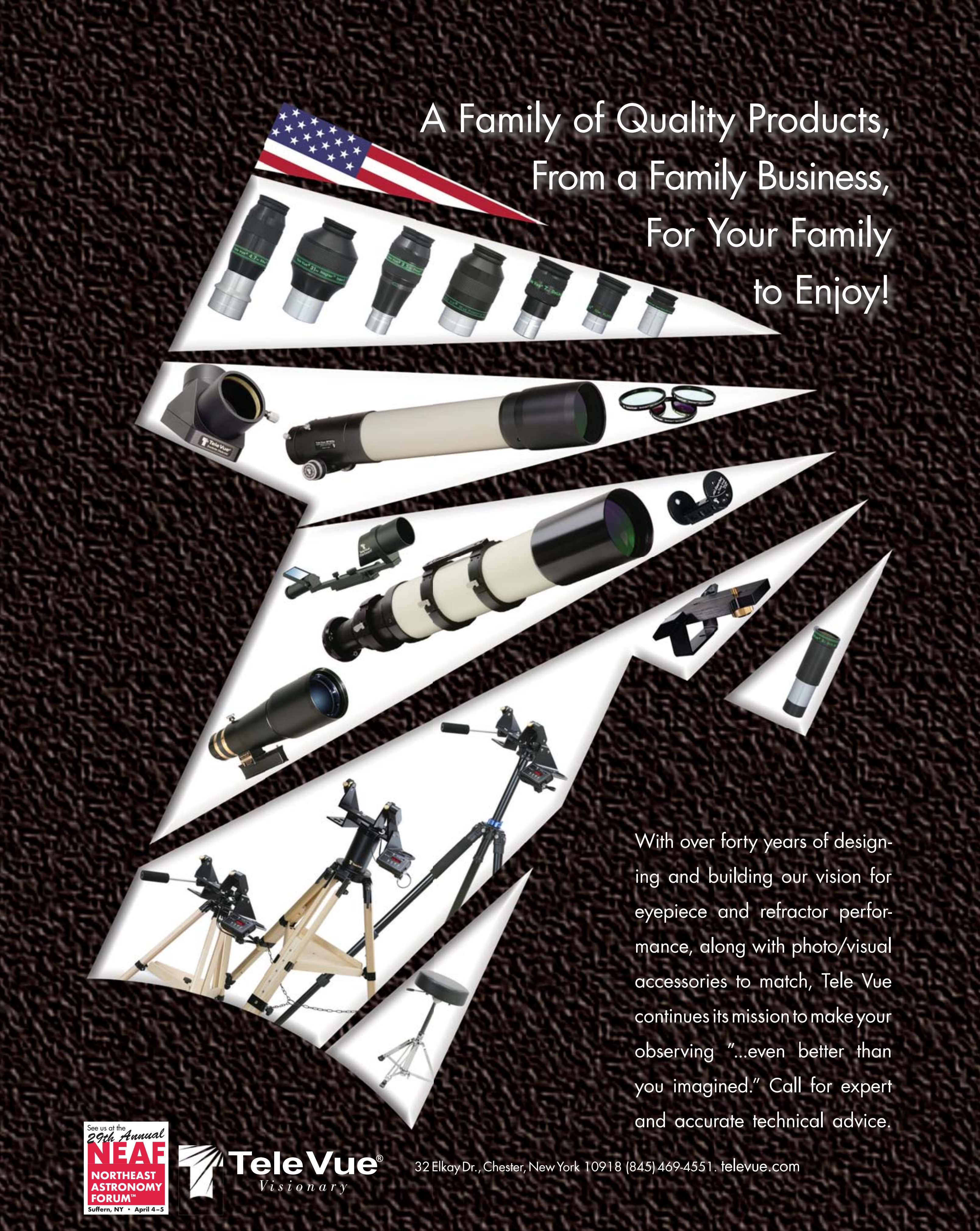
Page 14

skyandtelescope.org

The Untimely End of Amateur CCDs?
Page 30

Mitchel's Mountains on Mars
Page 52

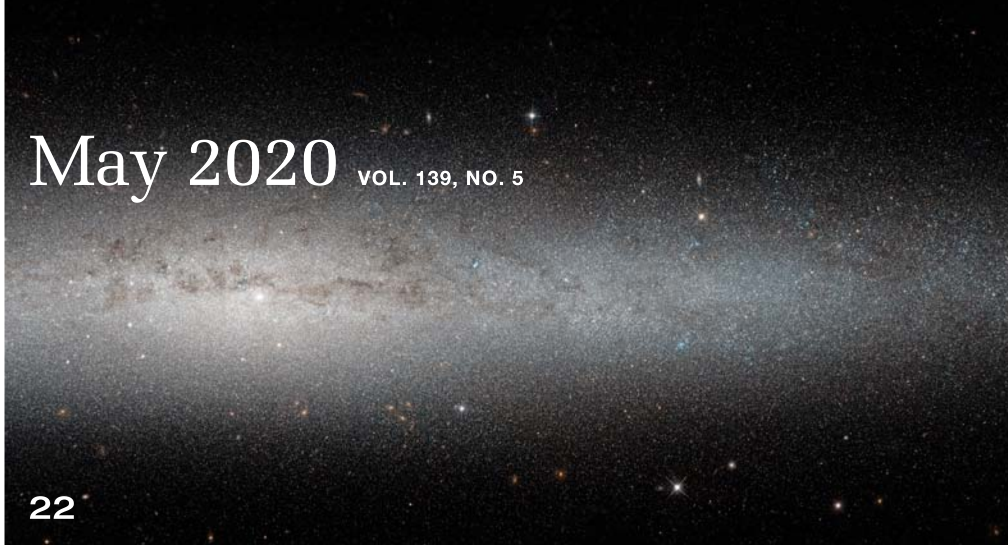
The Discovery of Jupiter's Moons
Page 60


A Family of Quality Products,
From a Family Business,
For Your Family
to Enjoy!
With over forty years of designing and building our vision for eyepiece and refractor performance, along with photo/visual accessories to match, Tele Vue continues its mission to make your observing "...even better than you imagined." Call for expert and accurate technical advice.
See us at the 29th Annual NEAF NORTHEAST ASTRONOMY FORUM™ Suffern, NY • April 4–5
Tele Vue®
Visionary
32 Elkay Dr., Chester, New York 10918 (845) 469-4551. televue.com

CONTENTS

SKY&TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY



NASA / ESA

FEATURES

Cover Story:

14 Rugged Worlds
The two spacecraft sent to Ryugu and Bennu have unveiled asteroids with formidable surfaces and mysterious histories.
By Camille M. Carlisle

22 May's Galaxy Cascade
Starting in Draco and spilling down into Coma Berenices, May's night skies offer a delightful string of galaxies that one can peruse from top to bottom.
By Ted Forte

30 Changing of the Guard
CMOS is set to become the dominant scientific-imaging medium — but is it up to the task?
By Richard S. Wright, Jr.

34 Revising the Story of Planet Formation
New technology has given astronomers access to the dusty regions where planets are born.
By Megan Ansdell

60 Seventy-nine and Counting: Finding Jupiter's Moons
The discovery of the Jovian satellites enhanced our understanding of the solar system and changed the course of history.
By F. Michael Witkoski

OBSERVING

41 May's Sky at a Glance
By Diana Hannikainen

42 Lunar Almanac & Sky Chart

43 Binocular Highlight
By Mathew Wedel

44 Planetary Almanac

45 Under the Stars
By Fred Schaaf

46 Sun, Moon & Planets
By Fred Schaaf

48 Celestial Calendar
By Bob King

52 Exploring the Solar System
By Thomas A. Dobbins

54 Deep-Sky Wonders
By Sue French

57 Going Deep
By Dave Tosteson

S&T TEST REPORT

66 Orion Premium Linear BinoViewer
By Dennis di Cicco

70 Optolong L-eNhance Filter
By Johnny Horne

COLUMNS / DEPARTMENTS

4 Spectrum
By Peter Tyson

6 From Our Readers

7 75, 50 & 25 Years Ago
By Roger W. Sinnott

8 News Notes

12 Cosmic Relief
By David Grinspoon

65 New Product Showcase

72 Astronomer's Workbench
By Jerry Oltion

74 Gallery

83 Event Calendar

84 Focal Point
By Frank Ridolfo

ON THE COVER

Ryugu *(left)* and Bennu, to scale

BENNU: NASA GSFC / UNIV. OF ARIZONA; RYUGU: JAXA / UNIV. OF TOKYO AND OTHERS

ONLINE

FOLLOW US ON SOCIAL MEDIA
Stay updated with news and cool images and videos:
Facebook: **@SkyandTelescope**
Twitter: **@SkyandTelescope**
Instagram: **#skyandtelescopemag**

EXPLORE THE NIGHT BLOG
Follow Contributing Editor Bob King as he takes readers on an adventure through the sky.
skyandtelescope.com/king

ASTROPHOTO GALLERY
Enjoy readers' best images and upload your own to share with your fellow enthusiasts. Be sure to check out the Editor's Pick winners.
skyandtelescope.com/gallery

SKY & TELESCOPE (ISSN 0037-6604) is published monthly by AAS Sky Publishing, LLC, owned by the American Astronomical Society, 1667 K Street NW, Suite 800, Washington, DC 20006, USA. Phone: 800-253-0245 (customer service/subscriptions), 617-500-6793 (all other calls). Website: skyandtelescope.org. Store website: shopatsky.com. ©2020 AAS Sky Publishing, LLC. All rights reserved. Periodicals postage paid at Washington, DC, and at additional mailing offices. Canada Post Publications Mail sales agreement #40029823. Canadian return address: 2744 Edna St., Windsor, ON, Canada N8Y 1V2. Canadian GST Reg. #R128921855. POSTMASTER: Send address changes to Sky & Telescope, PO Box 420235, Palm Coast, FL 32142-0235. Printed in the USA.

A Vote for Motes

IN *SKY & TELESCOPE* and in the community we serve, we often toss around a certain astronomical term without thinking much about it: *dust*. "Interstellar clouds of gas and dust," we'll say, or "Check out that galaxy's dust lane, will you?" But in light of several articles in this issue, it's worth pausing to consider just what astronomers mean by dust and how much we owe to it.

Cosmic dust comes in many sizes and flavors. It all starts with those chemical building blocks, elements such as carbon or silicon. When interstellar particles with such elements at their core grow too large to be called molecules — when, through collision, aggregation, and other processes, they reach umpteen millions of atoms — we start calling them dust. We're still talking tiny: only up to micron-size, or one-millionth of a meter (0.000039 inch). By comparison, a droplet of water in fog is about 10 microns in diameter; a strand of spider silk is 3 to 8 microns across.

Bits of cosmic dust stick together, of course. When a particle reaches a size you could see if it were perched on your fingertip, we often label it a pebble. After all, these centimeter-size grains are, in essence, minuscule rocks. That's what you see shooting out of the asteroid Bennu in the photo on page 20. In her article on protoplanetary disks (page 34), Megan Ansdell describes how astronomers use the ALMA radio-telescope array to study pebble-size dust and the SPHERE instrument to analyze micron-size dust, which she likens to smoke.

Hubble close-up of the Horsehead Nebula

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

Then there's the dust that grows so large you could stand on it (see cover). It's arresting to think that our very Earth, as all planets, arose from motes: particles to pebbles to planetesimal to planet. Did our vast world really begin as mere specks? It had to start somewhere, and just as we might follow a mighty river back to its source in a hillside spring, could we, if we had a time machine, trace our globe back to grains?

Back to Earth: As all astronomers know, dust enables us to see and learn from wonders of the night sky that might otherwise remain invisible to us. Supernova remnants. Meteor showers. The zodiacal light. Star-blocking clouds like the Coalsack. Star-forming regions like the Orion Nebula. Dust storms on Mars. The tails of comets (page 41). Want to add your own examples?

Then there's the fact that we're all stardust, as Carl Sagan reminded us. Every atom in our bodies, save for atoms of hydrogen and one or two of the other lightest elements, was forged in stars billions of years ago.

So let's give a nod to cosmic dust. It's us.

Peter

Editor in Chief

SKY&TELESCOPE
The Essential Guide to Astronomy

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

EDITORIAL
Editor in Chief Peter Tyson
Senior Editors J. Kelly Beatty, Alan M. MacRobert
Science Editor Camille M. Carlisle
News Editor Monica Young
Associate Editor Sean Walker
Observing Editor Diana Hannikainen
Consulting Editor Gary Seronik
Editorial Assistant Sabrina Garvin

Senior Contributing Editors
Dennis di Cicco, Robert Naeye, Roger W. Sinnott

Contributing Editors
Howard Banich, Jim Bell, Trudy Bell, John E. Bortle, Greg Bryant, Thomas A. Dobbins, Alan Dyer, Tom Field, Tony Flanders, Ted Forte, Sue French, Steve Gottlieb, David Grinspoon, Shannon Hall, Ken Hewitt-White, Johnny Horne, Bob King, Emily Lakdawalla, Rod Mollise, James Mullaney, Donald W. Olson, Jerry Oltion, Joe Rao, Dean Regas, Fred Schaaf, Govert Schilling, William Sheehan, Mike Simmons, Mathew Wedel, Alan Whitman, Charles A. Wood

Contributing Photographers
P. K. Chen, Akira Fujii, Robert Gendler, Babak Tafreshi

ART, DESIGN & DIGITAL
Art Director Terri Dubé
Illustration Director Gregg Dinderman
Illustrator Leah Tiscione
Webmaster Scilla Bennett

ADVERTISING
Advertising Sales Director Tim Allen

AMERICAN ASTRONOMICAL SOCIETY
Executive Officer / CEO, AAS Sky Publishing, LLC
Kevin B. Marvel
President Megan Donahue, Michigan State University
President Elect Paula Szkody, University of Washington
Senior Vice-President Michael Strauss, Princeton University
Second Vice-President Joan Schmelz, Universities Space Research Association
Third Vice-President Geoffrey C. Clayton, Louisiana State University
Treasurer Nancy D. Morrison, University of Toledo (ret.)
Secretary Alice K. B. Monet, U.S. Naval Observatory (ret.)
Trustees Marcel Agüeros, Columbia University; Kelle Cruz, CUNY Hunter College & AMNH; Kelsey Johnson, University of Virginia
At-Large Trustees Tereasa Brainerd, Boston University; Hannah Jang-Condell, University of Wyoming

Editorial Correspondence (including permissions, partnerships, and content licensing): Sky & Telescope, One Alewife Center, Cambridge, MA 02140, USA. Phone: 617-500-6793. E-mail: editors@skyandtelescope.org. Website: skyandtelescope.org. Unsolicited proposals, manuscripts, photographs, and electronic images are welcome, but a stamped, self-addressed envelope must be provided to guarantee their return; see our guidelines for contributors at skyandtelescope.org.

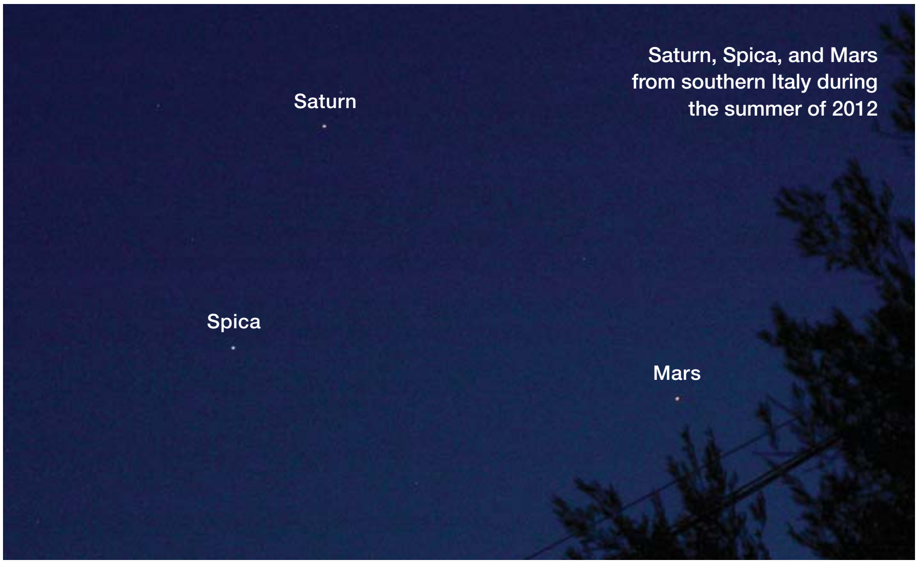
Advertising Information: Tim Allen: 773-551-0397
E-mail: tallen@skyandtelescope.org
Web: skyandtelescope.org/advertising

Customer Service: Magazine customer service and change-of-address notices: skyandtelescope@emailcustomerservice.com
Phone toll-free U.S. and Canada: 800-253-0245
Outside the U.S. and Canada: 386-597-4387

Visit shopatsky.com
Shop at Sky customer service: shopatsky.com/help

Subscription Rates:
U.S. and possessions: $54.95 per year (12 issues)
Canada: $69.95 (including GST)
All other countries: $84.95, by expedited delivery
All prices are in U.S. dollars.

Newsstand and Retail Distribution:
Marisa Wojcik, mwojcik@i-cmg.com
Comag Marketing Group



Saturn, Spica, and Mars from southern Italy during the summer of 2012

My Planet Adventure

Karl-Ludwig Abken's first-time observation of Neptune (*S&T:* Jan. 2020, p. 6) reminded me of my own planet adventure in the summer of 2012. While staying with my family in the small fishing village of Pioppi in southern Italy, I was lucky enough to be able to see all eight planets.

Mars was closing in on Saturn in the evening sky, while Venus and Jupiter glimmered in the morning sky as they slowly moved apart. Uranus and Neptune are difficult to see from the northern latitude of 60° where we live, but in Pioppi they were high above the dark sea horizon in the middle of the night.

Mercury was low in the morning sky, so it took extra effort to spot it. While making a one-night stop in Pompeii, I managed to get a glimpse of the innermost planet by climbing a chair on the balcony of our hotel room, which was just a mile or so from the ruins of an ancient Temple of Mercury. It was an appropriate conclusion to a fortnight with planets.

Markus Hotakainen • Espoo, Finland

Forensic Astronomy

I was quite entertained by Jeffrey Dobereiner's article "Shadow of a Doubt" (*S&T:* Jan. 2020, p. 26). Attorney Abraham Lincoln also saved an innocent man from a murder conviction using astronomy, which was described by Dan Abrams and David Fisher in *Lincoln's Last Trial*.

Duff Armstrong had been indicted for murdering a man one night at the end of a picnic. An eyewitness testified that he was within 150 feet and easily saw Armstrong strike the victim in the light of the full Moon. Lincoln then cross-examined the witness by producing an 1857 almanac proving that there was little more than a quarter Moon that night, and that the Moon had already set by the time of the incident. The picnic ground had been pitch-black. Lincoln established the prosecution's pivotal witness as a liar, and Armstrong was acquitted by the jury after only one hour.

I recently published a book of scientifically based short stories, *Seeking Hidden Treasures*. I think that anyone who enjoyed Dobereiner's article would appreciate my fiction.

James Magner, M.D.
Woodbridge, Connecticut

Historical Dramatic Irony

I always appreciate your articles on the history of astronomy, and "Just Over a Century Ago" by Klaus Brasch (*S&T:* Dec. 2019, p. 58) was no exception. Regarding the controversy surrounding the origin of the Moon's craters, allow me to bring the debate up to the year 1953.

That was the year the eminent British astronomer Patrick Moore published his illustrated, 255-page *A Guide to the Moon*. In it, Sir Patrick had no doubt that lunar craters were volcanic in origin.

Moore died in 2012 (*S&T:* March 2013, p. 16), so I wonder how long he took to accept Eugene Shoemaker's definitive 1960s findings, confirmed by the Apollo 11 samples, that the Moon's craters are of meteoric origin.

Herman Heyn
Baltimore, Maryland

In his article, "Just Over a Century Ago," Klaus Brasch alludes to astrobiology as one of the "'sciences without subject matter,' until recently." This is astounding news to me.

I have been reading *Sky & Telescope* and many science books for over 50 years, and all I have observed is the repeated disappointment among scientists where any detection of extraterrestrial life is concerned.

What is the actual, substantive content of astrobiology? I want to know what genuine indigenous life forms have been found on any celestial body other than Earth.

As far as I am aware, the unambiguous answer is none.

Daniel W. Rosser
Onarga, Illinois

Klaus Brasch replies: *As for the substantive content of astrobiology, I recommend readers look at NASA's website:* ***https://is.gd/astrobiology_nasa****.*

NASA's 1976 Viking missions, its current Curiosity rover, and the European Space Agency's upcoming Rosalind Franklin rover are all designed to look for life signatures on Mars.

Even more ambitious is NASA's proposed Europa Clipper mission to investigate this icy Jovian moon and see if its subsurface ocean could harbor life.

All this and more falls under the purview of astrobiology.

NIGHTSCAPE: MARKUS HOTAKAINEN

Another Kind of Focusing Mask

I thoroughly enjoyed Dick Suiter and Bill Zmek's article "Mesh Focusing Masks" (*S&T:* Jan. 2020, p. 30), and I will definitely try making my own Oleshko mask.

I was surprised that they did not mention the "triangle variation" of the Hartmann mask, which uses three triangles. When the star is out of focus, three distinct images appear in the eyepiece. When focus is achieved, the images merge. The triangular holes produce diffraction spikes, which become symmetrical when the focus is perfect. The spikes serve to better fine-tune the focus over the traditional Hartmann design.

It's easy to make, many websites offer directions, and it lets in more light than a two-hole Hartmann mask. It might not be as accurate as an Oleshko mask, but it has served me well for years.

Tom Sales
Somerset, New Jersey

Thank You, *S&T*, from a New Astronomer

I just recently subscribed to *S&T*, and as a former professional journalist and reporter, I am sincerely impressed! The artwork, diagrams, and photographs are awesome and informative. The writing is superior to that of most newspapers and magazines. The editing is obviously superb. Someone at *S&T* knows what they are doing, and it shows.

Some of the information is a bit over my head, as I'm only an amateur astronomer with his very first telescope, but that is expected. Your experienced astronomers need and deserve the technical information. I'll catch up sooner or later.

Larry Oakley's "Greeting the Queen of Night" (*S&T:* Jan. 2020, p. 84) was a neat finishing touch! Keep doing that! I have, on occasion, picked up issues of *S&T* over the years, and unlike so many other publications, it keeps getting better each year!

Talbert McMullin
Gilbert, Arizona

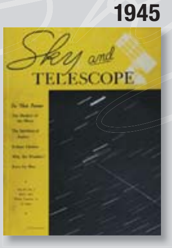
FOR THE RECORD

- The sundial diagram illustrating the Sun's position at various times and dates (*S&T:* Jan. 2020, p. 28) incorrectly showed the hour lines radiating from the zenith. They actually radiate from the north celestial pole, as shown at **https://is.gd/shadowsundiagram**.
- A 6-minute error in determining Greenwich Time would lead to a navigator's error of 90 nautical miles, not 6 (*S&T:* Mar. 2020, p. 60), when sailing near the equator.
- When computing longitude, subtract Greenwich Time from local time and multiply by 15, not divide, as stated in "Captain Cook's Astronomy" (*S&T:* Mar. 2020, p. 61).

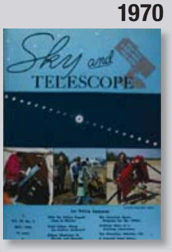
SUBMISSIONS: Write to *Sky & Telescope*, One Alewife Center, Cambridge, MA 02140, USA or email: letters@skyandtelescope.org. Please limit your comments to 250 words; letters may be edited for brevity and clarity.

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

1945



1970



1995

May 1945

Forecasting Weather "Quite recently, Dr. Charles G. Abbot, retired secretary of the Smithsonian Institution, announced that in the future it will be possible to foretell in January the kind of weather which will be available for a June wedding. He believes that in the postwar world there will be no necessity for uncertainty as to the weather of the future. His theory is, of course, that the weather on the earth is largely controlled by the variations occurring from day to day in the sun's heat. . . .

"It is rather astonishing to realize that all our weather, cyclonic and frigid as well as calm and warm, rainy as well as sunny, is made 93 million miles away, on the sun."

The renowned solar astronomer was not alone in expecting great advances in weather forecasting with the advent of digital computers during World War II.

May 1970

Venus's Day "R. L. Carpenter of the Jet Propulsion Laboratory remarks: 'The rotation period of Venus has become particularly interesting not only because it is retrograde but also because it is remarkably close to the so-called synodic resonance period . . . of 243.16 days. If Venus should indeed have this period, then it would rotate backwards relative to the Earth exactly four times between each successive inferior conjunction and thus present the same side to the Earth each inferior conjunction.' . . .

"He has discussed JPL radar observations made from 1962 to 1967 at four consecutive inferior conjunctions . . .

"Carpenter finds 242.982 days for the sidereal rotation period of Venus, with an estimated uncertainty of only ±0.04 day. But this is 0.18 day less than the resonance period, and therefore he suggests that the rotation of Venus may not be in synodic resonance with the earth."

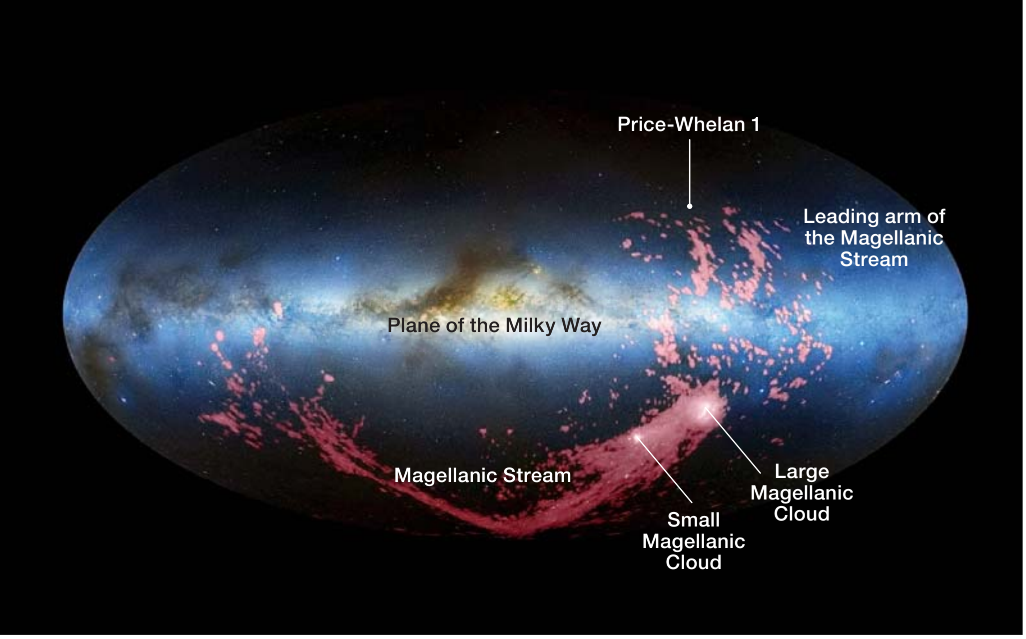
A 1979 study agreed. But a new wrinkle emerged in 2012: Venus's day may have lengthened by several minutes in recent decades.

May 1995

Io Erupts "In early March an observing team led by John R. Spencer (Lowell Observatory) was monitoring the Jovian moon Io as part of an educational program for young students called the Jason Project. But the participants got much more than the routine images they bargained for. The heat-sensitive camera observing Io witnessed a major volcanic outburst at 18h Universal Time on March 2nd — the first such event to be imaged from Earth as it happened. . . .

"The initial outburst was probably quite hot, as it shone brightly at 3.5 microns — a wavelength normally dominated by reflected sunlight.

"At longitude 95° and latitude –45°, the eruption site does not match any of the satellite's known active volcanic centers."



MILKY WAY

Baby Stars Found in Ancient Part of Our Galaxy

ASTRONOMERS HAVE DISCOVERED a collection of young stars in a surprising location: the Milky Way's halo.

Adrian Price-Whelan (Flatiron Institute) discovered the stars while digging through data collected by the European Gaia mission (*S&T:* Mar. 2020, p. 34). The newfound stars are 117 million years old and move together as a set. They're similar to open clusters like the Pleiades in both age and mass. But at 94,000 light-years away, the new stars are 200 times farther away than the Seven Sisters. They're also more spread out, spanning some 2,500 light-years, and are not gravitationally bound.

▲ A newfound group of young stars, the Price-Whelan cluster sits on the periphery of the Milky Way. These stars probably formed from material originating from the Magellanic Clouds.

D. NIDEVER ET AL. / NRAO / AUI / NSF / MELLINGER / LEIDEN / ARGENTINE / BONN SURVEY / PARKES OBSERVATORY / WESTERBORK OBSERVATORY / ARECIBO OBSERVATORY

By rights, the stars shouldn't be out there at all. There's not much star-making gas in the Milky Way's halo, as most of the gas is too hot and diffuse to collapse into new suns. What little cool gas there is resides in the Magellanic Stream, a long gaseous ribbon that travels with the Large and Small Magellanic Clouds through our galaxy's outer regions.

And the new stars appear to be sailing right in front of that ribbon of gas.

To investigate the stars' properties, David Nidever (Montana State University), Price-Whelan, and colleagues took spectra of 28 of the brightest stars in the group. The measurements showed that the stars have a fairly pristine composition. Both their composition and velocities match that of the leading arm of the Magellanic Stream. In two papers in the *Astrophysical Journal*, the team concludes that these stars likely formed from the gas at the head of the Magellanic Stream.

Murmurs of excitement from fellow astronomers met Price-Whelan and Nidever when they reported these results at the winter meeting of the American Astronomical Society in Honolulu. Observers have been looking for stars associated with the Magellanic Stream for decades, explains Jeremy Bailin (University of Alabama), in part to help pin down its distance. It's difficult to determine the distance to hydrogen gas, but based on the stars' distances, the astronomers estimate that the Magellanic Stream is roughly half as far away as previously thought.

The stars lie in front of the stream, not in it. The team thinks this offset occurs because the halo's hot gas drags on the gaseous stream but not on the stars. Over time, the gas slows down and falls behind the stars. In fact, the stars' ages match when the stream last passed through our galaxy's outer disk. That passage could have compressed the stream's gas, spurring starbirth.

■ CAMILLE M. CARLISLE

COSMOLOGY

Lensed Quasars Shed Light on Dark Matter, Dark Energy

GRAVITATIONALLY LENSED QUASARS imaged by the Hubble Space Telescope are helping astronomers measure fundamental properties of the universe. Two research teams reported results from these cosmic mirages at the winter meeting of the American Astronomical Society in Honolulu.

In one case, Anna Nierenberg (JPL / Caltech), Daniel Gilman (University of California, Los Angeles), and colleagues studied eight such gravitationally lensed quasars, where the gravity of a massive foreground galaxy bends light from a background quasar. Most of the lensing mass is actually in the galaxy's dark matter halo. So astronomers can use the relative brightness within each set of quasar images to determine the distribution of mass in the foreground halo.

The researchers found that dark matter clumps up in blobs just 1/100,000 times the mass of the Milky Way. If dark matter consisted of "warm," or fast-moving, particles, it wouldn't be able to form such low-mass chunks. Dark matter must instead consist of "cold," or slow-moving, particles. The results appear in two companion studies published in the *Monthly Notices of the Royal Astronomical Society*.

Meanwhile, another group of astronomers, led by Sherry Suyu (Max

STARS

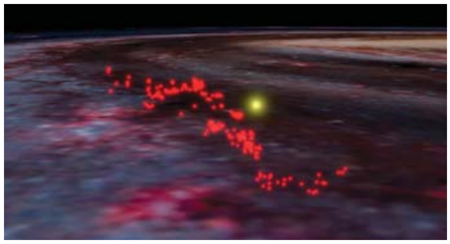
Nearby Stellar Nurseries Ride a Giant Wave

A NEW MAP OF THE MILKY WAY shows a gigantic "wave" of stellar nurseries riding just outside the Sun's orbit within the spiral disk of our galaxy.

The Milky Way isn't flat like a pancake: Its stars, and the gas clouds they form in, all move in a large gas disk that has warps and crinkles. Astronomers have now discovered a new warp that's only about 500 light-years away at its closest point to the Sun. And it's huge — so far, its mapped expanse stretches some 9,000 light-years.

João Alves (University of Vienna), Catherine Zucker (Harvard), and colleagues suspected that a connection existed between nearby star-forming clouds as they were mapping out the clouds' precise locations. But it wasn't until Alves, Zucker, and Alyssa Goodman (also at Harvard) plotted the clouds using the *WorldWide Telescope*, an open-source visualization software, that they saw the shape and extent of the structure.

Many nearby stellar nurseries trace a giant wave that lines up with the Local Arm, the section of spiral that our Sun inhabits in the Milky Way, Goodman explained at the winter American Astronomical Society meeting in Honolulu.



▲ In this illustration, the locations of star-forming clouds (red dots) are overlaid on an image of the Milky Way Galaxy.

The team's study also appeared January 7th in *Nature*.

The wave looks like a straight line from above; it's only when seen from the side that the crests and troughs appear, rising some 500 light-years above and below the disk's midplane. The wave includes major star-forming clouds familiar to skygazers — Orion, Perseus, and the North America Nebula.

Astronomers don't yet know how old this structure is or how it formed. However, the stars that formed in the gas clouds are just a few million years old, and the team can use them to track the structure's movements, Zucker explains. Based on these data, the researchers think the wave is oscillating, circling the galaxy like a sea monster on an orbit that intersected with the Sun's some 13 million years ago.

■ CAMILLE M. CARLISLE

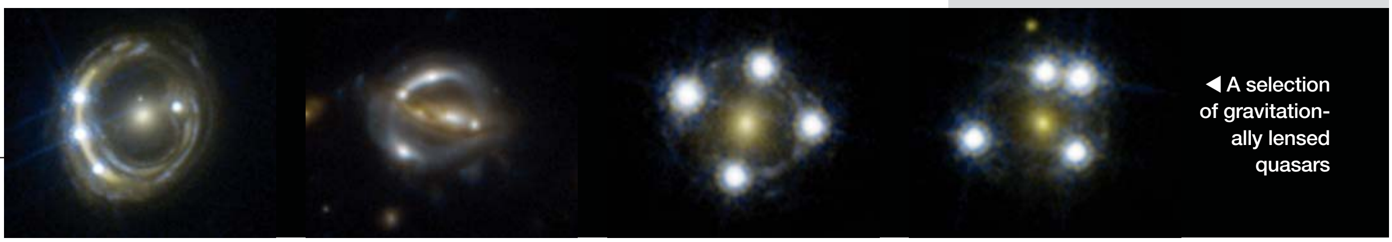
Interact with visuals showing the discovery at https://is.gd/stellarwave.

IN BRIEF

Second Planet Around Proxima Centauri

Astronomers announced the discovery of Proxima Centauri c in the January 15th *Science Advances*. It's the second planet around the cool, red star 4.2 light-years away; the first, Proxima Cen b, was found in 2016. The new super-Earth has at least six times Earth's mass. To find it, Mario Damasso (Astrophysical Observatory of Torino, Italy) and colleagues analyzed data collected between 2000 and 2017 by the UVES and HARPS spectrographs at the Very Large Telescope and the La Silla Observatory, respectively. The astronomers found a periodic, 5.2-year "wobble" in Proximas Centauri's spectrum indicating a planet, but they caution that follow-up observations are needed to confirm the planetary nature of the signal. Since Proxima Cen c orbits about 1.5 astronomical units from its cool star — about 30 times farther out than b — the planet would be too cold to host life as we know it. Moreover, Proxima Cen c appears to orbit far beyond the system's *snowlines*, the regions where gaseous compounds such as water, carbon monoxide, or ammonia solidify into ices. The planet's orbit would thus challenge planet-formation theories, which suggest that these regions should be sweetspots where super-Earths come together.

■ JULIE FREYDLIN



◀ A selection of gravitationally lensed quasars

Planck Institute for Astrophysics, Germany), also used Hubble images of lensed quasars, this time focusing on how their light flickers. This study will also appear in the *Monthly Notices of the Royal Astronomical Society*.

Each quasar image represents a different path the light takes to the observer. When the quasar flickers, light traveling a longer path will arrive later, so astronomers will see the same flicker multiple times. They can then measure the time delays to paint a 3D picture of the gravitational lens.

From this picture, astronomers can estimate the distances to the quasar and the lensing galaxy in a way completely independent from other distance measures. Based on these distances, the team estimated that the universe is currently expanding at a rate between 71.5 and 75 km/s/megaparsec.

This finding confirms other results based on relatively nearby objects, which show a similarly fast expansion rate. But calculations based on the cosmic microwave background emitted shortly after the Big Bang suggest that the current expansion rate ought to be slower. The gravitational-lensing study therefore deepens the ongoing controversy (*S&T:* June 2019, p. 22).

■ GOVERT SCHILLING

RADCLIFFE WAVE: WORLDWIDE TELESCOPE, COURTESY OF ALYSSA GOODMAN; QUASARS: NASA / ESA / S. H. SUYU / K. C. WONG

COSMOLOGY

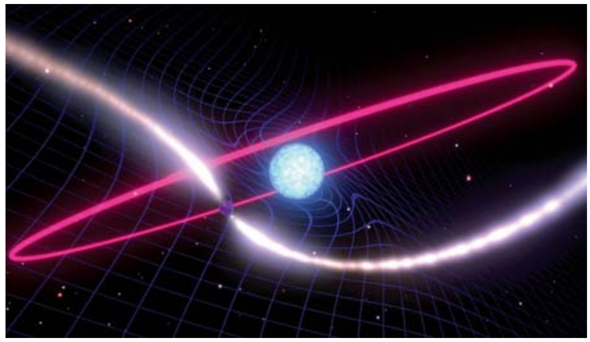
White Dwarf's Whirlwind Spin Drags Spacetime

ASTRONOMERS OBSERVING a white dwarf–neutron star pair have confirmed another aspect of Einstein's general theory of relativity.

Albert Einstein predicted that massive rotating bodies drag spacetime around them, like a spinning bowling ball would warp a sheet underneath it. In a binary system, a fast-spinning body will thus change the system's orbital inclination as seen from Earth in an effect called *Lense-Thirring precession*. As a result the orbit itself will wobble like a spinning coin. Satellites have measured this effect several times in Earth's weak gravitational field. But in the January 31st *Science*, Vivek Venkatraman Krishnan (Swinburne University of Technology, Australia) and colleagues announce the first detection of spacetime dragging in a strong gravitational field.

The detection comes from a binary system containing a radio pulsar, designated PSR J1141-6545, and its white dwarf companion. The duo is coupled in a 4.74-hour oval orbit that would almost fit inside our Sun.

The white dwarf appears to be older than its neutron star companion, which may explain its fast spin. Since the neutron star was a massive star before it went supernova, theorists think it transferred its outer layers to the white dwarf, spinning it up in the process. Now, the rapidly rotating white dwarf drags on spacetime, which should slowly shift the pulsar's orbit.



▲ A rapidly spinning white dwarf drags spacetime, affecting the orbit of its pulsar companion via Lense-Thirring precession.

Krishnan and colleagues analyzed the pulse arrival times over a period of almost 20 years using data collected by the Parkes and UTMOST radio telescopes in Australia. In the process, they reconstructed the slow change in the pulsar's orbit, finding that the spacetime-dragging effect had shifted the orbit by some 150 kilometers over two decades. The new result provides the first firm detection of Lense-Thirring precession beyond Earth's orbit.

The new result also sheds light on the history of the stellar pair. Based on observations of the pulsar, the researchers estimate that the white dwarf takes less than 3 minutes to spin around. Most isolated white dwarfs take hours rather than mere minutes to rotate, so this result aligns with the idea that the white dwarf achieved its fast spin thanks to mass siphoned from the pulsar progenitor before it went supernova.

■ GOVERT SCHILLING

WHITE DWARF AND NEUTRON STAR: MARK MYERS / ARC CENTRE OF EXCELLENCE FOR GRAVITATIONAL WAVE DISCOVERY (OZGRAV); THUBAN BINARY: NASA GODDARD SPACE FLIGHT CENTER / CHRIS SMITH (USRA)

STARS

See Ancient "North Stars" Eclipse Each Other

THUBAN, THE WELL-KNOWN double star 300 light-years away in Draco — and the "North Star" of the ancient Egyptians — turns out to be an eclipsing binary. Astronomers found the eclipses in data from NASA's Transiting Exoplanet Survey Satellite (TESS) and announced the discovery at the winter American Astronomical Society meeting in Honolulu. The results also appear in the October 2019 *Research Notes of the AAS*.

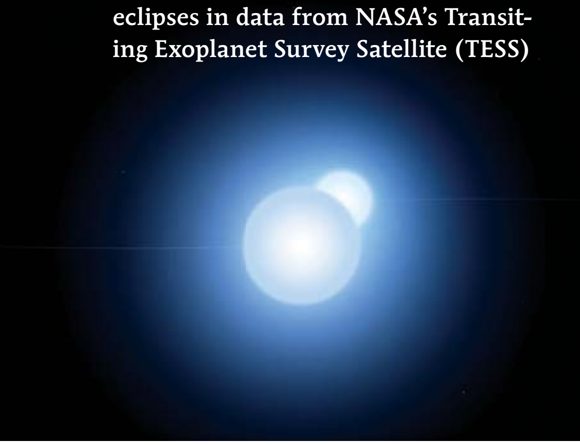
Spectra had shown Thuban to be a binary system. The light is dominated by the primary, a giant star several hundred times brighter than the Sun. The secondary is a main-sequence star. But astronomers hadn't known that the two stars eclipse each other as seen from Earth.

"The first question that comes to mind is, 'How did we miss this?'" says the study lead Angela Kochoska (Villanova University).

Thuban's stars partially eclipse each other twice every 51.4 days. However, the eclipses themselves are brief, only six hours long, and the changes in brightness are small. The primary eclipse causes a variation of only about 0.1 magnitude; the secondary eclipse is marked by an even smaller dip, 0.02 magnitude. Even the space-based Kepler mission hadn't caught the variations, because at magnitude 3.7 Thuban was too bright for Kepler to look at without saturating its detector.

TESS, though, is designed to monitor bright, nearby stars as it surveys large swaths of sky, so it was able to uncover the subtle dips in Thuban's light curve. Amateurs may spot the changes, too, though they will likely need specialized equipment to do so. If you're up for the observing challenge, you can find timing information for 2020 at https://is.gd/thubaneclipse.

■ MONICA YOUNG



◀ This illustration shows the giant star Thuban eclipse its smaller companion star.

FAST RADIO BURSTS

New Radio Flash "Repeater" Pinned Down

RECENT OBSERVATIONS have pinpointed the location of a fifth fast radio burst (FRB), shedding light on the environments that create these brief but powerful radio-wave flashes.

Benito Marcote (Joint Institute for VLBI, The Netherlands) announced at the American Astronomical Society meeting in Honolulu that he and his colleagues have pinned down another radio flash, the second repeating FRB to have a known location. The result appears in the January 9th *Nature*.

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) telescope discovered the radio flash, referred to as FRB 180916, in 2018. As the source continued to emit flashes, eight radio dishes of the European VLBI Network pinpointed the source to the outskirts of a spiral galaxy, whose light traveled almost half a billion years to Earth. The astronomers used the 8.1-meter Gemini North telescope on Mauna Kea, Hawai'i, to image the region: Whatever was producing the radio flashes had a nursery of newborn stars for company.

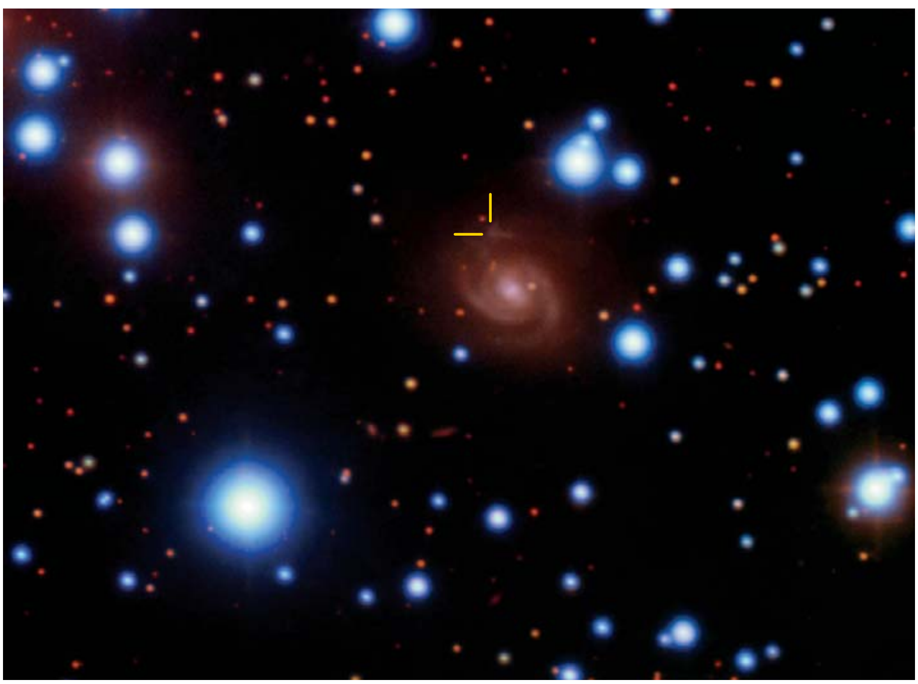
This environment is similar to the star-forming region hosting the first repeater, but it contrasts with the locations of single FRB flashes, Marcote says. All those have been localized to massive galaxies with low star-formation rates. The find suggests that repeating and non-repeating FRBs might have different origins.

Yet astronomers are still far from understanding what those origins are. New results from the CHIME collaboration, to appear in the *Astrophysical Journal Letters*, will help: The unique telescope discovered nine additional repeaters in 2019 observations, but what's more, the collaboration is also still analyzing some 700 additional FRB detections, to be published in a forthcoming catalog.

"By the end of 2020, we will have more than 1,000 FRBs, at least a few dozen that will be precisely localized, and we can answer some questions," predicts study coauthor Jason Hessels (ASTRON, The Netherlands). "Or at least we'll have some new questions."

■ MONICA YOUNG

▼ A star-forming region in a spiral galaxy hosts FRB 180916.



GEMINI OBSERVATORY / NSF'S NATIONAL OIR ASTRONOMY RESEARCH LABORATORY / AURA

IN BRIEF

Most Planets Lost in Globular Clusters

At most one-fifth of planetary systems around stars in globular clusters may survive, student Melissa Cashion (Texas A&M University) reported at the recent meeting of the American Astronomical Society in Honolulu. Globular clusters are dense, long-lived clusters of many thousands of stars, and it's unclear how planets fare in such an environment. Cashion and her colleagues simulated clusters with 800,000 stars, with some fraction of them beginning with a Jupiter-mass planet circling at the same distance that Jupiter circles the Sun. The astronomers then followed the stars and their planets over 12 billion years, watching things unfold. Most planetary systems were destroyed in the first billion years, they found, with planets jumping to different stars — or in rare cases, black holes. Some planets wound up permanently circling another companion, but most went rogue, wandering the cluster starless or even ejected from the cluster entirely. A 5% to 20% survival rate is "not too bad, considering all the chaos," Cashion says.

■ CAMILLE M. CARLISLE

New Horizons Still Exploring the Kuiper Belt

Ever since the New Horizons spacecraft passed Pluto and set its sights on Arrokoth (formerly 2014 MU_{69}), its team has been taking pictures of other, faraway worlds in the Kuiper Belt. Although these small bodies have been nothing but blurry blobs as the craft passed them — at distances from one-tenth to 1 astronomical unit — scientists are still able to learn about their shapes. The team watches how the worlds change in brightness over time as they're seen from different angles, then combines that information with Earth-based observations. This work indicates that Kuiper Belt objects have a variety of shapes, Simon Porter (Southwest Research Institute) and colleagues reported at the meeting of the American Astronomical Society in Honolulu. One, called 2011 JY_{31}, is probably spherical; two others appear to be conjoined twins, like Arrokoth. A third looks like a binary system. The results add to growing evidence that binaries and contact binaries might be common in the outer solar system (*S&T:* Feb. 2020, p. 34).

■ CAMILLE M. CARLISLE

Venus Is Dead. Long Live Venus.

In which I attempt a contrarian argument against my own contrarian argument

FOR MORE THAN TWO DECADES I've been arguing that Venus — so often voted "least likely to succeed" by astrobiologists — might possibly harbor life. Not on the scorching surface but high up in the clouds, where temperatures are mild, nutrients and energy abound, and droplets consist of water that, while steeped in sulfuric acid, are less acidic than some environments where life is found.

This contrarian position has produced some eye-rolling at conferences, but nobody has come up with a good reason why it's wrong. And now a funny thing has happened: An international workshop on Venusian cloud life held in Moscow in October 2019, along with several recent publications, appear to have moved the idea from the fringe to near-respectability.

Several results contribute to this shift. Observations from the Venus Express and Akatsuki missions have deepened some of the Venusian mysteries that cloud life might explain, such as unidentified airborne material that absorbs more than half the solar energy falling on Venus. Exoplanets in the "Venus zone" have renewed astronomers' interest in the possible habitability of close-in planets. And new calculations point toward Venus having had water oceans for much of its lifetime.

So now let me tell you everything that's wrong with the idea. Here's why Venus is most likely a dead world:

Maybe life can't live in clouds. Although microbes thrive in clouds on Earth, no known species lives its entire life cycle in this environment.

Maybe the chemistry of Venus's clouds is just too harsh. While Earth does have acid-loving microbes, we don't know the detailed composition of the Venusian cloud particles or whether they would be compatible with any form of life.

Maybe life couldn't migrate to the clouds when the oceans disappeared, or maybe the clouds haven't been continuously habitable. Evolution on Earth shows that life is extremely good at finding habitable niches and evolving when conditions change. But we don't know if Venus has been continuously cloudy since the surface became uninhabitable, so a cloud niche may not have been stable over long time scales.

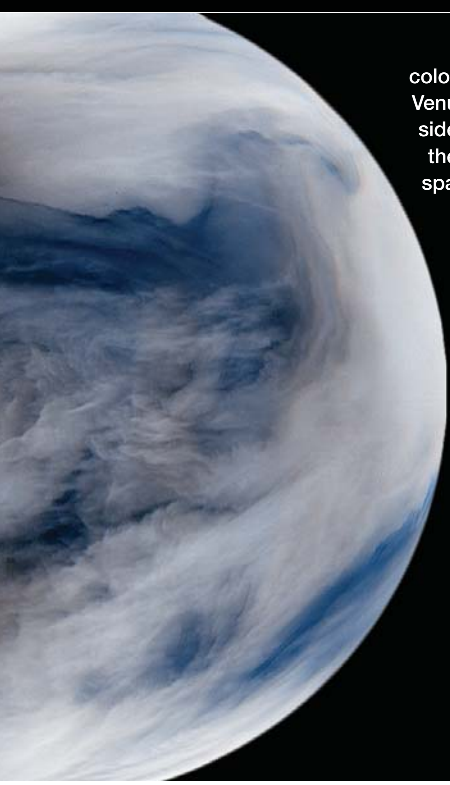
Maybe an ocean never had the right conditions. Some scientists think that for life to start you need oceans and continents. If early Venus had too much water and no land/water interface, life might not have arisen. Or a specific necessary environment, such as seafloor hot springs, might have been absent or chemically different enough to preclude life's origin.

Maybe an ocean didn't last long. Calculations showing that an ocean could have lasted for billions of years depend on several assumptions about early Venus. They require that the planet always rotated slowly, as it does now; a fast-rotating Venus would have quickly lost its oceans. But we have no idea what the early rotation rate was.

Venus may never have had an ocean. The young Sun may have vaporized any water, with the solar wind blowing away a steam atmosphere before it condensed on the surface.

Maybe Earth just lucked out. Life could be improbable, dependent as much on some absurd twist of fate as on specific planetary conditions, stages, or events.

So what do you think? I've made my best attempt to tell you why Venus should be dead — though I haven't really convinced myself. In any case, I think it's worth a look!



◀ A false-color image of Venus's nightside taken by the Akatsuki spacecraft in 2016

■ DAVID GRINSPOON is the author of *Venus Revealed: A New Look Below the Clouds of Our Mysterious Twin Planet*.

 by Camille M. Carlisle

The two spacecraft sent to Ryugu and Bennu have unveiled asteroids with formidable surfaces and mysterious histories.

Carl Hergenrother's brain was fried. He'd been awake all night, writing up results for a morning presentation at the science team meeting for NASA's OSIRIS-REX mission, which had arrived at asteroid 101955 Bennu just a month prior. Running on maybe a half hour of sleep, he decided the only thing his mind was good for was to blink through the week's backlog of navigation images and check for anything interesting.

He watched in a daze as Vega and Lyra went by, then Orion, then distant Earth and its Moon. Suddenly, he hit upon an image of what looked like a dense star cluster sitting just off the asteroid's limb. Enough of a backyard astronomer to quickly tell one cluster from another, Hergenrother (University of Arizona) knew at a glance that he wasn't looking at one of the well-known celestial groupings such as the Coma or Hyades clusters. In fact, he didn't know of any cluster at the coordinates captured in the image.

A Lot in a Name

Bennu takes its name from an ancient Egyptian deity connected to the Sun, creation, and rebirth, and its surface features are named for birds or bird-like creatures in mythology. Ryugu (or "Ryugo-jo") is a dragon palace in a Japanese fairy tale; the asteroid's feature names come from children's stories.

Puzzled, he pulled up the free software *Stellarium* and plugged in the coordinates. The background stars matched up, but there was no sign of the cluster's 20 or so pinpricks. After processing the image and others taken around the same time, he made a startling discovery: The "stars" had trails that all traced back to a single point on the asteroid's surface. These weren't stars — they were particles.

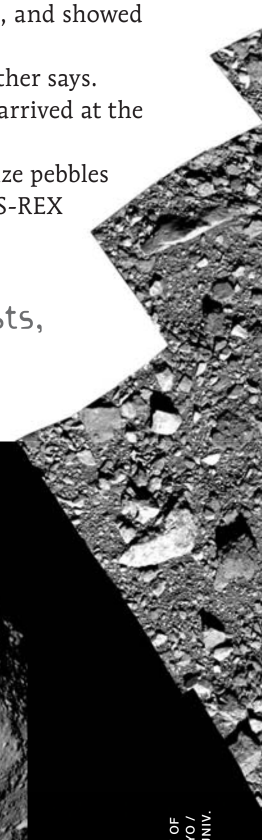
Bennu was firing rock bullets.

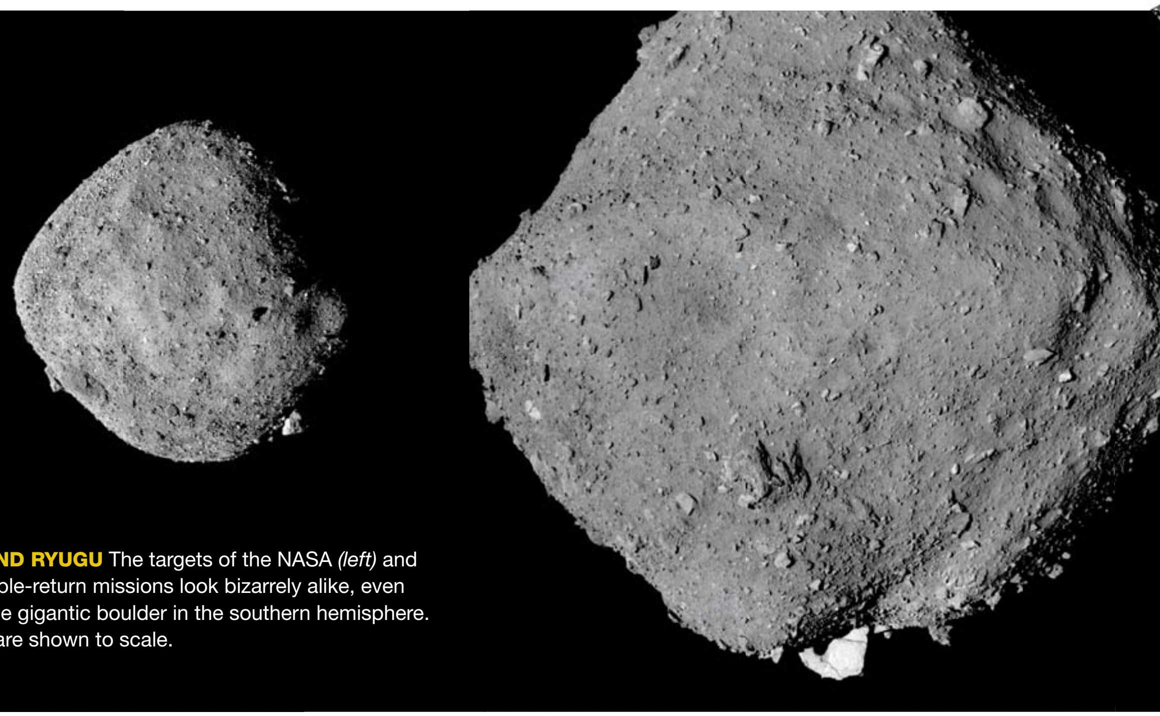
The particles put Hergenrother in a pickle. His presentation that morning was supposed to be about how OSIRIS-REX hadn't seen any signs of activity from the asteroid. This wasn't the moment to break the news to the whole team. So he hedged. Later, when everyone broke for lunch, he grabbed some of the mission leaders, including principal investigator (PI) Dante Lauretta (also University of Arizona), and showed them the images on his screen.

"Dante just kind of turned white," Hergenrother says. The PI's jaw dropped. "Here we are, we had just arrived at the asteroid, and the thing's shooting at us!"

Bennu's intermittent coughs of centimeter-size pebbles are one of several surprising results from OSIRIS-REX

These unassuming space rocks are precious to planetary scientists, because they're time capsules.



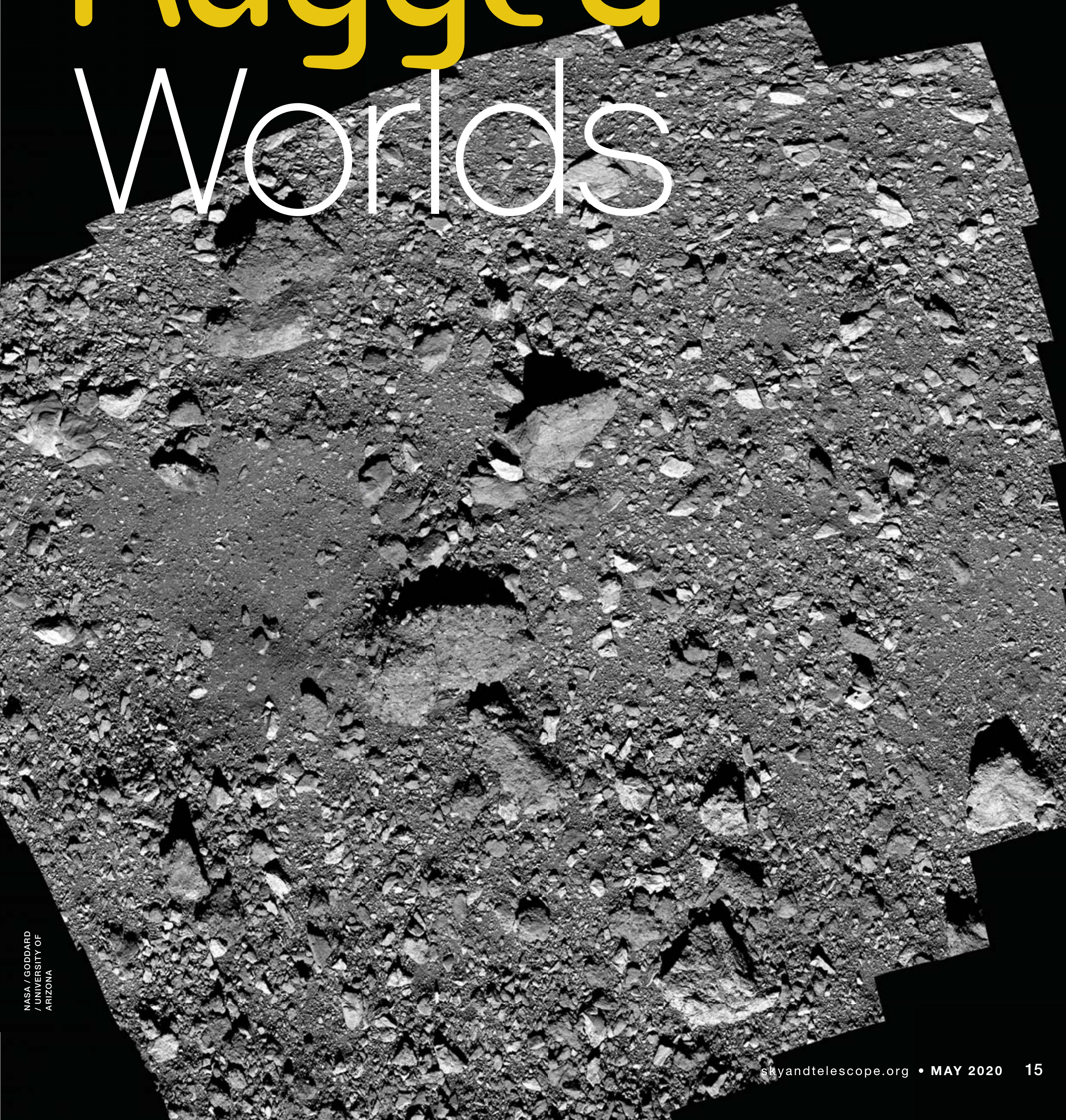


BENNU AND RYUGU The targets of the NASA *(left)* and JAXA sample-return missions look bizarrely alike, even down to the gigantic boulder in the southern hemisphere. Asteroids are shown to scale.

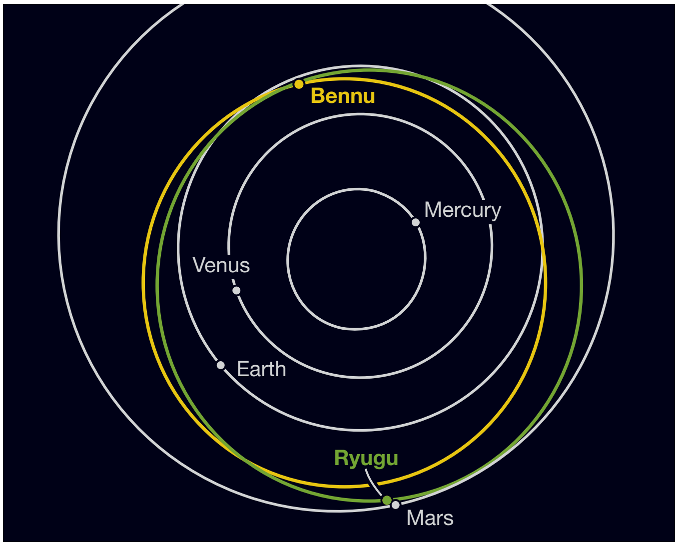
BENNU: NASA / GODDARD / UNIVERSITY OF ARIZONA; RYUGU: JAXA / UNIV. OF TOKYO / KOCHI UNIV. / RIKKYO UNIV. / NAGOYA UNIV. / CHIBA INST. OF TECHNOLOGY / MEIJI UNIV. / UNIV. OF AIZU / AIST

Rugged Worlds

NIGHTINGALE This 55-image mosaic shows the worn-looking crater on Bennu (center left) where OSIRIS-REX's primary sample site lies. The large boulder at center is about the size of a semi truck.



NASA / GODDARD / UNIVERSITY OF ARIZONA



▲ **NEAR-EARTH ASTEROIDS** Both Bennu and Ryugu cross Earth's orbit as they go around the Sun, making them *potentially hazardous asteroids*. The two have probably been in the inner solar system for several million years. Jupiter and Saturn's gravitational effects on the main belt drive asteroids inward, where they may survive for 10 million years or so before hitting something or being kicked out. Positions are for May 1st.

and its Japanese counterpart, Hayabusa 2, which recently left asteroid 162173 Ryugu after more than a year of exploration. Both projects are sample-return missions, designed to briefly touch down on the asteroids' surfaces, nab handfuls of debris, and bring the bits back to Earth for study (*S&T:* June 2018, p. 22). And both have revealed wondrously rubbly and perplexing worlds.

Formidable Terrain

Asteroids are not glamorous spacecraft targets. They don't have swirling cyclones like Jupiter or ancient, dried-up deltas like Mars. But these unassuming space rocks are precious to planetary scientists, because they're time capsules. Their chemical, structural, and geological makeups record a play-by-play of the solar system's early years. Therefore, in order to understand the origins of our planet and the compounds that make up our bodies, scientists turn to these chunks of planetary detritus.

Spacecraft have visited several asteroids, and we also have meteorites fallen to Earth that, based on their composition, we think come from different kinds of asteroids. We've even brought back samples from one: 25143 Itokawa, visited by the first Hayabusa spacecraft some 15 years ago. Itokawa proved a dead ringer for the most common type of stony meteorite, called *ordinary chondrites*.

But ordinary chondrites aren't the most pristine planetary crumbs out there. For that, we need *carbonaceous chondrites*. Scarce on Earth, these meteorites are the closest chemical matches to the Sun and look like the majority of the asteroids we observe. So to acquire the least tainted bits of the solar system's building blocks, scientists decided to snatch rocks from two carbonaceous asteroids whose orbits cross that of Earth: Ryugu and Bennu.

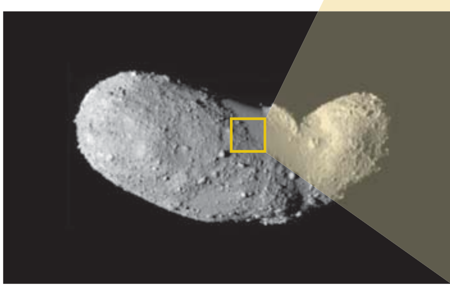
Small asteroids such as these — Bennu is about 500 meters wide, Ryugu 1 km — are rubble piles, conglomerations of debris from larger asteroids that broke up. Astronomers didn't know much about these two particular worlds when they picked them, only what they could infer from ground- and space-based telescopes. Because the surfaces of Ryugu and Bennu heat and cool quickly as they spin from daylight to darkness, scientists expected the two asteroids to have relatively smooth, beach-like regions like those found on Itokawa, and not to be covered in large rocks, which should take longer to warm and chill. OSIRIS-REX in particular was designed with a beach landscape in mind.

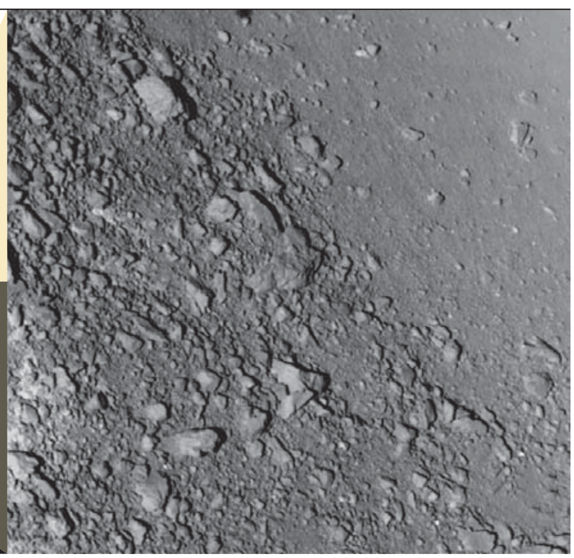
Nature had other ideas.

The spacecrafts' cameras revealed that both asteroids' surfaces are a sea of shards. Boulders ranging from about a meter to 100 meters wide dominate the landscape, with more big boulders near the poles than at the equator. It's as though someone took meteorites and strewed them everywhere — there's not a smooth region to be found. Upon seeing Bennu's surface, "My impression was 'Yikes! Where are we going to go on this asteroid?'" Lauretta said last September at a planetary science conference in Geneva, Switzerland.

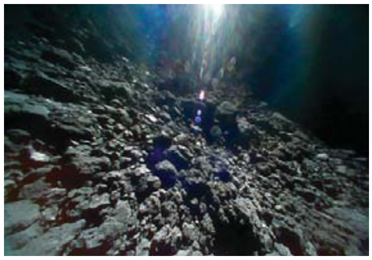
A range of rock types populates the asteroids, which are about as dark as fresh asphalt. Many rocks appear to be rubble piles themselves, mosaics of fragments fused together. There are boulders with a crumbly, cauliflower

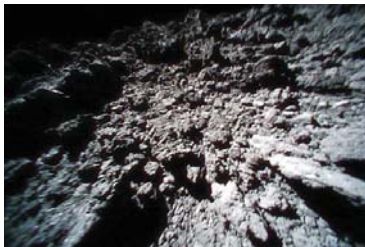
▼▶ **ITOKAWA** *Below:* The target of the first Hayabusa mission, 25143 Itokawa is a near-Earth asteroid with few craters and patches of smooth-looking terrain. Its longest dimension is 540 meters, about the same size as Bennu. *Right:* This close-up shows the smooth region around part of Itokawa's neck. Most boulders shown are a few meters wide.





ORBITS: LEAH TISCIONE / S&T; ITOKAWA AND CLOSE-UP: JAXA





▶ **A BEACH OF ROCKS** Hayabusa 2 deployed two of its Minerva-II rovers to Ryugu's surface in September 2018. Rover-1B took these shots on September 23rd.

texture and others that look smooth and sharp-edged. Some are distinctly brighter than others. It's unclear how many of the differences are due to composition, as opposed to different degrees of exposure to space weathering and other processes.

Scientists on both teams suspect the rocks were able to masquerade as smoother surfaces when seen from afar because they're extremely porous — so porous that Hayabusa 2 scientists can't see the difference between Ryugu's fine-grained regolith and its boulders when they look at the surface in infrared, says the navigation cameras' science team leader Seiji Sugita (University of Tokyo). On both Ryugu and Bennu, the whole surface heats up at more or less the same rate. "That's the surprising discovery," he says. "We are really scratching our heads."

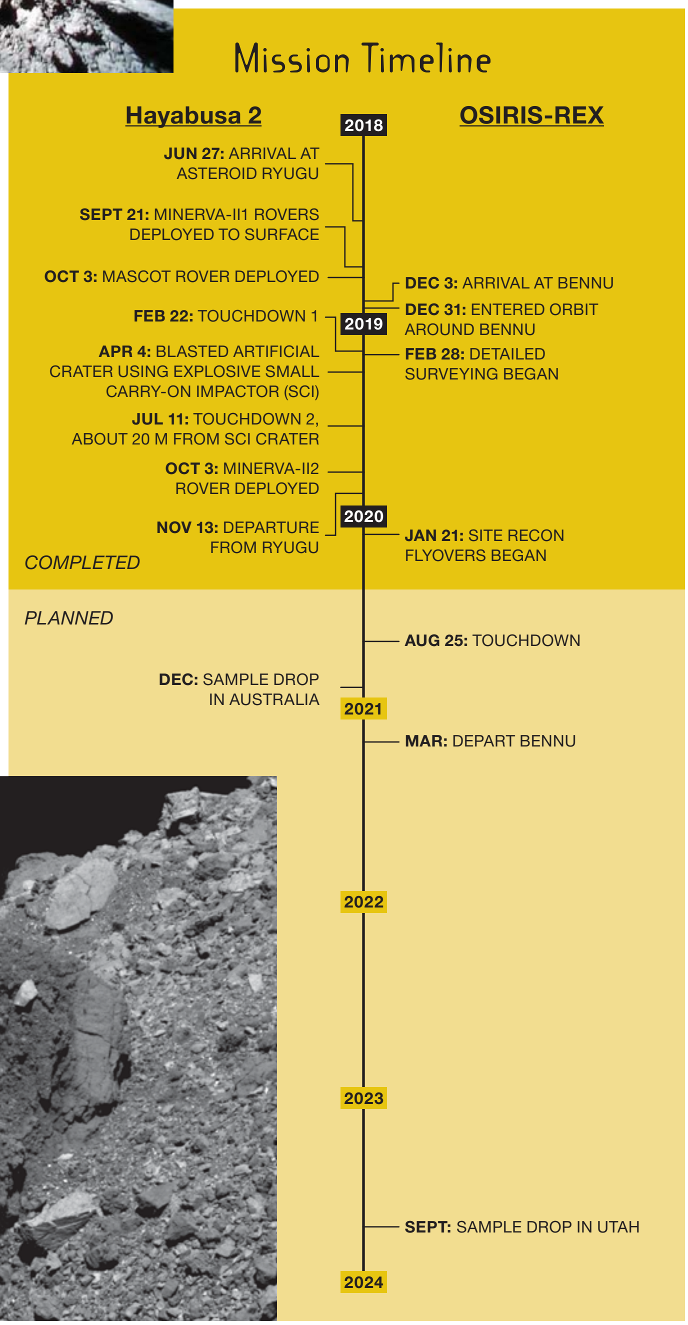
Another Hayabusa 2 experiment also suggests the asteroids are extraordinarily porous. Before its second and final touchdown on Ryugu, the spacecraft launched an explosive projectile to blast a hole in the surface, digging up material previously protected from space weathering. The scientists expected the resulting crater would be a few meters wide. Instead, the explosion dug a 13-meter-wide pit. Probably the rocks' low porosity, paired with the asteroid's weak gravity, explains the peculiarly large hole, mission manager Makoto Yoshikawa (Japan Aerospace Exploration Agency) said at the Geneva conference.

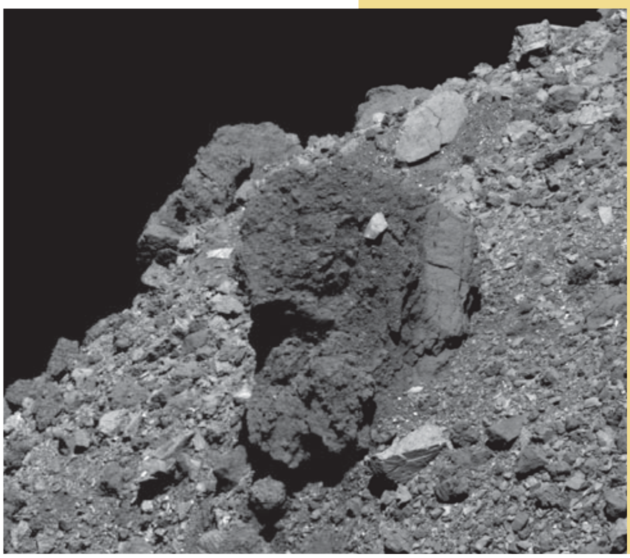
Hiding Their Ages (For Now)

Bennu and Ryugu are eerily similar. Both have the same diamond shape, the same density, same albedo. That's not what scientists expected: The two teams intended to go to different asteroids and then compare them. "When we got there, to Ryugu, we were like, 'Did, did we get to the right asteroid?'" Sugita jokes. "It was kind of a weird atmosphere."

Craters mottle both of the asteroids' surfaces, with large ones on the ridges that girth their equators. The pockmarks look soft-edged, not sharp like many on the Moon or Mars. Ryugu's big craters are about as densely packed as those on Bennu, but both appear to be short on craters smaller than 50 meters or so, implying something has erased them.

Such resurfacing might be connected to the strange die shape, Sugita suggests.





▶ **CAULIFLOWER** This strange, hummocky rock near Bennu's equator is one of the darkest boulders on the asteroid. The small, light-colored rock perched on it is 1.9 m (6.2 ft) long, about the size of a person. The backup touchdown site, called Osprey, lies directly behind the boulder from this perspective.

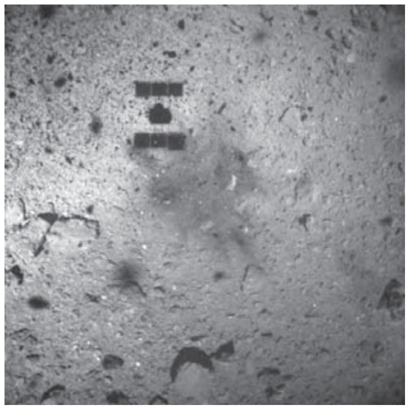
RYUGU'S SURFACE: JAXA (2); CAULIFLOWER ROCK: NASA / GODDARD / UNIVERSITY OF ARIZONA; MISSION TIMELINE: TERRI DUBÉ / *S&T*

Bennu rotates every 4.3 hours, which means that every 4.3 hours its airless surface experiences a temperature rollercoaster.

Ryugu's equatorial ridge draws a symmetric circle around the asteroid's middle when viewed from above the poles, like a skirt whirled out by a rapid spin. The overall slope of the ground is also low and gentle, close to the critical angle for landslides if the asteroid had once been spinning about twice as fast as it is now, project scientist Seiichiro Watanabe (Nagoya University, Japan), Sugita, and their colleagues calculated last year. Perhaps Ryugu spun itself into its odd shape, generating landslides and erasing craters.

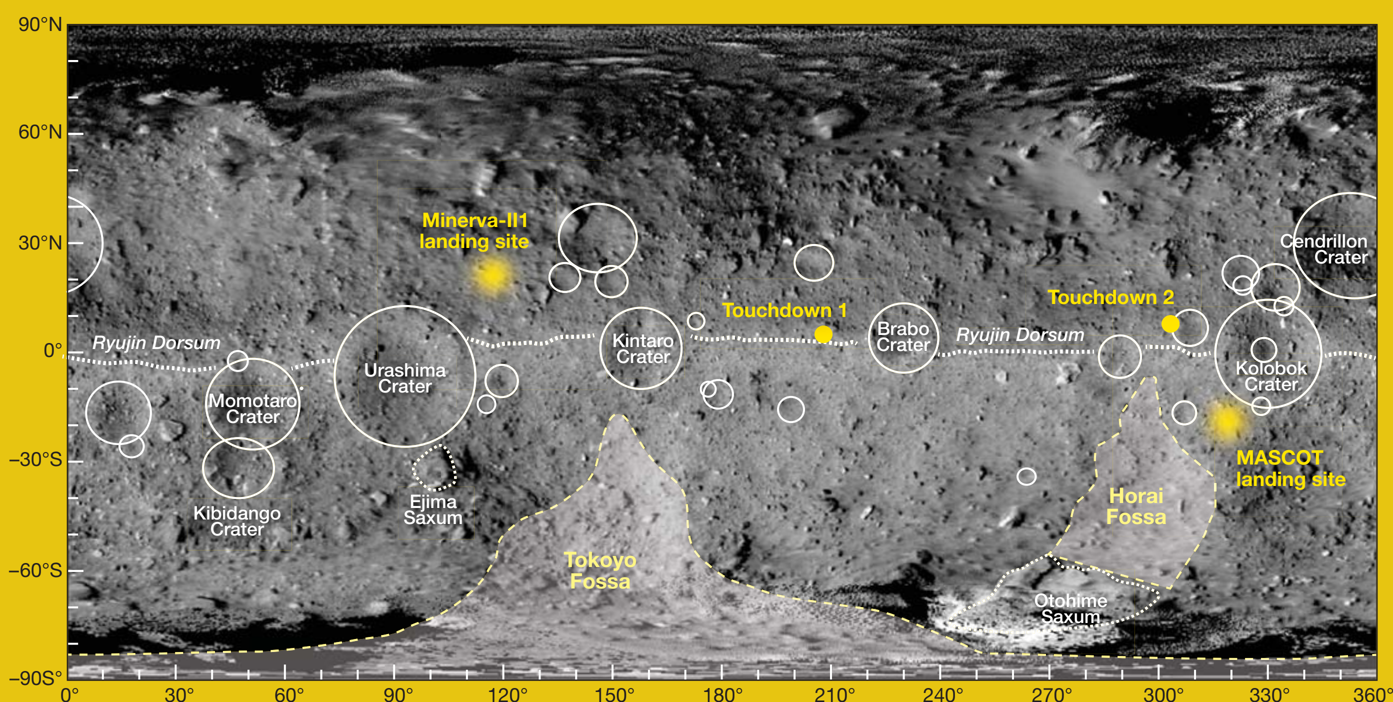
Lauretta is hesitant to favor a scenario for how the asteroids came by these shapes. At first, he was "fully onboard" with the rapid spin solution. But the large, ancient craters on the equatorial ridges give him pause. Those must have formed at least several million years ago, back when both worlds were still in the main asteroid belt between Mars and Jupiter and vulnerable to big crashes. That implies the ridges are old, perhaps even as old as the asteroids themselves. Simulations by Patrick Michel (Côte d'Azur Observatory, France) and others also indicate that a body built up from the shattered remains of an earlier asteroid can end up with a die shape, no landslides required.

That there are craters at all on Bennu and Ryugu "really shocked me," says asteroid scientist Bill Bottke (Southwest Research Institute, Boulder). Many small asteroids shed material, for various reasons. He thus expected the spacecrafts' targets to be essentially blank slates, wiped clean by all the goings-on. Perhaps it's easier to make craters on these bodies' surfaces than we thought, he says — a solution supported by Hayabusa 2's impact experiment. Or, he speculates, maybe asteroid surfaces don't erase themselves easily. That would imply that regions covered with large craters, such as the equatorial ridges, are ancient, whereas those with few small craters are young, such as ones near the poles.



◀ **LEFT A MARK** Hayabusa 2's shadow sails over the first touchdown site on February 22, 2019, just after completing the maneuver.

▼ **RYUGU** Hayabusa 2 dropped rovers at two known locations (yellow, hazy spots) on Ryugu, touched down twice, and mapped dozens of craters (white circles) as well as two large trenches, called *fossae*. The largest boulder, Otohime Saxum, appears stretched out here because of the severe projection distortions near the map's poles. The team has not yet identified where the final rover, Minerva-II2, landed.



SHADOW OF HAYABUSA 2: JAXA / UNIV. OF TOKYO / KOCHI UNIV. / RIKKYO UNIV. / NAGOYA UNIV. / CHIBA INST. OF TECHNOLOGY / MEIJI UNIV. / UNIV. OF AIZU / AIST; SURFACE MAP OF RYUGU: JAXA AND S. SUGITA ET AL. / *SCIENCE* 2019

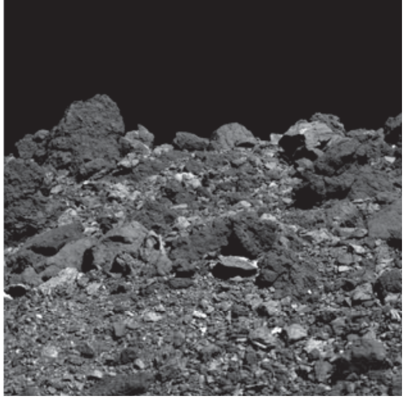
For now, scientists can't tell how old Bennu and Ryugu are. Both are near-Earth asteroids, strays that were kicked out of the main belt and into the inner solar system by the combined gravitational influences of Jupiter and Saturn. (This combined resonance also sculpts the inner edge of the asteroid belt.) Asteroids only survive in near-Earth orbits for about 10 million years before hitting a planet or the Sun, or being evicted from the system altogether. Based on where their orbits trace back to in the asteroid belt, Ryugu and Bennu are probably roughly a billion years old, Lauretta says.

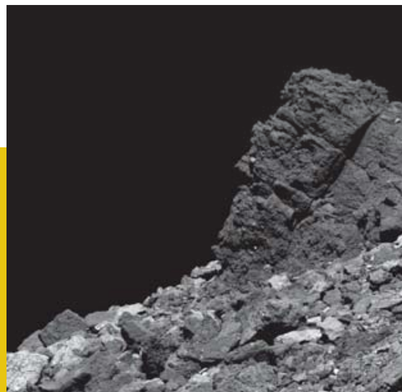
The samples that OSIRIS-REX and Hayabusa 2 will bring home could tell us the little worlds' ages. The catastrophic impact that created the rubble the asteroids formed from would have reset certain chemical clocks, Lauretta explains. One useful clock is the ratio of potassium to argon. Potassium is a rock-loving element, incorporating itself into things like salts and feldspars. But it decays into argon, a noble gas — which doesn't like to bond with anything. Once the potassium atom decays, the now-argon atom will sit unhappily in the crystal structure until it receives the energy needed to kick it out. An impact can deliver that energy. The impact doesn't necessarily destroy the rock, he says, but it's enough to drive the argon out and reset the radioactive clock. From that point on, any argon in the rock dates back to the impact that made the pieces that formed the asteroid.

Water, Water Everywhere

One dramatic difference between Bennu and Ryugu is water. Prior spectroscopic observations had hinted that Ryugu's surface bore hydrated minerals, while Bennu looked relatively dry. Scientists found the reverse. Ryugu has much less water caught up in its rocks' crystalline structure than what's typically seen in a carbonaceous chondrite meteorite.

And Bennu? Bennu is practically soaked.





◀ **UP CLOSE** Shots of Bennu reveal an imposing surface replete with boulders. These rocks look deceptively small: The one in the top image's upper left is 14.5 m (48 ft) wide, the length of a boxcar; the little rock on the flat one in the middle image is the size of a horse; and the bottom image's boulder is as tall as a 747 aircraft's tail.

▼ **BENNU** The OSIRIS-REX team has chosen two potential landing sites on Bennu: Nightingale and Osprey. Also shown are the origins for the three largest particle ejection events (the Jan. 6 event launched from near the south pole). The various smaller ones come from all over the asteroid. The team hasn't assigned official feature names yet.

BENNU'S SURFACE: NASA / GODDARD / UNIVERSITY OF ARIZONA (3); SURFACE MAP OF BENNU: NASA / GODDARD / UNIVERSITY OF ARIZONA, D. S. LAURETTA ET AL. / *SCIENCE* 2019

"We saw this signal from *way* out, from thousands of kilometers away from the asteroid," Lauretta says — as soon as the team turned on the visible and infrared spectrometer, which detects water's absorption signal. Those data show that water has altered practically all the rocks that make up Bennu's surface. The rocks must be fragments from a large asteroid that had massive amounts of hot water percolating through it, altering its rocks, changing their chemistry, and building the clay minerals that dominate Bennu's surface today. "Think of a Yellowstone kind of environment," he says. "We went there to go find hydrated minerals — which generally are very rare in the solar system and in meteorites — and we got a whole asteroid full."

The difference between Ryugu and Bennu is puzzling because, based on the asteroids' orbits, scientists think the two worlds come from the same parent body. Perhaps something about the way in which the two rubble piles agglutinated affected how much water they held on to. Or perhaps Ryugu has been in the inner solar system much longer and been dried out by sunlight. Or maybe the asteroids aren't siblings after all.

◀ **TARGET PRACTICE** This continuous image sequence taken from an altitude of 1 km tracks a descending target marker, dropped on September 17, 2019, in preparation for the Minerva-II2 deployment on October 3rd.

▼ **ACTIVE ASTEROID** This enhanced, two-image composite shows some of the 93 particles observed launching from Bennu on January 19, 2019. The event was one of the three largest seen thus far.

Of all the discoveries so far, why Ryugu is so dry is the question Sugita most wants answered. "I think this really tells us what controls the water amount in the asteroid belt," he says. If scientists can determine why some asteroids retain water and others don't, it could help us understand how much water the planetary building blocks carried and why Earth and the other inner solar system planets formed with the amounts of water that they did. In 10 or 20 years, he predicts, we will look back on the discovery of Ryugu's dryness and say, "That moment, we learned something important."

Asteroid Spittle

And then there's Bennu's particle coughing fits. OSIRIS-REX has detected a few dozen outbursts, ranging from tiny explosions of 70 or more pebbles down to individual escapees. Many particles escape forever; others orbit for days before landing again. The sum effect is like a constant swarm of bees, Hergenrother says.

The Hayabusa 2 team can't tell whether Ryugu also spews shards — the spacecraft only darted close to Ryugu's surface to drop its rovers and take samples, and it also doesn't have as sensitive a camera. OSIRIS-REX, on the other hand, stayed within a couple of kilometers of Bennu's surface for months. No spacecraft has done that before. "It's very possible this happens on all asteroids, and it just hasn't been seen yet," Hergenrother says.

The team favors three possible causes for the ejections: the sublimation of water molecules liberated from minerals by grinding, cracking, and heating, which then propels grains off the surface; meteoroid impacts; and *thermal fracturing*.

Bennu rotates every 4.3 hours, which means that every 4.3 hours its airless surface experiences a temperature rollercoaster, plunging to 250 kelvin at night and surging to 400 K just after local noon. This dramatic cycling can cause rocks to crack and crumble — in fact, Hayabusa 2 images show that more than half of the cracks on Ryugu's surface line up north-south, as expected if the rocks cracked because they repeatedly rotate into darkness and light. Researchers see hints of a similar alignment on Bennu.

The three largest swarms of particles seen from Bennu thus far all launched during local afternoon. This makes sense if the cause is thermal fracturing, because it takes roughly three hours for heat to penetrate the rock's upper couple of centimeters, creating a difference in temperature that would stress the rock. But the other events happened at random times, even at night.

The range in timing suggests that more than one mecha-

TARGET DESCENT: JAXA / UNIV. OF TOKYO / KOCHI UNIV. / RIKKYO UNIV. / NAGOYA UNIV. / CHIBA INST. OF TECHNOLOGY / MEIJI UNIV. / UNIV. OF AIZU / AIST; SPEWING PARTICLES: NASA / GODDARD / UNIVERSITY OF ARIZONA / LOCKHEED MARTIN

▲ **TOUCHDOWN** Hayabusa 2 executed its second touchdown on July 11, 2019, near Ryugu's equator. The images capture 4 seconds before, the moment of, and 4 seconds after touchdown.

nism is at work, or perhaps they work together. Thermal stress could weaken the surface, "and then if a micrometeorite comes in and hits it, it's going to respond in a spectacular way," Lauretta speculates. If thermal fracturing is the root cause, then all near-Earth asteroids should be doing this, he adds. But if water is the key factor, then only Bennu and other hydrated asteroids will launch particles.

Since space agencies aren't likely to send a fleet of spacecraft to check dozens of near-Earth asteroids for this activity, the OSIRIS-REX team has found a clever alternative: The researchers partnered with SETI scientists to look for meteors that might be from Bennu's debris. So far, nothing. But after a couple of years, they hope to have enough observations to identify any potential links between meteor populations and near-Earth asteroids.

Landward, Ho

Hayabusa 2 has already finished its investigation of Ryugu, leaving the asteroid last November with two samples safely stowed. It will drop these in Australia during an Earth flyby at the end of 2020. With the extra propellant onboard, the spacecraft might continue on to whizz by another asteroid.

OSIRIS-REX, which arrived at its asteroid about five months after Hayabusa 2 did, intended from the beginning to take more of a tortoise pace with its sampling. But the jagged surface hasn't done the team any favors, either. The original plan to monitor the spacecraft's descent with lidar doesn't offer the guidance accuracy necessary to avoid potential hazards. Instead, the researchers will track features using a catalog they'll upload to the craft in advance.

OSIRIS-REX has a primary and a backup sample site, both announced in December 2019. The first, Nightingale, is a relatively smooth spot in a 70-meter-wide crater high in the northern hemisphere. Scientists think the crater and the debris it unearthed are fairly fresh. The backup site, dubbed Osprey, sits in a much smaller, equatorial crater surrounded by several types of rocks.

The spacecraft will do multiple recon passes of both sites in the first half of 2020 before touching down, hopefully in late August. It has until early 2021 to snatch its sample, then the craft will start the trip back to Earth. The cargo should drop in Utah in September 2023.

The retrieved rocks won't be in perfect condition. Both missions' grab-and-go strategies involve some rather violent jostling, and then there's the atmospheric entry. "It's coming in at 12.4 km/s, so it's going to shake up a bit on that ride," Lauretta says. "No getting around that. I tried."

Still, scientists expect to learn much from Hayabusa 2 and OSIRIS-REX's samples. The asteroid pieces, shaken up though they may be, will be treasures of chemical and geological insight, providing glimpses of how everything we see in the solar system — including the delightful array of carbon-based life around us — came to be.

■ Science Editor **CAMILLE M. CARLISLE** gasped when she first saw Ryugu's rugged landscape in a rover surface image.

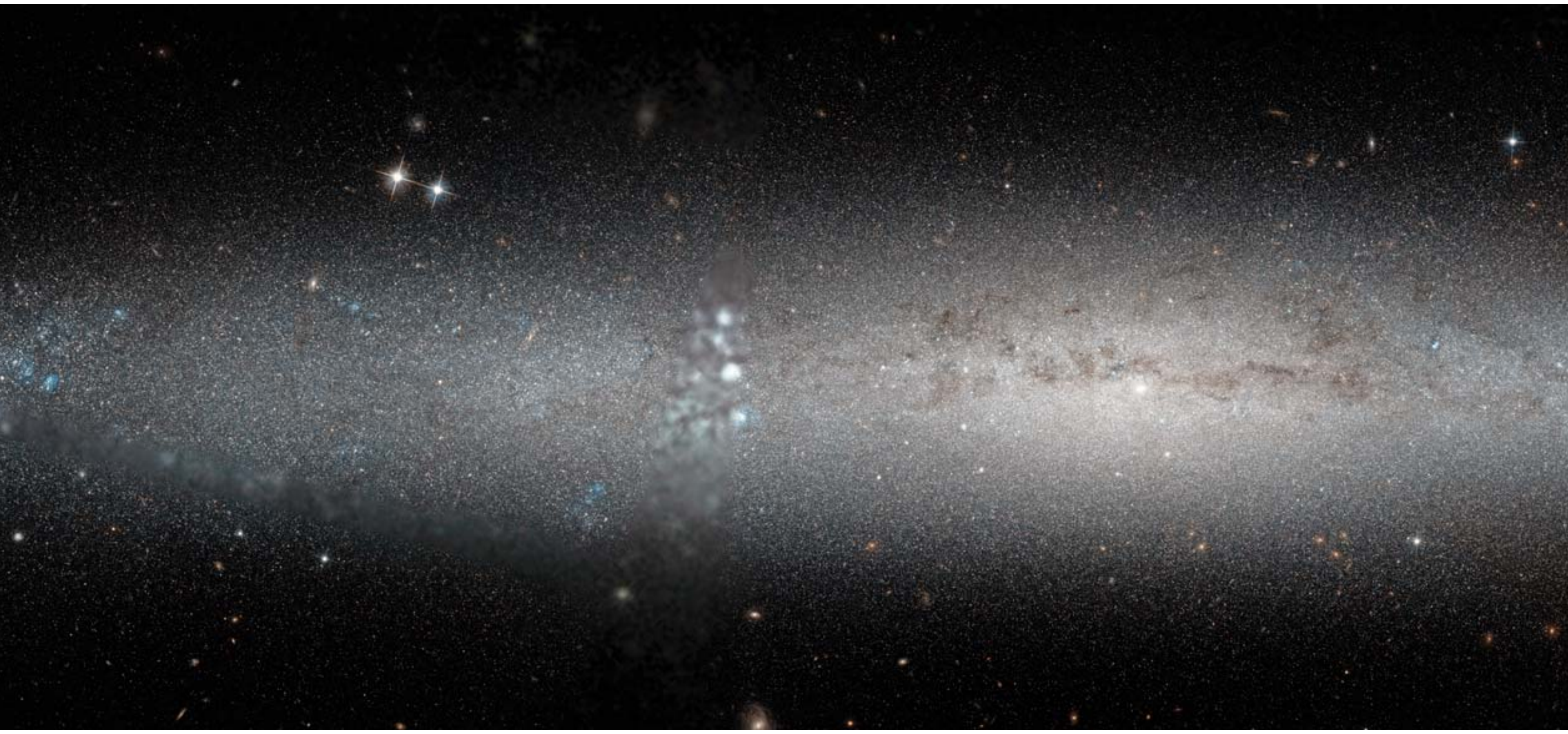
Asteroid Prospecting?

Both scientists and starry-eyed entrepreneurs speak of mining asteroids for water and metals. But although these space rocks may someday provide valuable resources, we have a long way to go before that day comes. "We're talking about the space economy of the 22nd century," says asteroid expert Richard Binzel (MIT).

Water will likely be the first resource utilized, he says. But first we have to learn how to recognize which asteroids have minable water — something that, given the surprise of a wet Bennu and dry Ryugu, we clearly need to work on. The samples OSIRIS-REX and Hayabusa 2 bring back will tell us how much water the asteroids' minerals contain and potentially indicate how much future spacefarers could extract globally.

"But I don't predict it for this century," Binzel says. "I would love to be wrong."

JAXA (3)



May's Galaxy C

Glance at a star map that highlights bright deep-sky objects and your eye will almost certainly be drawn to a remarkable line of galaxies that straddles the meridian on May evenings. Stretching almost 40° from Draco to Coma Berenices, a string of 10th- and 11th-magnitude galaxies hugs the imaginary line that demarcates 12 hours of right ascension. This majestic cascade bears some of the best observing targets in the spring sky.

The pattern is mostly coincidental; few, if any, of the objects in the queue are physically associated with one another. The nearest galaxy is about 10 million light-years from us, and the most distant one in the string lies more than 100 million light-years away.

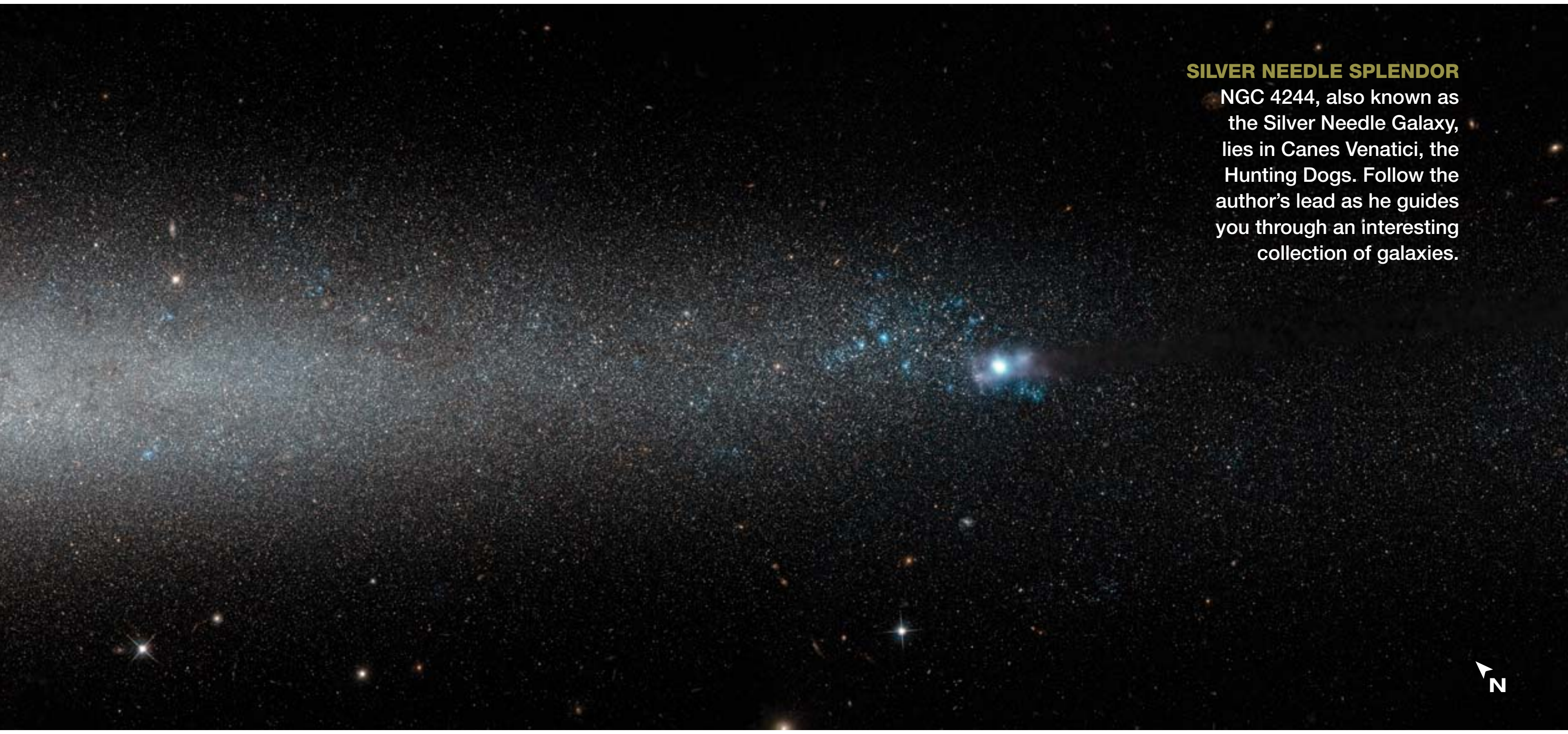
Many of the galaxies on our tour are classified as *low-ionization nuclear emission-line region*, or LINER, galaxies. These galaxies exhibit spectra dominated by emission lines from weakly ionized or neutral atoms, while the contribution from strongly ionized atoms is less prominent. Astronomers disagree on what the origin for this effect is. Perhaps a supermassive black hole is fueling an active galactic nucleus, or the emission might be due to an energetic star-forming region. There's also no consensus as to the mechanism for the origin of the ionization. Is it due to propagating shock waves or a photoionization process? These are still open questions. LINER galaxies are quite common and are not confined to a particular galaxy type.

Starting in the Dragon

The line's northern anchor is the barred spiral **NGC 4236** in Draco. In total visual magnitude, it's the brightest galaxy on the list, but its huge size renders it almost invisible in small scopes. Don't let its low surface brightness deter you, though, for it's well worth the effort to try and eke out every detail you can pull from its faint glow. Low power and averted vision will eventually reward the patient observer with a view of a large, nearly edge-on behemoth. See if you can detect a bright detached region at the northern end of the galaxy. This is an enormous H II region (a region of ionized hydrogen). Other knots are visible across its expanse appearing as small splotches of brighter nebulosity, especially at its southern end. There is very little brightening toward the center of NGC 4236, nothing that one could describe as a brighter core.

Draco is also home to our next target. **NGC 4125** is about 4.3°, or a typical finderscope field, south of NGC 4236. It

NGC 4244: NASA / ESA



SILVER NEEDLE SPLENDOR NGC 4244, also known as the Silver Needle Galaxy, lies in Canes Venatici, the Hunting Dogs. Follow the author's lead as he guides you through an interesting collection of galaxies.

ascade

Starting in Draco and spilling down into Coma Berenices, May's night skies offer a delightful trickle of galaxies that one can peruse from top to bottom.

forms a pair with tiny NGC 4121, which lies less than 4′ away. Sir William Herschel discovered most of the objects discussed here in the late 18th century, but not NGC 4125. John Russell Hind first noticed this galaxy on January 4, 1850, while observing with a 7-inch refractor from a private observatory in London. NGC 4125 is a rather bright and easy target that will seem to stand out even in a small telescope. A much brighter core dominates its large oval glow.

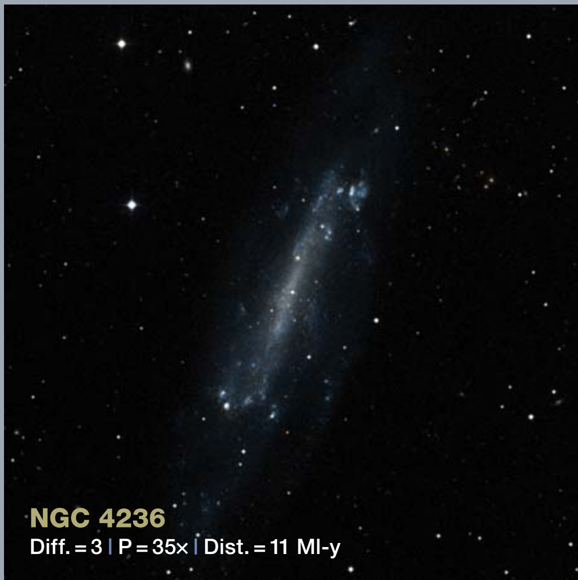
Large-telescope users were treated to a bright supernova in 2016 (the Type 1a SN 2016coj) nestled in the core of NGC 4125. In my 30-inch Dob, the supernova gave the galaxy the appearance of having a dual nucleus. Minus the supernova now, the core still has an almost stellar center.

Moving into the Big Bear

Just above the bowl of the Big Dipper, **NGC 4036** forms a wide pair with the 11.3-magnitude **NGC 4041** some 15′ to the northeast. But they're not true neighbors: the two galaxies lie some 31 million light-years apart, with NGC 4041 farther away. NGC 4036, a lenticular galaxy with a LINER-type nucleus, has a bright elongated center with an overall spindle shape. The Type Ia SN 2007gi reached 13th magnitude southeast of its nucleus in August 2007. NGC 4041, on the other hand, is an open-faced spiral whose bright center appears very round. Averted vision shows an extended halo without any visible spiral structure. NGC 4041 is also a Seyfert galaxy. This class of galaxies, named after the American astronomer Carl K. Seyfert, are similar to quasars in that they have active nuclei, but unlike quasars the host galaxy is visible in Seyferts.

NGC 3998, another Seyfert galaxy (and a LINER), forms a much closer apparent pair with 14th-magnitude NGC 3990 a little less than 3′ to its west. NGC 3998 is the brightest and easternmost member of a fine group of five NGC galaxies that can fit into a single eyepiece field. It's a large, bright, nearly

For each of the targets portrayed on the following pages, the field of view is 20′ × 20′. The observational difficulty level — 1 is obvious and 7 is not detectable — and power recommendation assume a 10-inch f/5 telescope. Distances (means) are also noted. The image area lower right of NGC 3953 is damaged. North is up in all images.


NGC 4236
Diff. = 3 | P = 35× | Dist. = 11 Ml-y

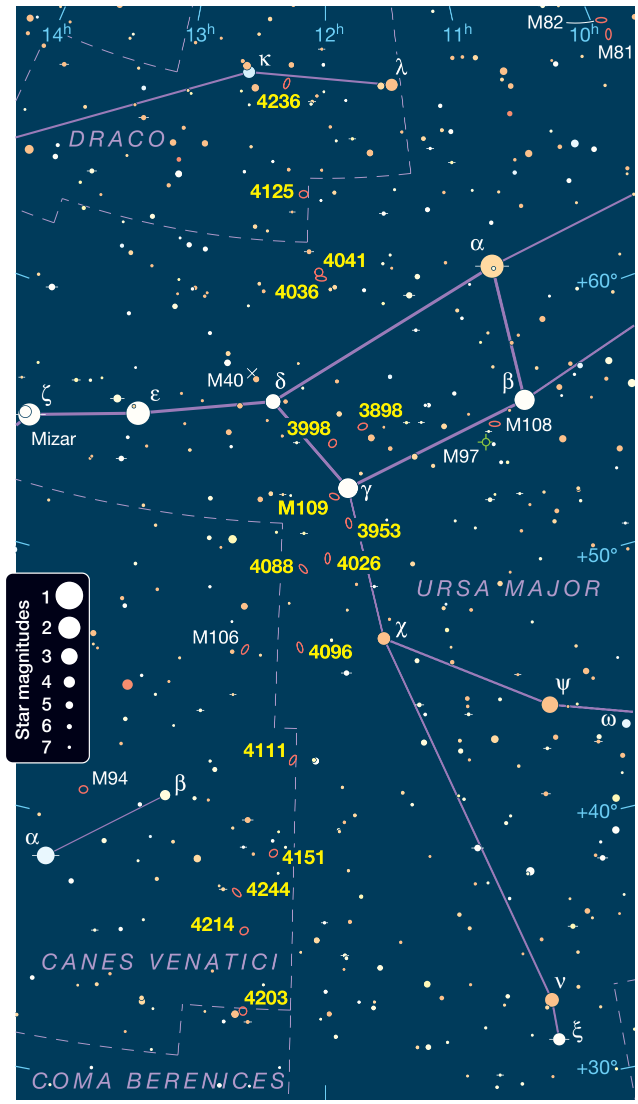
NGC 4125
Diff. = 3 | P = 35× | Dist. = 74 Ml-y

round lenticular galaxy with a much brighter core that harbors a supermassive black hole. Radio observations revealed a one-sided jet emanating from the galaxy. Two different studies that measured the mass of the central black hole yielded significantly different results: 810 million solar masses vs. 270 million solar masses. The larger mass is inferred from the motions of stars in the core and the lesser by the motion of gas clouds. Reconciling these disparate results may lead astronomers to a much better understanding of the relationship between the formation of black holes and the galaxies within which they reside, making this object one of several important laboratories for studying galaxy formation.

A little less than 1.5° to the northwest, **NGC 3898** dominates another group of five galaxies, making this stop along our tour worthy of an extended stay. NGC 3898 is also large and bright with an almost stellar core in an oval envelope. A spiral, it's another example of a LINER galaxy.

Heading back to NGC 3998 we find the only Messier object along our path is a little more than 2° south of it. **M109** (also cataloged as NGC 3992) is one of the objects that was added to the Messier catalog in the century after its publication. It has an interesting discovery history. Charles Messier's friend and colleague, Pierre Méchain, is usually listed as the discoverer of this beautiful barred spiral. But some researchers maintain that Méchain's March 1781 observation was possibly of NGC 3953, and so the discovery of M109 might indeed belong to Messier himself. William Herschel independently discovered the object on April 12, 1789, and it's therefore included in the Astronomical League's Herschel 400 Observing Program as a "Herschel object."

Easily found some 38′ southeast of Gamma (γ) Ursae Majoris (Phad), M109 is a stunning example of an open-faced barred spiral. Its mottled outer halo gives just a hint of spiral structure. Closer to the core, a stubby bar ends in



ALL GALAXY IMAGES: POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY

NGC 4036
Diff. = 3 | P = 70× | Dist. = 70 Ml-y

NGC 4041
Diff. = 3 | P = 60× | Dist. = 102 Ml-y

NGC 3998
Diff. = 2 | P = 60× | Dist. = 65 Ml-y

NGC 3898
Diff. = 2 | P = 70× | Dist. = 72 Ml-y

two curved extensions: the origins of spiral arms that quickly dissolve into the dusty halo and are lost. With a comparison photo in hand and a liberal splash of imagination, one can almost trace the arms through the glow of the extended halo. Averted vision greatly enlarges the extent of its visible outer reaches. A bright star superposed just to the north of the nucleus has no doubt caused many a would-be supernova discoverer a momentary rush of excitement.

M109 is the brightest in a group of galaxies named after it (the M109 Group, also known as the Ursa Major Cloud) and forms a pair with faint UGC 6923 lying 15′ to the southwest. About 1° farther to the southwest is **NGC 3953**, a barred spiral LINER, which is quite possibly the object Méchain discovered — hence the confusion regarding the pedigree of M109. NGC 3953 is bright and large with a brighter middle that concentrates into a stellar core. It's quite a fine object in its own right, and more than a few observers have suggested that it should share the M109 moniker and henceforth be called M109B (along with M109A, the original M109). History records that Herschel discovered NGC 3953 on the same night as M109. But if this was indeed the object Méchain saw in 1781, then the distinction should perhaps go to him.

NGC 4026 is the next object in our cascade. Also belonging to the M109 Group, this bright spindle-shaped lenticular has a bulging middle that gives it a lenslike appearance along a nearly north-south line. Larger scopes will show fainter extensions on both ends of the brighter central region. It's known to harbor a black hole that may weigh in at 200 million solar masses.

NGC 4026 straddles the 12-hour center line opposite **NGC 4088**, which forms a wide pair with 13th-magnitude NGC 4085, some 11′ almost due south. NGC 4088 is a remarkable corkscrew-shaped spiral with a bright core and faint spiral arms. Dense clumpy knots in both tightly wound arms help to trace its squashed S-shape. A supernova in the spring of 2009 (the Type II SN 2009dd) manifested itself as a tiny 14th-magnitude pinpoint southwest of the core of this galaxy and provided me with a memorable experience at a star party. Pointing my 18-inch telescope at NGC 4088, I shared the view with some novice observers who were treated to their first-ever view of an exploding star in a distant galaxy. The excitement and awe that this transient event elicited was infectious, and before long a crowd of observers had queued up. For many, it was the first time that they had ever had the opportunity to trace the spiral arms of a faint galaxy in a large aperture scope. I will forever associate NGC 4088 with that fondly remembered event.

Pointing my 18-inch telescope at NGC 4088, I shared the view with some novice observers who were treated to their first-ever view of an exploding star in a distant galaxy.

NGC 4088
Diff. = 3 | P = 65× | Dist. = 45 Ml-y

NGC 4096
Diff. = 3 | P = 85× | Dist. = 38 Ml-y

NGC 4111
Diff. = 2 | P = 100× | Dist. = 42 Ml-y

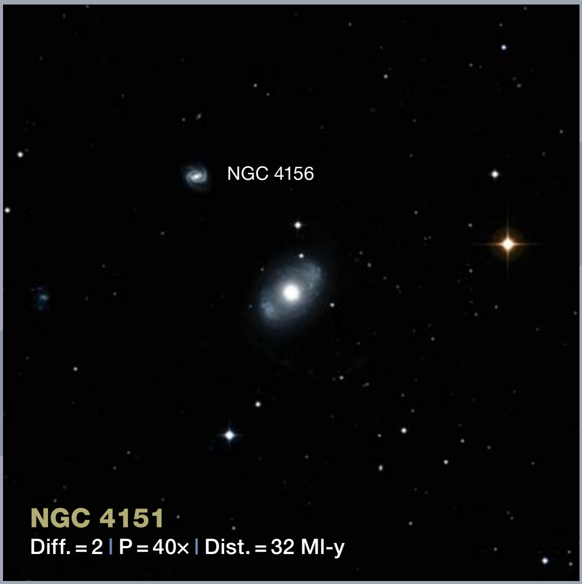
Our last stop in Ursa Major is **NGC 4096**, a member of a galaxy group dominated by M106, which lies a little more than 2° to the east. A nearly edge-on spiral, it's dusty and somewhat asymmetrical. The core, if you can call it that, is off-center toward the northern end of the elongated streak, and its western edge seems a bit detached at the southern end.

Sliding Down into the Hunting Dogs

NGC 4111 lies about 4.5° south of NGC 4096, across the border in Canes Venatici. It's the brightest in a group of galaxies that includes 14th-magnitude NGC 4109 and 13th-magnitude NGC 4117. A very attractive edge-on spiral (and a LINER) with a bright stellar core, it's in the same field with a pretty double star comprising 8th- and 12th-magnitude components. The bright core of this galaxy makes it detectable in as little as a 60-mm scope, and it can be fully enjoyed in an 8-inch scope. A knot at the southern end of the galaxy might be a faint star.

Around 3.7°, or about one finder field, south-southeast of NGC 4111 is the Seyfert galaxy **NGC 4151**. This bright open-faced spiral is paired with 14th-magnitude NGC 4156. NGC 4151 is one of the closest galaxies known to harbor an active supermassive black hole, and some speculate that it might even host a binary black hole. It also exhibits the brightest X-ray emission among Seyferts. The X-rays are produced either in a hot plasma cloud surrounding the accretion disk or in the base of a jet of outflowing matter. The galaxy's somewhat odd appearance has earned it the moniker the Eye of Sauron (from *The Lord of the Rings*). Its bright, round core looks to be surrounded by a darker ring bounded by two brighter patches to the northwest and southeast.

Perhaps the most impressive edge-on spiral in the cascade is **NGC 4244**, the Silver Needle. As its nickname implies, this slender streak shows very little central bulging. At more than



NGC 4151
Diff. = 2 | P = 40× | Dist. = 32 Ml-y

NGC 4244
Diff. = 3 | P = 35× | Dist. = 13 Ml-y

NGC 4214
Diff. = 2 | P = 35× | Dist. = 10 Ml-y

NGC 4203
Diff. = 3 | P = 85× | Dist. = 61 Ml-y

16′ in length, it's a popular "showpiece" for good reason. NGC 4244's elongated center is bright, but not uniformly so, with bright patches at both ends. The galaxy is dusty and mottled-looking with a hint of a central dust lane. Faint stars dot both ends of the extended halo.

NGC 4244 is about 13 million light-years distant and the largest member of the Canes Venatici I Cloud, a nearby, loose group of galaxies. The edge-on orientation of galaxies like NGC 4244 enables astronomers to accurately measure their rotation curves, and NGC 4244 in particular has been extensively studied in an effort to determine the shape and distribution of the dark matter envelope in which it's embedded.

Just 1.5° south is another member of the CVn I Cloud, **NGC 4214**, which is also considered to be part of the M94 Group of galaxies. Originally discovered by William Herschel on April 28, 1785, a later observation by his son, John, included an error in right ascension, and so it was recorded as a new object. John Louis Emil Dreyer then cataloged this duplicated object as NGC 4228 in his *New General Catalogue of Nebulae and Clusters of Stars*. Today, it's generally recognized that NGC 4214 and NGC 4228 are one and the same object.

NGC 4214 is a dwarf starburst galaxy, and at about 10 million light-years away, it's the closest galaxy on our tour. A starburst galaxy, as you might guess, is one with unusually high rates of star formation, perhaps resulting from a past merger or collision with another galaxy. It's fairly large with a bright but not very concentrated core. Mostly round, it's also a bit irregular and mottled. A faint star is seen to the northwest of the core, and the southeastern segment has a brighter knot that might also be a star.

Concluding in Coma Berenices

We will call an end to this imaginary cascade in Coma Berenices with **NGC 4203**: a bright, nearly round lenticular (and a LINER) that appears almost stellar. The mass of the central black hole has been measured at nearly 80 million Suns. The distribution of neutral hydrogen in the outer reaches of this galaxy betrays either a long-ago encounter with another galaxy or accretion from the intergalactic medium. NGC 4203 is visible in as little as a 60-mm scope and is a fine target for a 10-inch. It lies about 3′ almost due south of an 8th-magnitude star.

NGC 4203 is part of the Coma I Group. Beyond it, just a short hop southeast, you'll find yourself on the threshold of the *realm of the galaxies*: the remarkable dominion of countless "island universes" that populate Virgo and Coma Berenices. I can think of no better place to deposit a deep-sky observer.

■ Contributing Editor **TED FORTE** enjoys galaxy-hopping from his backyard observatory near Sierra Vista, Arizona. He finds sharing interesting deep-sky objects with the public to be a most fulfilling pastime.

A Waterfall of Galaxies

Object	Constellation	Surface Brightness	Mag(v)	Size/Sep	PA	RA	Dec.
NGC 4236	Dra	15.0	9.6	21.9′ × 7.2′	162	12^h 16.7^m	+69° 28′
NGC 4125	Dra	12.9	9.7	5.8′ × 3.2′	81	12^h 08.1^m	+65° 10′
NGC 4036	UMa	12.7	10.7	4.3′ × 1.7′	85	12^h 01.5^m	+61° 54′
NGC 4041	UMa	13.2	11.3	2.7′ × 2.5′	72	12^h 02.2^m	+62° 08′
NGC 3998	UMa	12.5	10.7	2.7′ × 2.2′	140	11^h 57.9^m	+55° 27′
NGC 3898	UMa	13.2	10.7	4.4′ × 2.6′	107	11^h 49.3^m	+56° 05′
M109	UMa	13.5	9.8	7.6′ × 4.6′	68	11^h 57.6^m	+53° 22′
NGC 3953	UMa	13.4	10.1	6.9′ × 3.5′	13	11^h 53.8^m	+52° 19′
NGC 4026	UMa	12.7	10.8	5.2′ × 1.3′	178	11^h 59.4^m	+50° 58′
NGC 4088	UMa	13.2	10.6	5.8′ × 2.2′	43	12^h 05.6^m	+50° 32′
NGC 4096	UMa	13.4	10.9	6.6′ × 1.8′	20	12^h 06.0^m	+47° 29′
NGC 4111	CVn	12.3	10.7	4.6′ × 1.0′	150	12^h 07.0^m	+43° 04′
NGC 4151	CVn	14.3	10.8	6.3′ × 4.5′	146	12^h 10.5^m	+39° 24′
NGC 4244	CVn	14.0	10.4	16.6′ × 1.9′	48	12^h 17.5^m	+37° 48′
NGC 4214	CVn	13.9	9.8	8.0′ × 6.6′	144	12^h 15.6^m	+36° 20′
NGC 4203	Com	13.3	10.9	3.4′ × 3.2′	10	12^h 15.1^m	+33° 12′

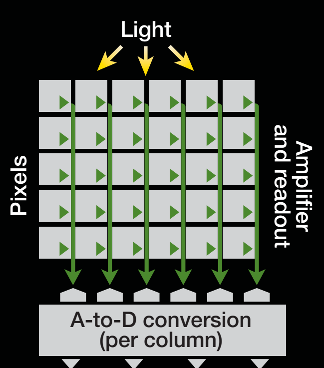
Angular sizes are from recent catalogs. Visually, an object's size is often smaller than the cataloged value and varies according to the aperture and magnification of the viewing instrument. Right ascension and declination are for equinox 2000.0. Data are only given for the primary targets in the images.

Changing of the Guard

CMOS is set to become the dominant scientific-imaging medium — but is it up to the task?

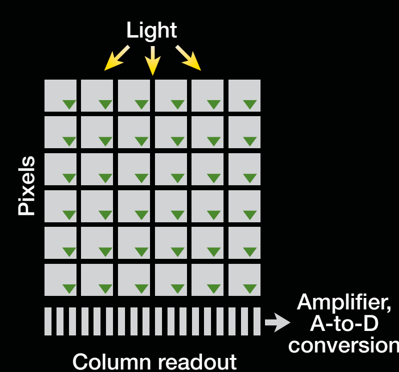
It wasn't that long ago that photography went through the major transition from chemical film-based emulsion to digital cameras. I remember well an editor of a computer magazine who would regularly pontificate about how ridiculous it was that anyone thought digital cameras would ever match the quality of film. He'd quote numbers that compared the sizes of pixels to film grains, highlighting the various shortcomings of digital cameras at the time, and to some degree he was right. What he didn't foresee is how quickly these shortcomings would be overcome. This is a cautionary tale, of course, to anyone watching the current transition from CCD-based image sensors to CMOS, a transition that's in full bloom for the astronomical imaging community.

Every technological advancement experiences growing pains, and the current transition in digital imaging from CCD to CMOS technology is no exception. Both charge-coupled devices (CCDs), and complementary metal oxide semiconductors (CMOS) sensors work on the same basic principles of physics. Specially treated silicon is laid out in a rectangular or square grid of "pixels." When light hits



▲ **HARD TO TELL** It's virtually impossible to see the difference between a CCD and CMOS camera. At left is a ZWO ASI071 CMOS camera, while the camera at right is a Starlight Xpress Trius 26C CCD.

◀▶ **UNDER THE HOOD** Although CCD and CMOS detectors function in largely the same way, one important difference is how they read out signal. A CCD (right) moves electrons (green arrows) off the detector in rows. The electrons are then sent off-chip to the amplifier and analog-to-digital converter. By contrast, the CMOS detector (left) has an amplifier behind every pixel and an A-to-D converter for each column.



ALL PHOTOS COURTESY OF THE AUTHOR UNLESS OTHERWISE NOTED; CHIP READOUTS: LEAH TISCIONE / S&T

one of these pixels, it receives a small electrical charge. The more light, the higher the charge. At the end of an exposure the pixels are read out, and each pixel is assigned a numeric value that increases with the amount of charge collected. This produces a two-dimensional record of the various light intensities across a plane in a format that a computer can display as an image. In this way (and only this way), both CCD and CMOS are essentially doing the exact same thing.

The Other Shoe Drops

The vast majority of image sensors used in our astronomical cameras are made by only two vendors, On Semiconductor (originally Kodak), and Sony. These two companies make the sensors used in many industries besides astronomy. In fact, astronomy is a tiny niche market for these manufacturers — automated manufacturing, security, and traffic monitoring are all multi-billion-dollar industries by themselves (some modern automobiles have as many as 20 image sensors!). The largest demand for imaging sensors is, of course, cellphones. One recent report stated that there would be over 6 billion cell phones in operation in 2020, with a market worth at least $335 billion. Astronomy is only a flea on the back of a very large cash cow.

In a surprise move late last year, On Semiconductor announced it is suspending production this year at its only remaining plant capable of making CCD sensors. The former Kodak CCD facility in Rochester, NY, will then cease operations in June 2020. Only a few years ago, Sony announced the discontinuation of CCD sensors but extended the life of its current chip offerings up until 2025. And while Sony is continuing to produce CCDs, it's no longer developing any new chip designs.

CMOS is the future of digital imaging, but why? Although both technologies do essentially the same thing with pixels and photons, the similarities end there. For starters, manufacturing technology for semiconductors has improved to the point where it's easy to integrate more circuitry onboard the image sensor. More of the supporting electronics can be bundled right on the same chip, making CMOS sensors much more flexible in terms of electronic design and capabilities. This extra integration makes the surrounding electronics design simpler as well, and more room for gates (the fundamental building blocks of integrated circuits) allows for a tremendous increase in readout speed. CMOS sensors are also smaller and consume far less power than CCDs — fewer supporting electronic components means smaller packaging.

◀ **PRETTY PICTURES** CMOS astronomical and DSLR cameras are perfectly capable of producing gorgeous deep-sky images. This image of M45, the Pleiades, was recorded with a CMOS-based modified Canon EOS 5D DLSR camera and Officina Stellare Veloce 200.

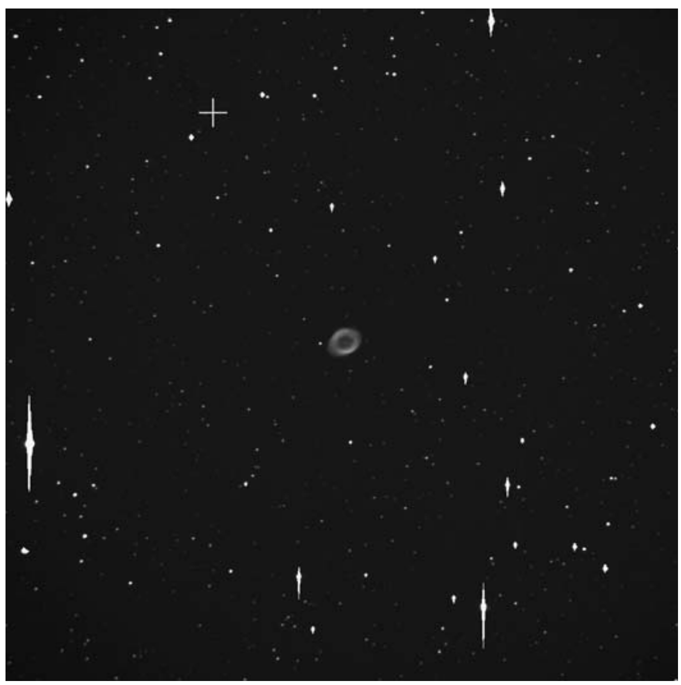
All these differences contribute to a manufacturing process for CMOS technologies that costs much less than it does to make CCDs.

So, CMOS is smaller, costs less to make, works faster, and consumes less power — a paramount factor for today's battery-driven world. With these kinds of advantages, you might well wonder why we are bothering with CCDs at all anymore. You would not be the only one.

The Road Ahead

Although CCD technology is older, it has some advantages over CMOS-based cameras when it comes to low-light photography. These advantages are shrinking quickly, though, and one industry insider recently stated that even Sony was surprised with how quickly the security-camera market abandoned CCDs in favor of their newer CMOS offerings.

One way that CMOS is already completely on a par with CCDs is in Quantum Efficiency. QE is a measure of how efficient a sensor's pixels are at converting individual photons into electrical charge. A sensor that registers half the light



▶ **SIGNAL OVERFLOW** CCD detectors used for astronomical research are almost without exception linear detectors, meaning they record light in a predictable, linear manner. Linear detectors often display "blooming spikes." Such overflow of signal from saturated pixels can be seen in this exposure of M57, the Ring Nebula, in Lyra.

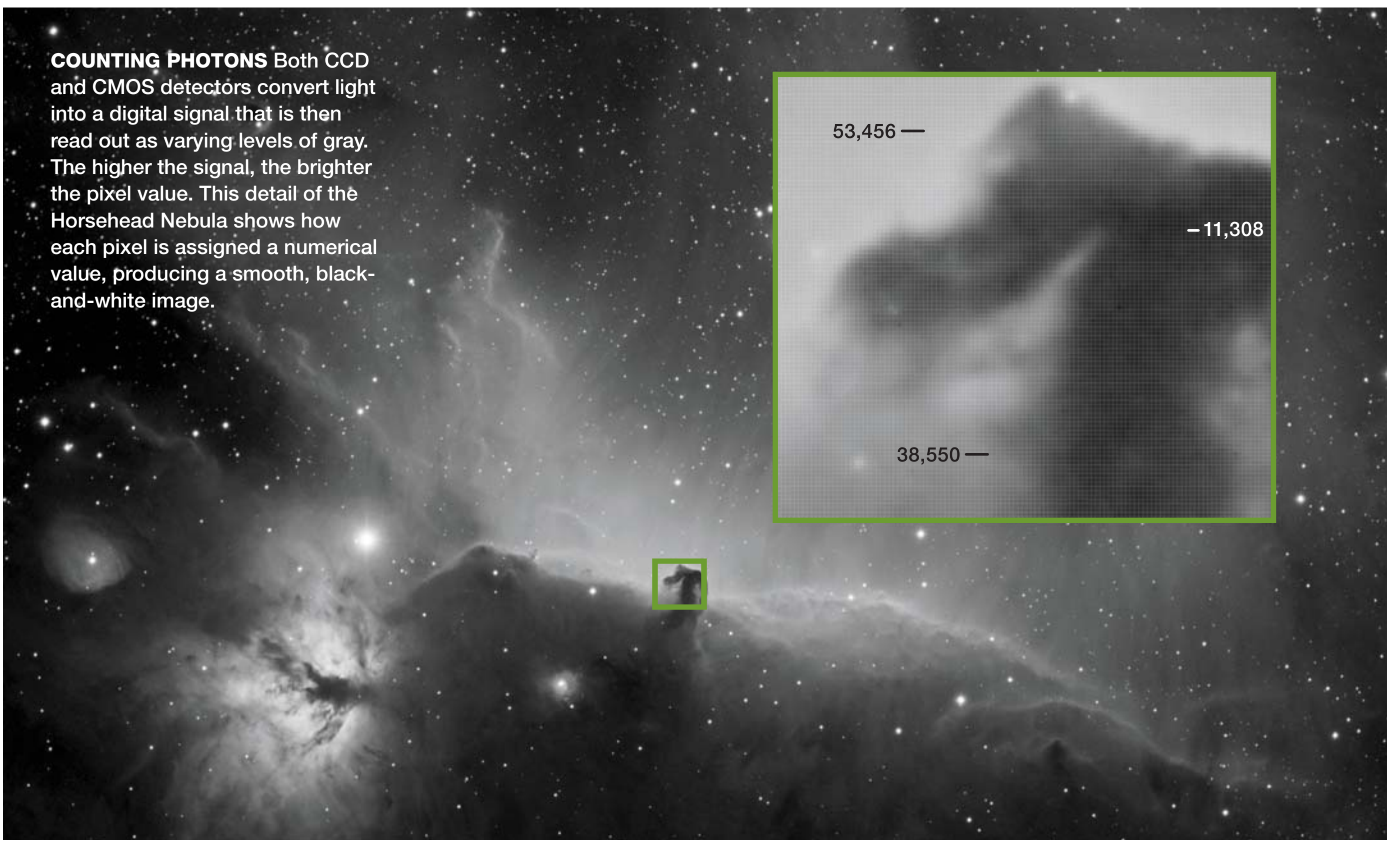
falling on it has a QE of 50%, while one that records ¾ of the light has 75% QE. The higher the QE, the better the sensor is for low-light applications. Early CMOS sensors had relatively poor QE compared to CCDs at the wavelengths astronomers are interested in and were generally poor choices for any kind of low-light imaging. Today, the top CCD and CMOS sensors are now flirting with QE's in the 90% range, meaning that there is no inherent QE advantage to either technology.

◀ **ALREADY BEST** CMOS detectors are vastly superior to CCD technology when it comes to readout speed. CMOS active-pixel designs are inherently useful for the "lucky imaging" technique of planetary astrophotography, in which hundreds of frames per second are recorded to capture the sharpest frames during the best moments of steady seeing. This detailed image of Mars was captured with a ZWO ASI120MM CMOS planetary camera and 12.5-inch Newtonian reflector recording 133 frames per second.

Another technical limitation of CMOS that has vanished in recent years is *read noise*. Read noise is a slight random fluctuation in data values that occurs as an image is read off a detector. Both CCD and CMOS started life with very poor read-noise performance, and CCDs were well ahead of CMOS for many years. Today, CMOS read-noise performance has caught up with and even surpassed most CCD designs. This tiny bit of noise has a very big impact on low-light applications in which the faintest signal is being sought, and so it's no small consideration for the astronomical market.

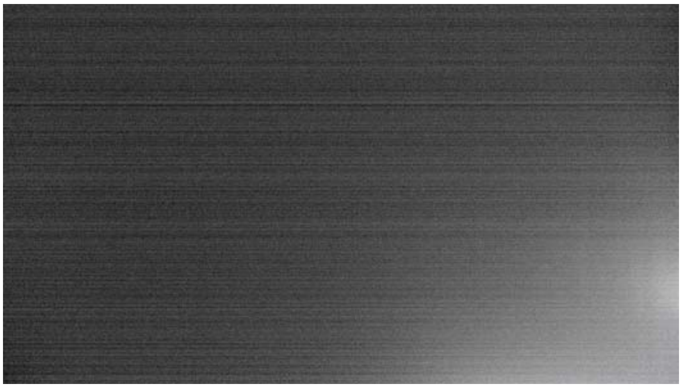
One weakness for low-light imaging with CMOS that is seeing rapid improvement is *amp glow*. A CCD detector requires an output amplifier in its supporting electronics that is part of the analog-to-digital conversion necessary to convert the collected photons to a digital signal. CMOS incorporates a single amplifier behind every pixel, meaning there are millions of amplifiers on every CMOS detector. It turns out that all those extra integrated electronics get warm and produce a lot more heat when the sensor is in operation. This heat shows up as a glowing pattern radiating out from the edges of the chip during long exposures — amp glow. Subtracting a dark frame during calibration can mitigate this, as it does with CCD calibration to some degree. But it is not 100% repeatable with CMOS images, and dark-frame subtraction will often leave some residual thermal signal that must be removed manually during post-processing. In addition, this accumulated thermal signal robs the chip of its ability to detect extremely faint objects, because these pixels are filling up too fast with polluted signal and noise.

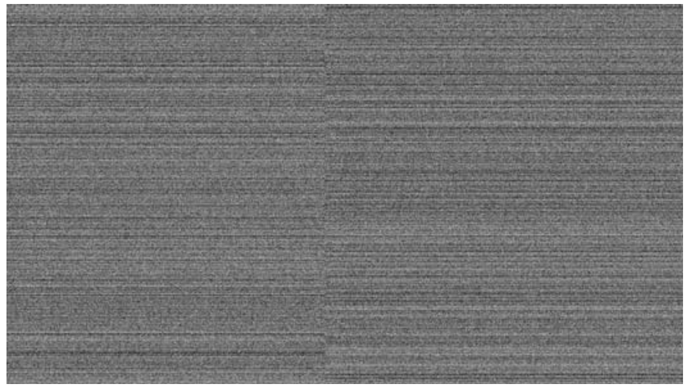
Amp glow is strong even in some very recent CMOS



COUNTING PHOTONS Both CCD and CMOS detectors convert light into a digital signal that is then read out as varying levels of gray. The higher the signal, the brighter the pixel value. This detail of the Horsehead Nebula shows how each pixel is assigned a numerical value, producing a smooth, black-and-white image.

MARS: SEAN WALKER / *S&T*





▲ *Left:* Problems with CMOS sensors only become apparent during long exposures. This dark frame is stretched to display the amplifier glow at bottom right. *Right:* Another problem with CMOS detectors used for scientific imaging is that they produce non-repeating fixed-pattern noise. Note how the dark pattern noise has shifted between frames. High-quality and newer CMOS cameras are doing much better at reducing this issue to near-imperceptible levels.

designs, but many newer sensors exhibit amp glow that is quite low, and some camera vendors are doing "tricks" with the electronics to keep it to a minimum. One scientist who is searching for ultra-faint targets tells me there is currently no CMOS sensor on the market that performs adequately for his very exacting work. I'll have to check in with him again in five years and see if this is still the case.

The last significant issue that CMOS has yet to overcome is the non-linear sensitivity to light. When we talk about linearity of a sensor, we are talking about the ratio of the signal recorded to the signal that was received. If you dump in twice the amount of light, you should get twice the amount of signal. CCDs that are intended for scientific use are 100% linear (non-antiblooming), so that when the signal is so high that they saturate, they spill the excess charge into adjacent pixels, called blooming spikes. Many CCD detectors used for astrophotography include an anti-blooming gate to redirect overflow charge and lose their linearity only at the upper end of their exposure range. CMOS sensors, on the other hand, are non-linear throughout much of their range. This varies from sensor to sensor. How this affects astronomy is that flat-field calibration, which corrects for pixel-to-pixel sensitivity differences, among other things, does not always work well with CMOS sensors; the math just doesn't work. Also, if your intended use is photometry (accurately measuring the brightness of a target), your calculated values may be suspect. They are likely close, but not as rigorous as if determined from a truly linear sensor.

If your goal is simply aesthetic astrophotography, sensor non-linearity is often negligible or can be mitigated in post-processing. Often, it's very slight (CMOS is still far superior to film). Of course, it requires more work than having a properly calibrated image in the first place, but it's not a show-stopper. I've seen some academic work recently in which this is the subject of intense research, and I wouldn't be surprised if technological advancements solve this problem within a generation or two.

Finally, another commonly discussed issue with CMOS sensors is *fixed-pattern noise*. Both CCD and CMOS sensors have fixed-pattern noise, often noticeable during longer exposure shots when particular pixels are susceptible to giving brighter intensities above the general background noise. This is easily removed by calibration with a bias or dark frame on a CCD sensor. With some CMOS cameras, the pattern noise often varies from frame to frame, and since it's not repeatable, it can't be simply subtracted. However, a lot of this pattern noise has more to do with the surrounding electronics implementation than it does with the sensor itself, and camera vendors are gaining more experience in taming this beast for our market. For example, the issue is already a nonfactor for most commercial DSLR cameras, as well as the latest generation of cell phones capable of low-light imaging.

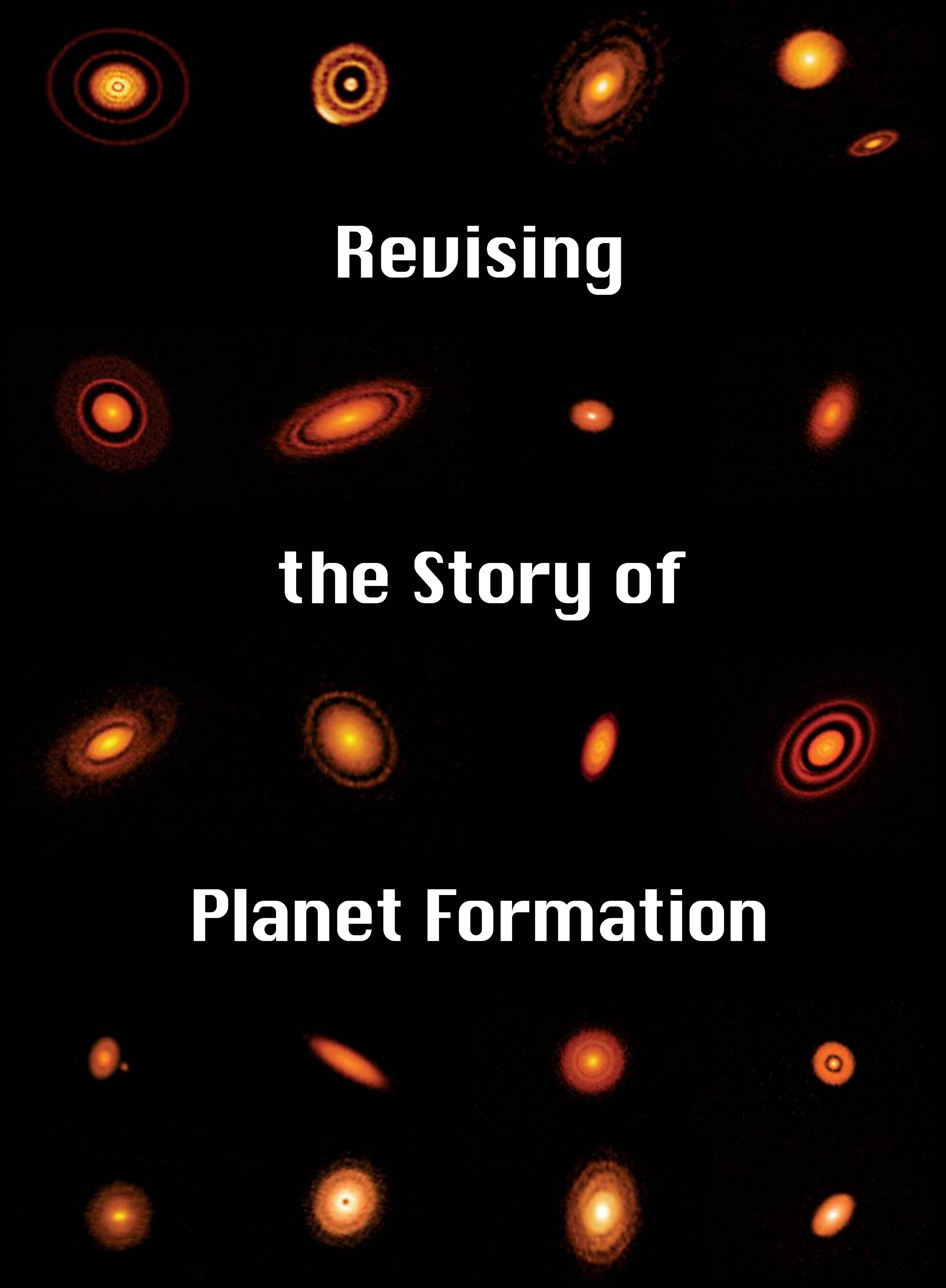
Onward into the Future

Technological progress is often fraught with growing pains, false starts, and compromises. There are still and possibly always will be some applications where CCD-imaging technology works best, such as in space where radiation hazards are very harsh on delicate electronics. To be sure, there will be manufacturers willing to meet that need for a price. For those of us on Earth without government-sized budgets, the juggernaut of CMOS is well beyond critical mass now. Clearly, the Sun is setting on CCDs for amateur astronomers and most ground-based imaging applications.

But I wouldn't be in a hurry to toss out your old CCD cameras. The current generation of CCD cameras is going to be available for a few more years yet, and it will offer some important advantages for the discerning imager. While CMOS sensors are still not quite up to the challenge of many kinds of scientific imaging, we can say confidently that they are getting very large in the rear-view mirror.

■ **RICHARD S. WRIGHT, JR.** is a software developer by day and an avid astrophotographer by night.

Revising the Story of Planet Formation



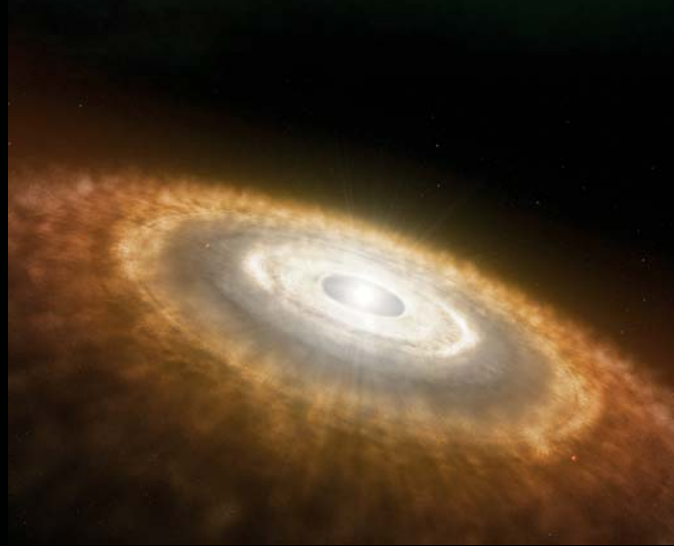
ALMA (ESO / NAOJ / NRAO), S. ANDREWS ET AL., NRAO / AUI / NSF, S. DAGNELLO

New technology has given astronomers access to the dusty regions where planets are born — and has complicated our picture of planet formation.

The question of how planetary systems form, and how those processes relate to what we see in our own solar system, is one of the most fundamental problems in astrophysics and a key piece in the puzzle of figuring out our place in the universe. With the recent success of exoplanet-hunting missions such as Kepler, we sometimes take for granted that, just a few decades ago, we were unsure whether worlds outside our solar system even existed. At that time, astronomers used the single known planetary system — our own — to shape our understanding of planet formation.

Our solar system features an orderly setup, with all the planets moving together in a nice flat plane and with plenty of space between orbits. There is also a dichotomy between the inner rocky planets (Mercury, Venus, Earth, Mars) and the outer gas and ice giants (Jupiter, Saturn, Uranus, Neptune). Based on this, we concluded that small, terrestrial worlds will always huddle close to their stars, whereas large, gaseous worlds will invariably circle farther out. The processes of planet formation must be tuned to create this setup, we thought.

But we now know that a model based only on our solar system is misleading. From systems where planets orbit two stars instead of just one (Kepler-16b) to those with Jupiter-mass planets on orbits of just a few days (Kepler-435b), our observations since the first exoplanet discoveries in the mid-1990s have continuously surprised us with a puzzling diversity of system architectures. Our solar system is not the blueprint we once assumed it was.



▲ **PLANET NURSERY** This artist's impression shows a young star surrounded by a disk of dust and gas, within which planets are coalescing. Astronomers can now take images of such disks around many young stars in our galaxy.

To understand how planets form, we cannot depend on our solar system alone to guide us. Instead, astronomers go back in time by observing planet formation in action around other stars much younger than our Sun. But even there, with few exceptions, we cannot directly observe forming planets: The light they emit is far too faint compared to that from their host star and the bright disks of dust and gas from which they are coalescing. So as an alternative, astronomers search for indirect signatures of forming planets in these protoplanetary disks.

Similar to exoplanets, observations of protoplanetary disks have experienced a boom in recent years as new state-of-the-art observatories have come online. While the details are still being worked out, it is becoming increasingly clear that the diversity of exoplanets is likely rooted in the diversity of the protoplanetary disks from which they came.

A Traditional Take on Planet Formation

The orderly setup of our solar system led scholars in the 1700s such as Kant and Laplace to conclude that planets likely form in flattened disks around young stars. These aptly named *protoplanetary disks* are natural consequences of the star-formation process, created due to the conservation of angular momentum as large molecular clouds of gas and dust collapse to form protostars.

◀ **DSHARP** Astronomers used ALMA to image the dust in these protoplanetary disks as part of the Disk Substructures at High Angular Resolution Project (DSHARP). Gaps and rings are common and may indicate ongoing planet formation. AS 205 (top right) and HT Lup (fourth row, far left) are both multiple-star systems, with each star sporting its own dusty disk.

▼ **DARK BIRTH** Protoplanetary disks appear dark in these Hubble images, silhouetted by light from brilliant starbirth in the Orion Nebula.

NATAL STAR: ESO / L. CALÇADA; HUBBLE IMAGES: MARK MCCAUGHREAN (MAX-PLANCK-INSTITUTE FOR ASTRONOMY) / C. ROBERT O'DELL (RICE UNIVERSITY) / NASA

By the end of the 1900s, the generally accepted theory was that the dust grains orbiting in these disks would collide, stick together, and build up into rocky bodies known as *planetesimals*, eventually growing into planet cores. The planet cores that grew quickly enough and were sufficiently massive to grab gas from what remained of the surrounding disk would become giant planets like Jupiter and Saturn; those with less mass would remain as smaller, rocky worlds like Earth.

In this picture, the split between the small inner and giant outer planets in our solar system could be naturally explained by the fact that the outer regions of protoplanetary disks should contain more planet-building material, and also that this material should more easily coagulate. That's because these outer regions are much colder due to their larger distances from their host stars, and so their dust grains are icy and thus more likely to stick together when they collide. (Think of how easy it is to pack snow into a ball compared to dry dirt or pebbles.) The extra stickiness accelerates the growth of dust grains into large planetary cores that can quickly accrete the surrounding gas to become giant planets.

Although we have since uncovered some roadblocks in this theory's specifics, the overarching picture holds: Planets are assembled in disks of gas and dust surrounding young stars that form as a natural consequence of the star formation process. Indeed, we see these protoplanetary disks around nearly all young stars in nearby star-forming regions, just as nearly all mature stars in our galaxy likely host at least one exoplanet.

However, as our observations of protoplanetary disks improve, we are finding that, as with exoplanets, the disks exhibit a surprising diversity that has challenged key parts of our traditional theories of planet formation.

We see these protoplanetary disks around nearly all young stars in nearby star-forming regions, just as nearly all mature stars in our galaxy likely host at least one exoplanet.

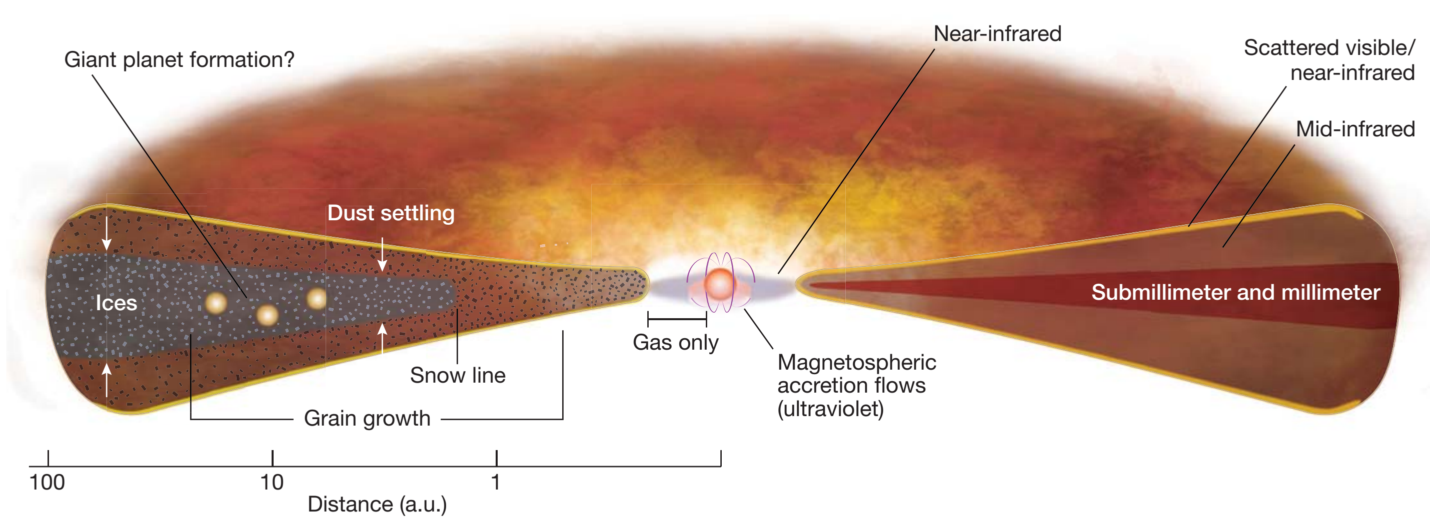
A Better View

In recent years two facilities in particular, the Atacama Large Millimeter/submillimeter Array (ALMA) and the Spectro-Polarimetric High-contrast Exoplanet Research (SPHERE) instrument, have been providing the most detailed views of protoplanetary disks that we have ever seen. These two facilities take very different observations, but the data sets complement each other to improve our understanding of planet formation.

ALMA is what we call an interferometer, consisting of more than 60 antennas spread up to 16 km across the Atacama Desert in Chile. These individual dishes work together to act as a single, much larger telescope to obtain sensitive, high-resolution images at radio wavelengths. In contrast, SPHERE is an extreme adaptive optics system used with one of the four 8.2-m Very Large Telescope (VLT) mirrors located on Chile's Cerro Paranal. This instrument produces high-resolution and high-contrast images at optical and near-infrared wavelengths.

SPHERE is tuned to detect the starlight that scatters off small, micron-size dust grains near the surfaces of protoplanetary disks. These dust grains are comparable in size to smoke particles, and like smoke they float easily, interspersed in the disk's gas. This behavior makes them good tracers of where the

▼ **DISK COMPOSITION** In the center of a protoplanetary disk, starlight sublimates dust, leaving a gas-filled hole around the star. This gas accretes onto the star. Farther out, the dust coagulates and settles toward the disk midplane. Beyond the snow lines, ices make grains stickier, fostering giant planet growth. Different wavelengths probe different parts of the disk. Distances are approximate.



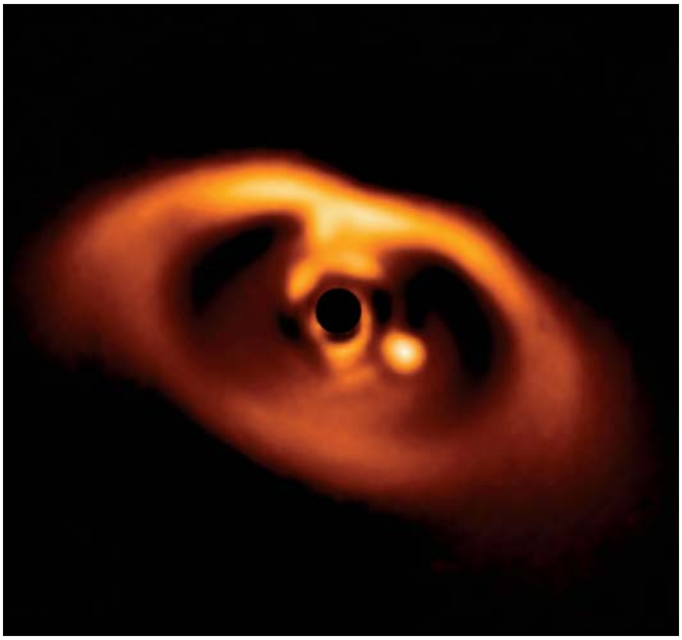
GREGG DINDERMAN / S&T

gas lies, which is useful since it's often much harder to observe the gas than the dust grains due to gas's weaker emission.

ALMA's longer radio wavelengths, on the other hand, are best suited for probing the glow radiating from larger, pebble-size solids heated by the starlight. These pebbles contain most of the mass that will eventually form planets. As they grow, they settle toward the midplane of the disk, which means that ALMA can see below the surface of the disk to detect what's happening inside it. ALMA can also directly observe the gas by measuring the faint emission from simple molecules such as carbon monoxide.

ALMA can resolve structures as small as 5 astronomical units across in protoplanetary disks located in the nearest star-forming regions — a 10-fold improvement over the previous generation of radio observatories. With ALMA's higher resolution, we now see that these disks are not smooth like frisbees but rather often have multiple concentric gaps and rings in their dust distributions. We think growing planets may create at least some of these structures as they carve their way through the dust that lies along their orbit. We can use detailed computer simulations to infer the masses of the planets based on the properties of the disk features.

In addition to these prolific concentric gaps and rings, ALMA has also revealed vortices, spiral arms, and large inner cavities in the dust distribution — all of which can also be explained by planets with a variety of sizes and orbits. However, actually observing these forming planets has proven extremely difficult. SPHERE has detected only one convincing case, PDS 70b. (Astronomers also recently discovered a second potential planet with another VLT instrument, using a technique that looks for effects the planet may have on the motions of gas in the disk.)



▲ **IN THE GAP** PDS 70b is the only system so far in which SPHERE has imaged a planet orbiting within an opening in the protoplanetary disk. Using gas motions, astronomers have found signs of a potential second planet, c (not shown).

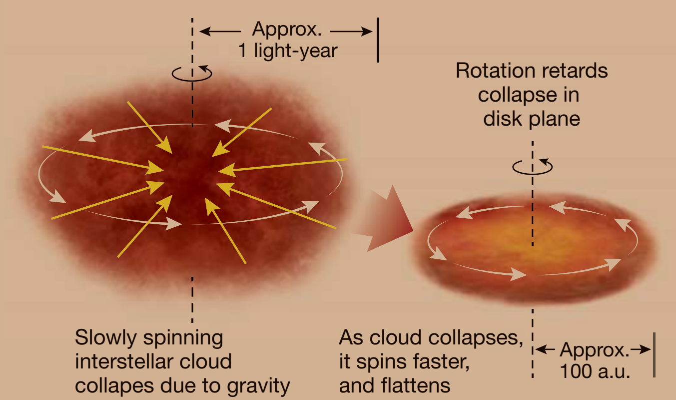
Indeed, the structures in protoplanetary disks may not be due solely to planets; other processes could also create similar patterns. In fact, the gaps and rings in the dust distribution could actually help the planets form by solving the *radial drift problem*. Pebbles should feel a stronger headwind from surrounding gas as they grow, making them fall rapidly into the central star and depleting the reservoir of planet-forming

How Protoplanetary Disks Form

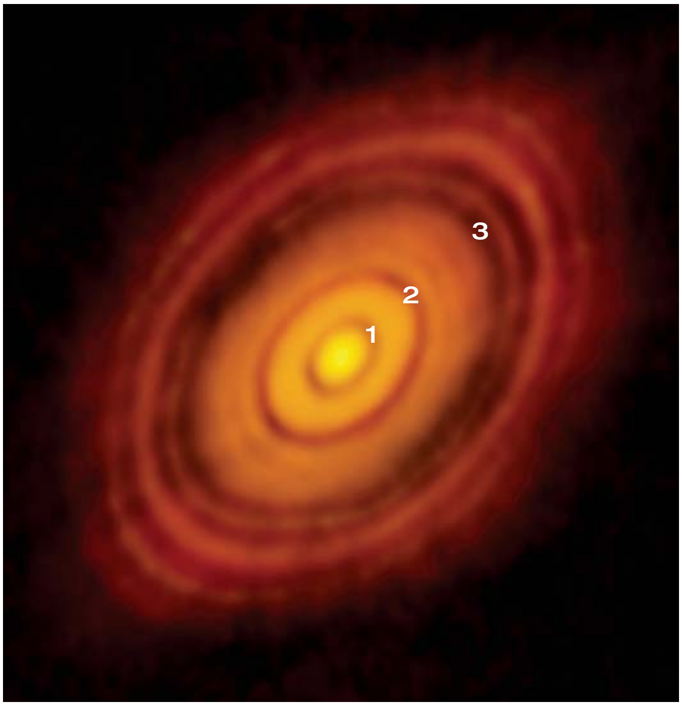
Stars form when large molecular clouds of gas and dust in interstellar space collapse under their own gravity. These large clouds contain many particles that move in random ways. But they will always have an overall "spin" to their collective motion, as it is difficult for all the particle motions to exactly cancel each other out.

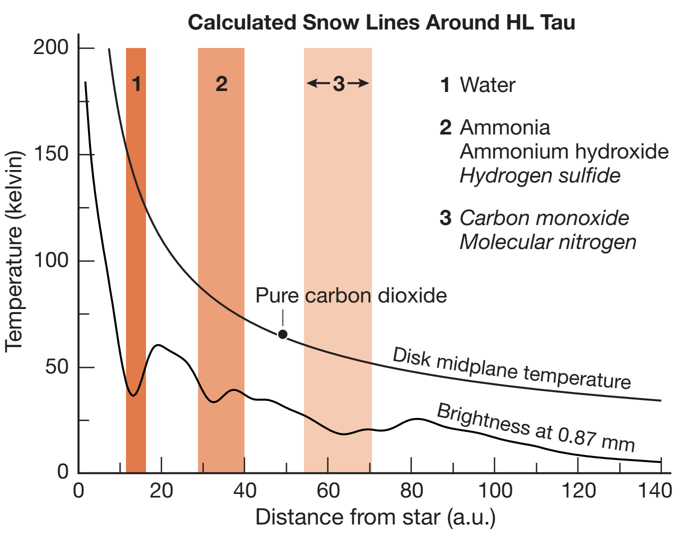
The overall spin of the system, or its *angular momentum*, must remain constant under the laws of physics (if there are no external torques operating on the system). This conservation law means that as the cloud collapses, it must spin faster if the collapse is purely toward the axis of rotation. This is the same reason why a spinning ice skater pulling their arms towards them will begin to spin faster.

Continually increasing the spin would eventually cause the cloud to fly apart, so a balance must be established to allow the star to form. Fortunately, the conservation of angular momentum still allows the particles to collapse parallel to the axis of rotation. As the particles bump into each other, their motions in this direction will cancel each other out, resulting in the formation of a flat disk.



PDS 70B: ESO / A. MÜLLER ET AL.; DISK FORMATION: GREGG DINDERMAN / *S&T*





material before planets can actually form. The gaps and rings in protoplanetary disks that we now commonly see with ALMA may show places where this inward drift has stopped, providing a sheltered place for pebbles to grow into planetesimals and eventually planet cores.

Still, despite the unprecedentedly high resolution of ALMA and SPHERE, we cannot probe closer to the star than the orbit of Jupiter in nearly all protoplanetary systems. This is a problem if we want to understand how planets like Earth form. We also want to compare our observations of protoplanetary disks to those of exoplanets, which are much easier to detect close to their host stars.

One innovative way of studying the inner disk regions is indirectly: by looking for the shadows that the inner disk casts on the outer disk. These shadows occur if the inner disk is warped or tilted compared to the outer disk. SPHERE has imaged many of these shadows, once again upending our view of a smooth protoplanetary disk.

Astronomers have also used light curves from the Kepler spacecraft to identify so-called "dipper" systems, which display drops in starlight that are much larger than expected if a planet were crossing in front of the star. These deep dips likewise point to large dusty structures of planet-building material that closely orbit the young stars and regularly block our view. Such findings hint at a dynamic planet-forming environment, which might help explain some of the unusual exoplanet systems we've discovered, such as those with highly elongated or tilted orbits.

The New Astrochemistry

Protoplanetary disks are not just physically dynamic but also chemically dynamic. Astronomers study the chemistry of pro-

◀ **HL TAU** The concentric rings in HL Tau's disk wowed astronomers when ALMA took this image in 2014. Researchers debate their origin, but one potential explanation for the rings is snow lines: Calculations of where various molecules freeze out in the disk indicate that three major gaps correspond to the snow lines for specific volatiles. (Those in italics would be trapped in water-ice cages called clathrates.) The ices might encourage grains to stick together, clearing out gaps in the disk.

HL TAU: ALMA (ESO / NAOJ / NRAO) / C. BROGAN & B. SAXTON (NRAO / AUI / NSF); GRAPH: K. ZHANG ET AL. / *ASTROPHYSICAL JOURNAL LETTERS* 2015; DISKS IMAGED BY SPHERE: ESO / H. AVENHAUS ET AL. / E. SISSA ET AL. / DARTT-S AND SHINE COLLABORATIONS

DISKS IN A DIFFERENT LIGHT
The Spectro-Polarimetric High-contrast Exoplanet Research (SPHERE) instrument on the Very Large Telescope in Chile blocks light from the central star while directly imaging starlight reflected off dust grains in the surrounding disk. Images have revealed disks with a wide variety of sizes and shapes.

RU Lup **V4046 Sgr** **PDS 66** **MY Lup**

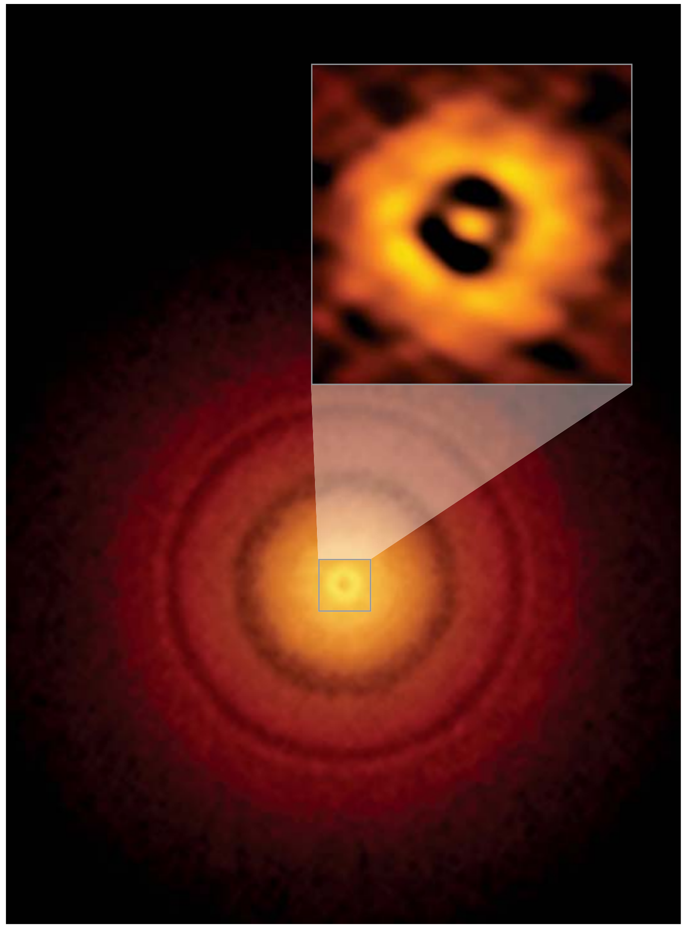
Snow lines are important because they affect the types of planets that can form at different locations in the disk.

toplanetary disks by observing emission from different types of gas molecules. Although we have so far focused on the dust component of protoplanetary disks because it is easier to observe, the gas component makes up 99% of the disk's mass, governs many of the key physical processes involved in planet formation, sets the chemical compositions of exoplanet cores and atmospheres, and has implications for the origins of life and habitability.

However, the main constituent of the gas, molecular hydrogen (H_2), is largely invisible to us because most of the protoplanetary disk is too cold to excite emission from this molecule. The remaining molecular gas species that are easier to excite are rare, making their emission faint and therefore difficult to observe. It wasn't until ALMA came online that we were able to begin studying the chemical nature of protoplanetary disks in detail.

One of the main focuses in the ALMA era has been on *snow lines*. These are the locations in the disk where the temperature becomes cool enough for a given chemical species (water, carbon dioxide, carbon monoxide, etc.) to condense from the gas phase into the solid phase. Each molecule "freezes out" at a different temperature than the others, so each will have its own distinct snow line at a specific distance from the star.

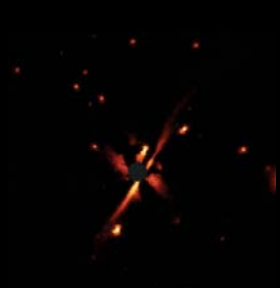
Snow lines are important because they affect the types of planets that can form at different locations in the disk. For example, when water molecules condense as ice onto dust grains beyond the H_2O snow line, they not only provide more solid material to form planet cores, but as described above they also accelerate growth by making grains stickier. The implications are potentially seen in our own solar system,



▲ **TW HYDRAE** In the protoplanetary system nearest Earth, ALMA images reveal a gap in the disk at 1 astronomical unit from the star. The TW Hydrae system is about 10 million years old and may provide a window to our own solar system's infancy.

where the water snow line marks the transition between the giant and terrestrial planets.

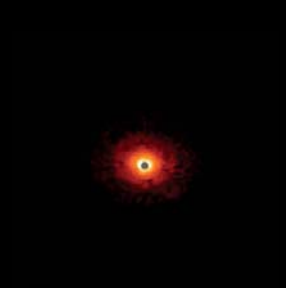
Snow lines can also determine the compositions of planet cores and atmospheres. For example, a gas giant formed in the cold outer regions of the disk should have an atmosphere



GSC 07396-00759

DoAr 44

RXJ 1615



AS 209

IM Lup

TW HYDRAE: S. ANDREWS (CENTER FOR ASTROPHYSICS, HARVARD & SMITHSONIAN), B. SAXTON (NRAO / AUI / NSF), ALMA (ESO / NAOJ / NRAO) poor in easily vaporized compounds such as H_2O and CO, as those volatiles should have condensed into ice and thus been locked into planet cores along with the solids. Therefore, we can use the chemical signatures in exoplanet atmospheres to infer where a planet formed, and thus whether it migrated into its current position. For example, analysis of the HR 8799 system, which hosts four super-Jupiter planets, revealed differences in the ratio of carbon to oxygen in the planets' atmospheres, consistent with the outer two planets having formed outside the water snow line and the inner two planets having formed inside of it.

When Do Planets Start to Form?

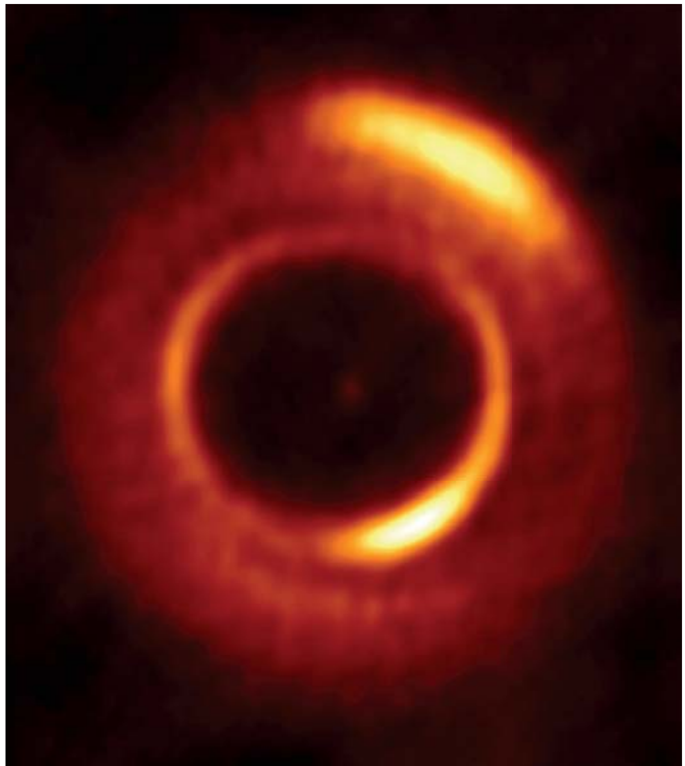
A big question that astronomers are now reviving based on these new observations is how quickly planets form. Traditionally, we estimated how long it takes a disk to dissipate and used that as a proxy. The reasoning is simple: Material must still exist around the star in order to make planets.

Astronomers can fairly easily determine whether or not there is any dusty material orbiting a star by searching for extra infrared emission. Dust grains warmed by their proximity to the star glow brightly at these wavelengths. Large-scale infrared surveys conducted by the Spitzer spacecraft in the 2000s confirmed that nearly all stars host protoplanetary disks when they are very young, roughly 1 million years old. But only 20% of stars still host disks by 5 million years of age, and by 10 million years all but 5% of stars have lost their disks. Therefore, astronomers have typically concluded that planets must form within the first 5 million years or so.

This timeframe set what we thought was a very strict limit, because our theoretical models struggled to make planets so quickly. But the infrared measurements from Spitzer didn't tell us much about the structure and amount of material around young stars, which can provide important clues to the planet formation process.

The recent results from ALMA and SPHERE now suggest that planet formation may occur even more rapidly than we thought based on Spitzer data. One of the starkest examples is the iconic HL Tau disk (see page 38), which was the first to be imaged with the full resolving power of ALMA. The HL Tau system is just 1 million years old; it is still deeply embedded in its natal cloud, which is dumping material onto the forming star and disk. However, ALMA can see through this cloud and has revealed a disk with many concentric gaps and rings. If forming planets carved these gaps, then they would indicate that planets come together when the star and disk themselves are still forming, on the order of hundreds of thousands of years rather than millions of years.

Evidence from our own solar system also supports such rapid planet formation. The age of Jupiter's core, inferred from dating different meteorite populations, indicates that it had already assembled by 1 million years after the start of the solar system. Scientists also think that on the order of 10 Earth masses of ice, rock, and metals went into forming Jupiter's early core, implying that the growth of planetesimals and planet cores occurs even earlier than 1 million years. If planets assemble at the same time as the star and disk, then we would have to fundamentally change our models of planet formation.



ONE-STOP SHOP The MWC 758 system shows not only a large (and slightly off-center) gap but also a faint spiral arm and two bright clumps within its disk.

NRAO / AUI / NSF

To chase down the answers to these mysteries, astronomers will soon add to their arsenal the next generation of 30-meter telescopes, which will give us an unprecedented ability to probe the structure and motions in young protoplanetary disks (*S&T:* Dec. 2018, p. 14). ALMA recently detected the first signatures of planet-building material flowing into a gap in a protoplanetary disk, where a young planet is thought to be orbiting. The observation provides an exciting preview of what is yet to come. We'll combine with these ground-based instruments the upcoming space-based missions like the James Webb Space Telescope (JWST), set to launch in 2021. Its sensitivity at infrared wavelengths will enable the first demographic chemistry studies of planet-forming environments. Together, these facilities promise to enable us to place our solar system within its larger galactic context, rather than the other way around.

■ **MEGAN ANSDELL** is a Research Fellow at the Flatiron Institute's Center for Computational Astrophysics and Center for Computational Mathematics. Her research focuses on observing planet formation and applying machine learning to astrophysical problems.

1 DUSK: Venus blazes in the western twilit skies throughout the month.

5 MORNING: The Eta Aquariids peak in the early hours of the morning. This meteor shower is more favorable for viewers at southern latitudes; however, this year's shower is predicted to be more active, so it behooves viewers in the Northern Hemisphere to also venture outside (see page 50).

12 DAWN: The waning gibbous Moon, Jupiter, and Saturn form a triangle straddling the border between Sagittarius and Capricornus.

13, 14 DAWN: The thinning Moon leaves the pair of gas giants and approaches Mars.

15 DAWN: The waning crescent Moon is about 4° lower left of Mars. Catch the duo before sunrise.

15 DUSK: Venus's crescent presents a good opportunity to test your eyesight (see pages 46 and 49). Steadily held binoculars will help.

21 DUSK: Venus and Mercury are in conjunction. Find the pair 1° apart low above the west-northwestern horizon.

23 DUSK: A very thin crescent Moon, just one day past new, is some 4° lower left of Venus. Look for Mercury to appear upper left of Venus as twilight deepens.

24 DUSK: The waxing Moon, Mercury, and Venus form a line roughly 12° long shortly after sunset. The viewing window is brief, so be sure to catch the sight before the trio sets.

26 EVENING: The growing crescent Moon is in Gemini, about 6° left of Pollux.

28 EVENING: The Moon has crossed into Leo and is 7° or so northwest of Regulus, the star marking the bottom of the Sickle.
— DIANA HANNIKAINEN

▲ The European Space Agency's Giotto mission flew by Comet Halley — the likely source of the Eta Aquariid meteor shower — in 1986. ESA

MAY 2020 OBSERVING

Lunar Almanac

Northern Hemisphere Sky Chart

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

NASA / LRO

MOON PHASES

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

FULL MOON
May 7
10:45 UT

LAST QUARTER
May 14
14:03 UT

NEW MOON
May 22
17:39 UT

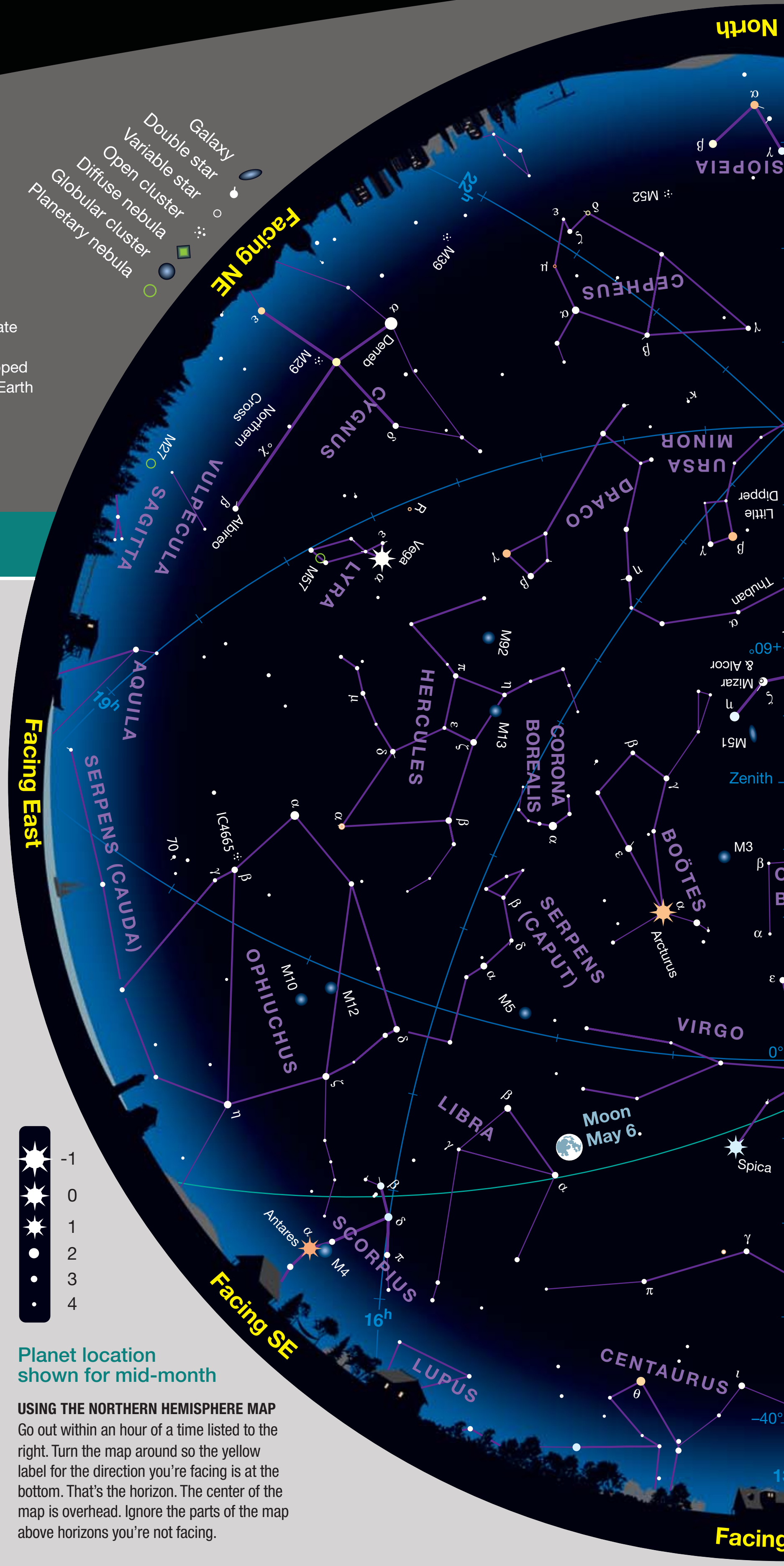
FIRST QUARTER
May 30
03:30 UT

DISTANCES

Perigee	May 6, 03^h UT
359,654 km	Diameter 33′ 13″
Apogee	May 18, 08^h UT
405,583 km	Diameter 29′ 28″

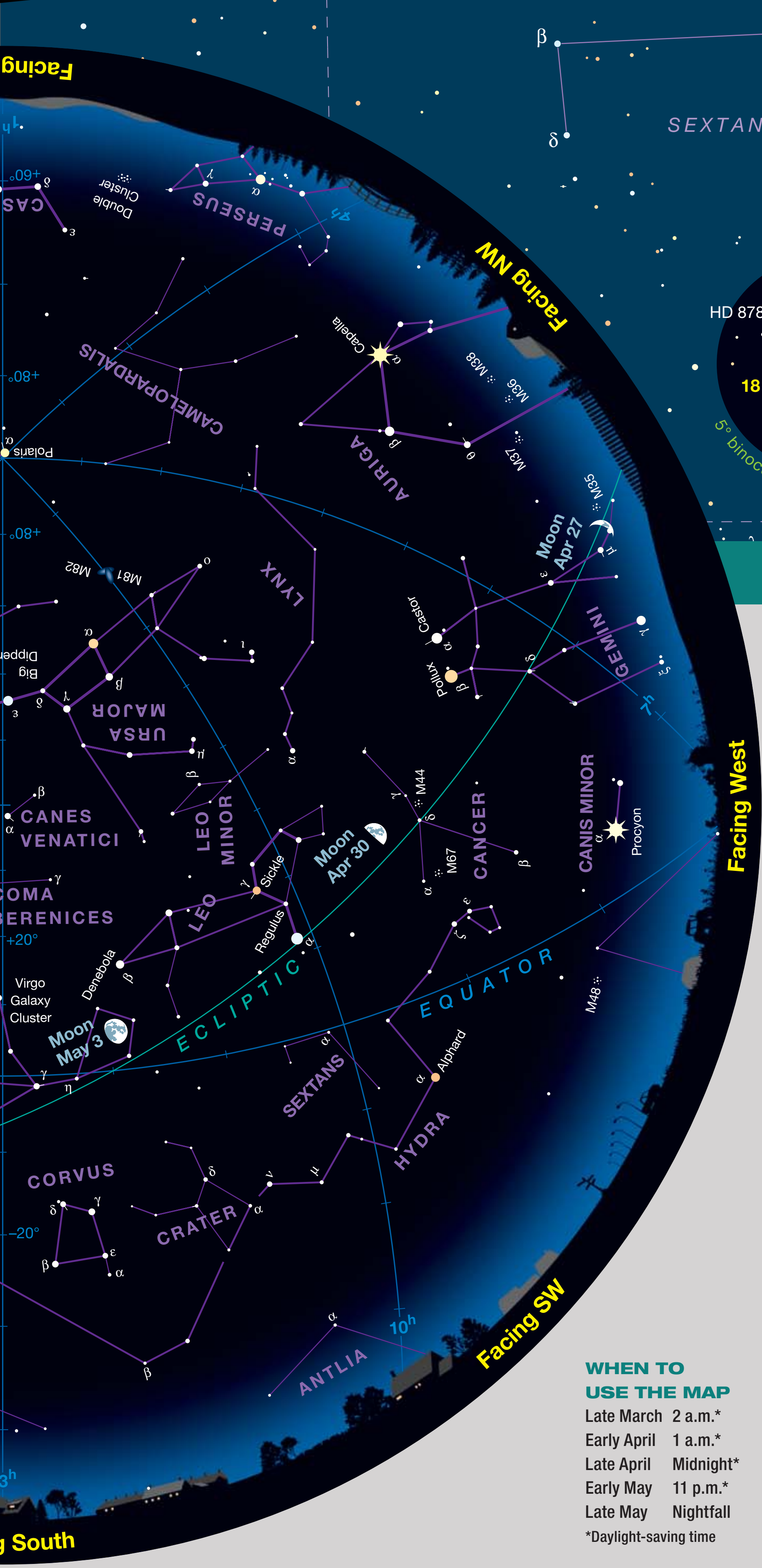
FAVORABLE LIBRATIONS

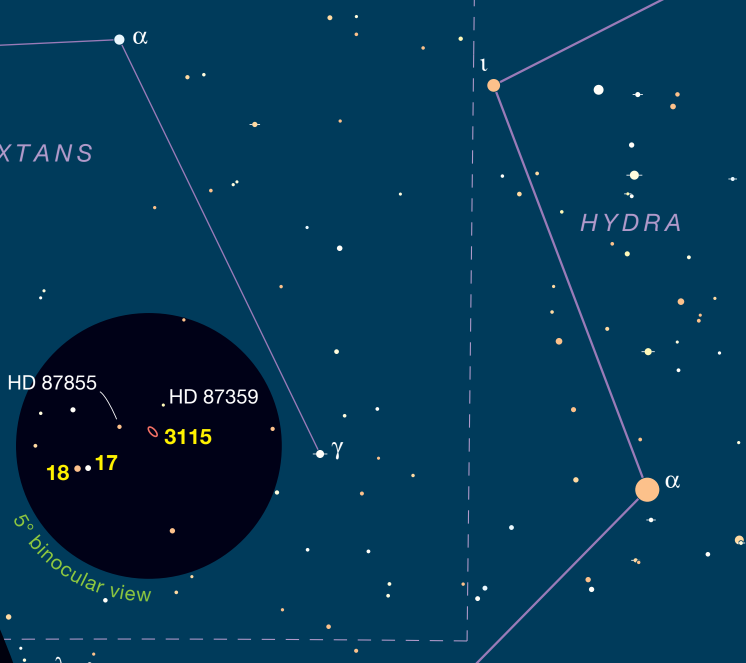
• Wilson Crater	May 5
• Haworth Crater	May 6
• Hale Crater	May 7
• Lyot Crater	May 8



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

A Spindle in the Sextant

Our target this month is a bit of a challenge: **NGC 3115** in the constellation Sextans, the astronomical sextant, one of several objects with the nickname "Spindle Galaxy." To find it, start at Alphard, or Alpha (α) Hydrae, scan 6° east to Gamma (γ) Sextantis, and then some 3° farther along the same line. It may help to imagine the galaxy as the apex of a flattened pyramid, the baseline of which is formed by the 7th-magnitude stars HD 87359 and HD 87855.

As the nickname implies, we see NGC 3115 almost edge-on. This is a boon to observers, as it concentrates the galaxy's light. At 9th magnitude, it's still not an easy catch, just a faint wisp of light even in 70-mm binos. You'll need reasonably dark skies and every trick in the observer's book — excellent dark adaptation, averted vision, and observing when the galaxy culminates — to snag this distant giant.

NGC 3115 harbors a dark secret: a central black hole two billion times the mass of the Sun. Observations from NASA's Chandra X-ray Observatory show that gas flowing toward the black hole starts to heat up at a distance of 700 light-years. So if you could teleport this monster black hole halfway between our solar system and the Orion Nebula, we'd be caught up in the flow of the warm gas as it's being pulled toward the black hole.

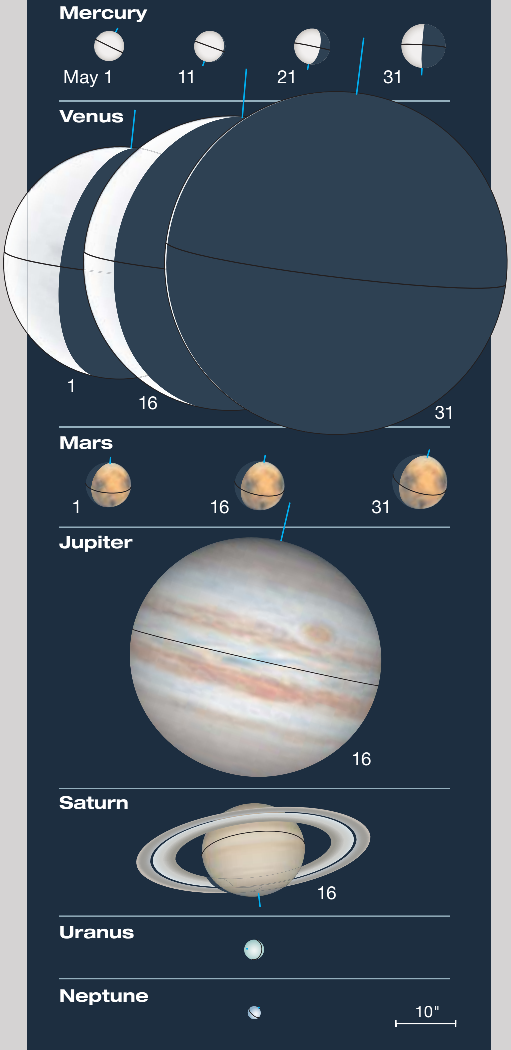
While you're in the neighborhood, check out the nearby optical double formed by **17** and **18 Sextantis**: 17 Sextantis is an *A*-type white main-sequence star, and 18 Sextantis is a *K*-type orange-red giant. With both stars just brighter than 6th magnitude and with a generous separation of 12′, you should be able to detect them — and see them as two separate stars — even with the naked eye.

■ MATT WEDEL is reporting from the field as he bushwhacks through the remote reaches of Hydra.

WHEN TO USE THE MAP

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

*Daylight-saving time



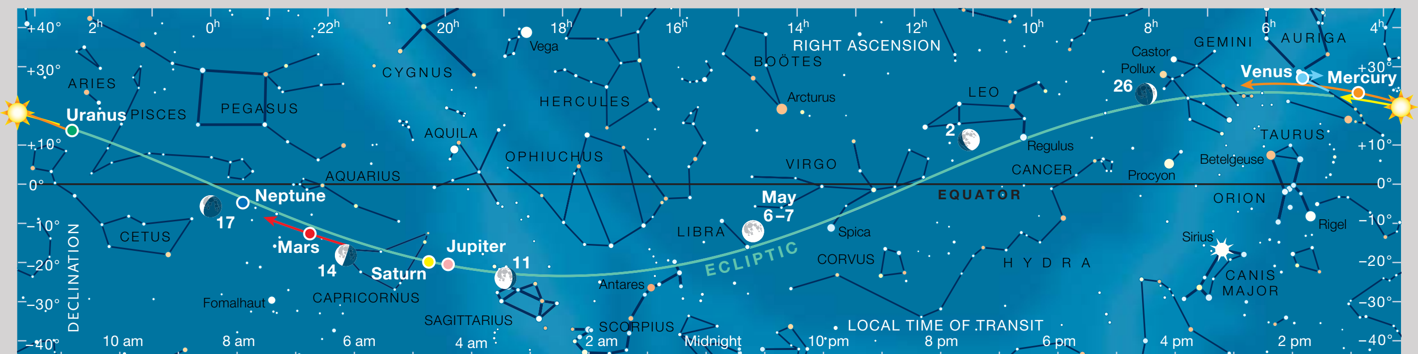
PLANET DISKS have south up, to match the view in many telescopes. Blue ticks indicate the pole currently tilted toward Earth.

PLANET VISIBILITY (40°N, naked-eye, approximate) **Mercury:** visible at dusk after the 11th • **Venus:** remains visible at dusk until the end of the month • **Mars:** a pre-dawn object throughout May • **Jupiter and Saturn** lie within 5° of each other all month and are positioned reasonably high before dawn

May Sun & Planets

	Date	Right Ascension	Declination	Elongation	Magnitude	Diameter	Illumination	Distance
Sun	1	2^h 33.6^m	+15° 04′	—	–26.8	31′ 45″	—	1.008
	31	4^h 32.3^m	+21° 55′	—	–26.8	31′ 33″	—	1.014
Mercury	1	2^h 16.8^m	+12° 53′	5° Mo	–1.8	5.1″	98%	1.326
	11	3^h 41.1^m	+20° 35′	7° Ev	–1.6	5.2″	95%	1.281
	21	5^h 05.0^m	+24° 58′	18° Ev	–0.7	6.0″	72%	1.115
	31	6^h 11.7^m	+25° 28′	23° Ev	0.0	7.4″	47%	0.910
Venus	1	5^h 09.7^m	+27° 45′	38° Ev	–4.7	38.9″	25%	0.429
	11	5^h 21.6^m	+27° 34′	31° Ev	–4.7	45.6″	16%	0.366
	21	5^h 17.1^m	+26° 23′	20° Ev	–4.4	52.7″	6%	0.317
	31	4^h 57.0^m	+24° 01′	6° Ev	—	57.4″	1%	0.291
Mars	1	21^h 37.1^m	–15° 55′	79° Mo	+0.4	7.6″	86%	1.229
	16	22^h 17.5^m	–12° 44′	84° Mo	+0.2	8.4″	85%	1.120
	31	22^h 56.3^m	–9° 20′	88° Mo	0.0	9.2″	85%	1.016
Jupiter	1	19^h 54.9^m	–20° 57′	104° Mo	–2.3	40.7″	99%	4.844
	31	19^h 54.4^m	–21° 03′	133° Mo	–2.6	44.6″	99%	4.425
Saturn	1	20^h 15.4^m	–19° 54′	99° Mo	+0.6	16.9″	100%	9.810
	31	20^h 14.5^m	–20° 00′	128° Mo	+0.4	17.8″	100%	9.356
Uranus	16	2^h 20.9^m	+13° 34′	18° Mo	+5.9	3.4″	100%	20.762
Neptune	16	23^h 26.0^m	–4° 48′	65° Mo	+7.9	2.3″	100%	30.344

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 timely information about the planets, visit skyandtelescope.org.



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

Fabled Females and a First Transit

Constellations that invoke mythological women populate May's night sky.

If you're reading this column in late March or early April, you can look in the west-northwest after nightfall and see Venus together with the Pleiades — the Roman goddess of love with the Seven Sisters of Greek mythology. To their right, you can also view Algol, the star of the monstrous Gorgon sister Medusa, and to their left the cluster of the Hyades sisters.

All these female heavenly characters are lost in the Sun's afterglow by early May — except for Venus, which twilight's glare consumes later in the month. But what other female or female-related constellations derived from Greek and Roman myth are visible in early April and in May? Answer: all of them. And, with the exception of Cassiopeia (which is at its lowest), all of these constellations are visible near their highest.

Females in the evening sky. Our May Northern Hemisphere Map is just one page-turn back from this column. Elevated to its highest in the south on that map is the only woman of the zodiac: Virgo, the Virgin. It's also the longest constellation of the zodiac and the second largest of the 88 constellations in area. Very near the meridian at this time is Virgo's brightest star, 1st-magnitude Spica.

But what other female characters are represented in this sky? One is the historic Queen Berenice II, queen of Cyrene and Egypt, whose amber tresses are part of the constellation Coma Berenices (Berenice's Hair) and the big, scattered Coma Star Cluster. Another is Ariadne, the Cretan princess who helped Athenian king Theseus escape from the Labyrinth after he killed the dreadful Minotaur, but whom Theseus abandoned on an island. Ariadne was rescued by the god Dionysius, who made her his queen and wife. And when Ariadne died, Dionysius placed her crown among the stars as the conspicuous semicircle known as Corona Borealis, the Northern Crown.

Interestingly, Coma Berenices and Corona Borealis are located on either side of Boötes, the Herdsman, home of spring's brightest star, Arcturus. The Coma constellation precedes Boötes and lies directly north of the western half of Virgo — the part that portrays the head and upper body of the reclining virgin. Corona Borealis follows Boötes and is found directly north of the eastern end of Virgo, her feet. The big Coma Star Cluster is about 5° in diameter, with at least five stars brighter than magnitude 5.5 and about a dozen brighter than 6.5. The somewhat wider semicircle of the Northern Crown features a magnitude-2.2 gem: Gemma, also known as Alphecca.

NORTHERN CROWN You can find the striking curve of Corona Borealis east of Boötes, which is dominated by the zero-magnitude red giant Arcturus (at lower right). During May, both constellations are well positioned for evening viewing.

AKIRA FUJII

My first transit. My previous two Under the Stars columns described the life-changing views I got of my first total solar eclipse of the Sun (March 7, 1970) and my first great comet (Bennett, at its best in April 1970). Now I want to mention a lesser but still exciting third wonder from that spring 50 years ago: May 9th's transit of Mercury. This and my next transit (on November 10, 1973) share one strange similarity. In both early-morning events, Mercury had just exited the Sun's disk on my telescope's projection screen when a motorist stopped on our quiet country road to ask what I was observing. The driver from the 1973 transit wondered if I was observing — in broad daylight — the still quite faint Comet Kohoutek. I wasn't.

All five of my Mercury transits (including last November's) and both of my Venus transits were amazing and gratifying visions of worlds snatched from out of the stupendous furnace of the Sun.

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

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

Five Planets Excite

The Evening Star slips away while the Red Planet gains size and brightness.

After spending March and April near its ultimate evening altitude, Venus plunges down into the Sun's afterglow in May and passes close to a climbing Mercury. As Venus exits the evening sky, Jupiter and Saturn make their entrance late at night and throughout May are the most closely paired they've been in 20 years.

Last in the night's promenade of bright planets is Mars. The Red Planet rises several hours after midnight and brightens rapidly to zero magnitude as its growing disk begins to show a few surface features in amateur telescopes.

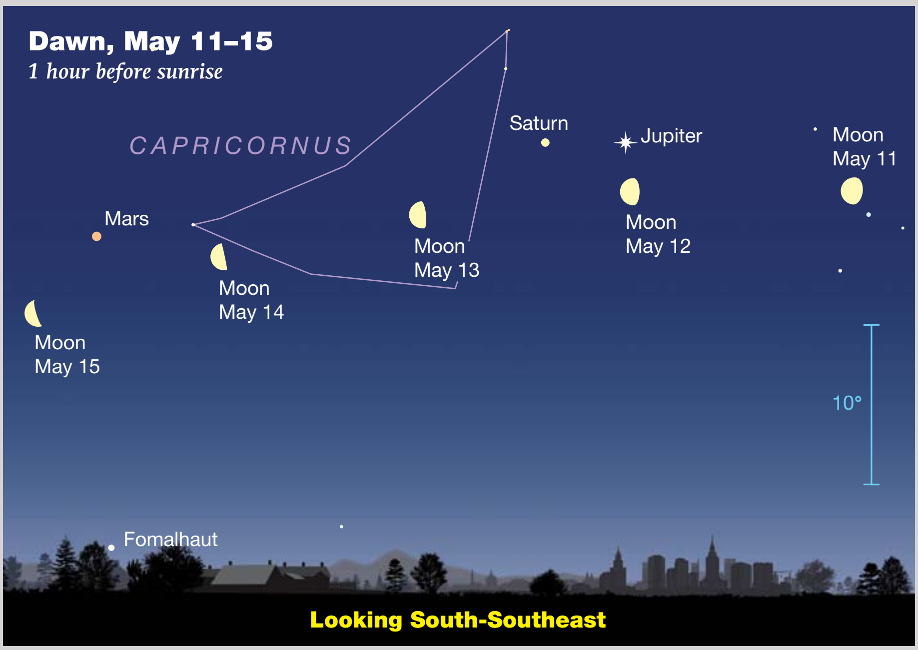
DUSK AND EVENING

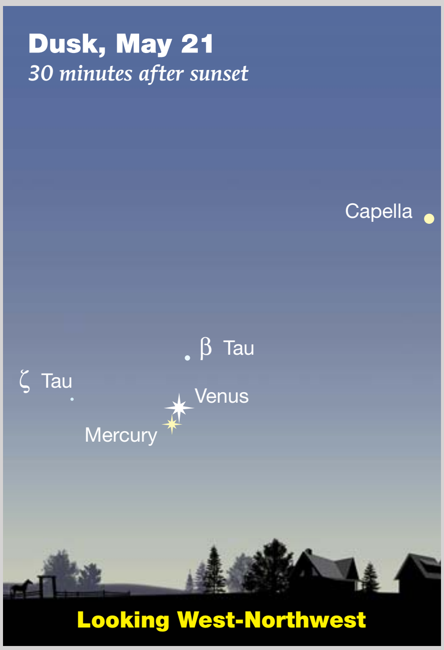
Venus begins May with a sunset altitude of about 35° (for observers at around 40° north latitude) and sets almost 3½ hours after the Sun. But by month's end the interval dwindles to less than ½ hour.

As the month starts, Venus is at a searing peak brightness of –4.7 and situated a few degrees from 2nd-magnitude Beta (β) Tauri, El Nath. The sunset altitude of Venus decreases to 23° on May 15th to only about 3° by the 31st. Over that same span, its brightness drops from magnitude –4.6 to –4.2. The current apparition finally ends when Venus reaches inferior conjunction with the Sun on June 3rd.

In a telescope, Venus begins May as a crescent about 40″ tall and 24% lit and grows to 50″ and thins to 11% lit on the 15th. That's a good date to try to see the crescent with steadily supported binoculars — or even without optics, if you have very sharp vision. Alternatively, try looking at the planet through a piece of cardboard with a roughly 1 to 2 mm wide hole in it. (For more on sighting Venus, see page 49.) As May ends, the planet's razor-thin crescent is about 57″ tall and only a few percent lit.

Mercury first becomes visible in evening twilight around May 11th, as a magnitude –1.5 object in the west-northwest, well below Venus. The two planets converge as Mercury climbs noticeably higher and Venus sinks lower each night. They come closest together for North America on the evening of the 21st, when Mercury glows about one degree to the lower left of Venus. By that date, Mercury has faded to –0.7 and its 6″-wide, 69%-lit disk contrasts remarkably with Venus's 53″-wide, 6%-lit disk (which also has a much higher surface brightness than Mercury's). For the rest of the month, while





Venus falls from view, Mercury gains altitude on its way to its greatest elongation from the Sun on June 4th.

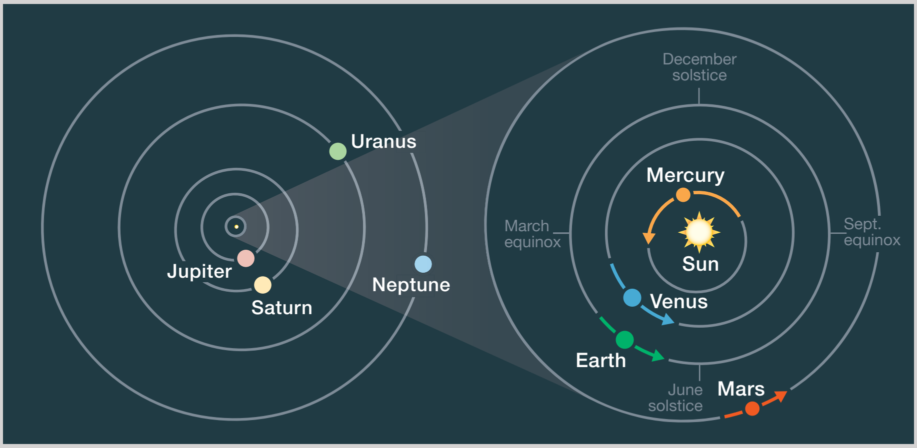
LATE EVENING TO DAWN

Jupiter and **Saturn** appear within 5° of each other all May, shining just on either side of the Sagittarius-Capricornus border (Jupiter in Sagittarius, Saturn in Capricornus). As Earth begins to overtake them in the race of the three planets around the Sun, Saturn appears to halt its direct (eastward) motion on the 11th, as does Jupiter on the 14th. Then both begin to retrograde (move westward relative to the background stars). The tightest pairing of the two occurs on May 18th when Jupiter is 4.7° west-southwest of Saturn.

This qualifies as a "quasi-conjunction" (an event in which two objects don't share the same right ascension or ecliptic longitude yet reach a minimum separation of 5° or less from each other). After this date, faster Jupiter begins to move away from Saturn, but a few months from now the two will start to converge again as they head toward their ultra-close true conjunction on December 21st.

Both Jupiter and Saturn rise around 1:30 a.m., daylight saving time, as May begins and around 11:30 p.m. as the month comes to an end. During May, Jupiter brightens slightly from magnitude –2.4 to an even more impressive –2.6, and Saturn increases from magnitude 0.6 to 0.4.

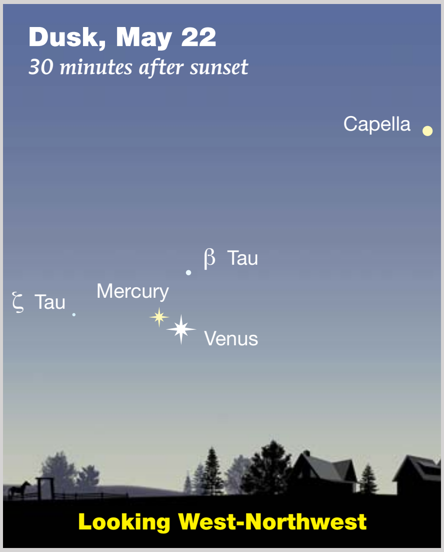
This month, Jupiter and Saturn are highest, and therefore usually sharpest in telescopes, during morning twilight. Jupiter's apparent equatorial diameter grows from about 41″ to 45″ in May. Saturn's disk is a little more than 17″ across, while its rings span about 37″ edge-to-edge and are tilted just under 21° from edgewise — a little shy of their 27° degree maximum.

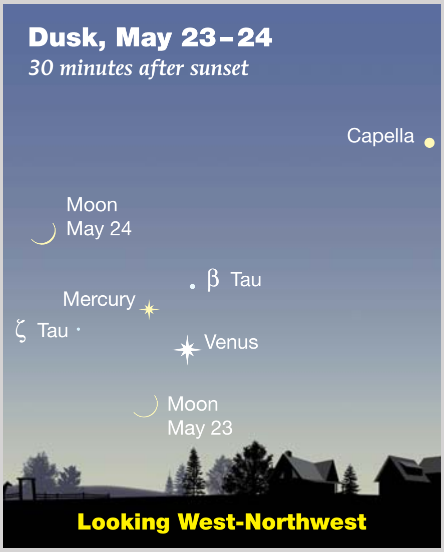


ORBITS OF THE PLANETS

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

◀▼ These scenes are drawn for near the middle of North America (latitude 40° north, longitude 90° west); European observers should move each Moon symbol a quarter of the way toward the one for the previous date. In the Far East, move the Moon halfway.





PRE-DAWN AND DAWN

Mars rises a little before 3 a.m. as May opens, and about an hour sooner as the month closes. At the same time, the planet brightens from magnitude 0.4 to 0 and its disk grows from 7.6″ to 9.2″ in diameter. Mars shines about one degree north-northwest of magnitude 3.6 Gamma (γ) Capricorni (Nashira) on May 1st, and the same distance north of magnitude 2.8 Delta (δ) Capricorni (Algedi) on the 4th. The Red Planet glides from Capricornus into Aquarius on the 9th.

Neptune rises a little before the start of morning astronomical twilight, while **Uranus** remains lost in the Sun's glare most of May, only emerging at dawn in the final week of the month. Neither planet is well-placed for observation.

MOON PASSAGES

The Moon is a waxing gibbous a few degrees above Regulus at nightfall on May 1st. The waning gibbous Moon is a few degrees below Jupiter at dawn on the 12th. The last-quarter Moon is several degrees to the right of Mars on the 14th. About 30 minutes after sunset on the 23rd, a very thin lunar crescent is less than five degrees to the lower left of Venus, with Mercury a similar distance to the upper left of Venus.

■ **FRED SCHAAF** teaches astronomy at both Rowan University and Rowan College in southern New Jersey.

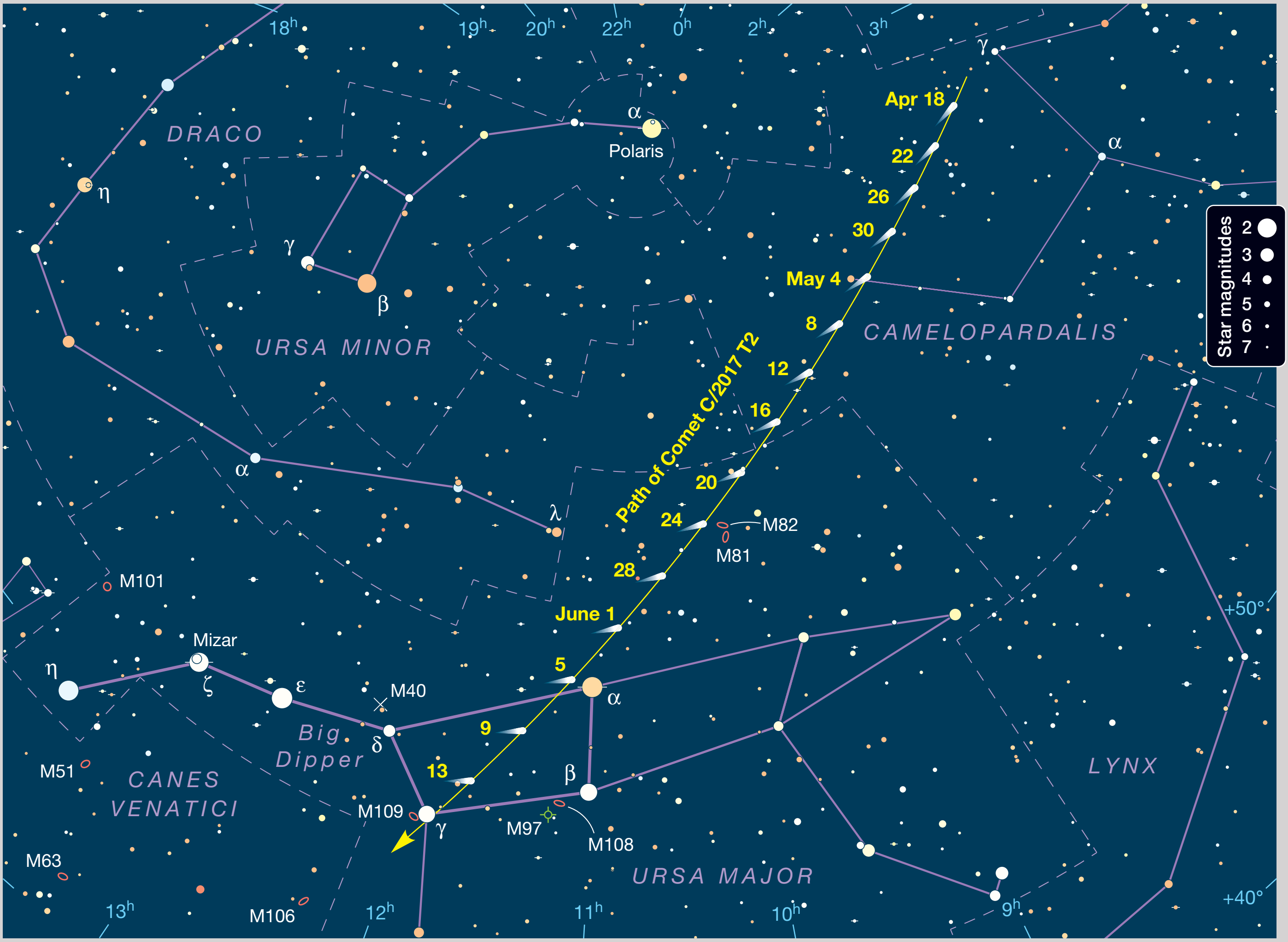
Comet T2 Hits the Big Time

What might prove to be the year's finest comet is at its best in May.

Grab our chart and click on your red flashlight. You'll want to spend a few nights with Comet PanSTARRS (C/2017 T2) this month. Now at its brightest, the comet was discovered by the Panoramic Survey Telescope and Rapid Response System (PanSTARRS) in May 2017, when the object was well beyond the orbit of Saturn. Three years later, it finally reaches perihelion on May 4th, at distance of 1.6 a.u. (242 million kilometers) from the Sun. Amateurs have been watching T2 slowly blossom from the 14th-magnitude midge it was more than a year ago into a binocular target.

The comet should reach and sustain at least 8th magnitude through May and into June as it ambles southeast from Camelopardalis to Ursa Major. With a minimum declination of +66°, the comet will be circumpolar and visible all night, even from the southern United States.

As May begins, Comet T2 will be traveling toward the Big Dipper at around 40 arcminutes per day, increasing to 50 arcminutes after mid-month. The chart below shows notable celestial pairings on its route that include the



▲ **TRIPLE TREAT** In January, Comet PanSTARRS (C/2017 T2) shared the field of view with the famed Double Cluster, in Perseus. On May 24th the comet pays a visit to the well-known Ursa Major galaxy pair, M81 and M82.

SEAN WALKER / S&T

galaxies M81 and M82 on May 22nd, and a 1° brush with Dubhe, the northernmost of the Dipper's two pointer stars, on June 3rd.

Under a dark, moonless sky the comet will look like a fuzzy, pale blob in a pair of 50-mm or larger binoculars. Telescope users can ferret out delectable details like a tail (which can change in both length and orientation over time) and a bright, misty head or coma — the object's temporary atmosphere of dust and gases released when solar heating vaporizes its volatile ices. Within the coma you can often see what appears to be a starlike center, called the *pseudo-nucleus*; the true, icy nucleus is buried within, obscured by its own dust and gas.

If you use high magnification in your scope to zoom into the coma, you might also detect hints of cometary jets — geyserlike dust plumes erupting from the nucleus. A jet looks like a tiny, low-contrast stub of brighter material extending sunward from the pseudo-nucleus. Activity within and near the true nucleus, especially sudden bursts of dust or episodes of fragmentation, can alter a comet's appearance in short order. This is especially true for "dynamically new" comets like this one, which is making its first trip near the Sun after several billion years locked up in the distant deep freeze of the Oort Cloud.

PanSTARRS is the name given to the survey's twin 1.8-meter Ritchey-Chrétien telescopes, named PS1 and PS2. The PanSTARRS project is operated by the Institute for Astronomy at the University of Hawai'i and receives most of its funding from NASA's Near-Earth Objects Observation Program. Located atop Haleakalā, on the island of Maui, PS1 saw first light in June 2006. With its 3° field of view and 1.4 billion-pixel CCD camera, it can scan 6,000 square degrees of sky every night, covering the entire sky in 40 hours. Its primary mission is to detect Near-Earth Objects (NEOs) that could pose potential impact threats. Along the way, PanSTARRS has swept up numerous asteroids, comets, variable stars, and supernovae — basically anything that fluctuates in brightness or moves!

With more than 200 comets to its credit (as of late January 2020), PanSTARRS has practically become a brand name, making it hard for some of us to keep them all straight! The dual instruments are extremely good at what they do, so expect to see hundreds of additional comet and asteroid discoveries in the years to come.

A Venusian Challenge

THROUGHOUT MAY, binoculars or a small telescope will easily show Venus as a miniature version of the crescent Moon, as the planet thins dramatically from 24% illuminated on May 1st, to a filament-thin 0.3% on the 31st. At the same time, its diameter swells from 40″ to 57″. This rapid increase in apparent size presents observers with an opportunity to discern the Venusian crescent without optical aid.

If you have 20/20 vision, your eyes have an angular resolution of roughly 60″. Theoretically, you should be able to resolve a crescent Venus when it's near its maximum apparent size. Is it really possible? Despite several attempts, I've never been able to do so, but I've read numerous reports of crescent sightings online and elsewhere. Some sound credible, others less so.

I've yet to see anything approaching a definitive study of the question, so let's see if we can get some answers. How about a Venus viewing party during the second half of May? Invite your astronomy buddies, neighbors, and family members. To avoid glare, which tends to expand the planet into a brilliant disk and render its shape more difficult to perceive, observe from early- to mid-twilight. Try the method Fred Schaaf describes on page 46. And be sure to view with your unaided eyes before confirming your observation with binoculars.

You may not be able to perceive a distinct crescent. Even when Venus is at its biggest this month, it remains slightly below the 60″ threshold mentioned earlier. Instead, look for an elongated shape or an indentation on the top edge of the planet. Send your observations to me at **nightsky55@gmail.com** and I'll include them in a future edition of Celestial Calendar.

Hello, Halley!

TWICE A YEAR, first in May and again in October, Earth plows through a trail of dust and bits of rock ejected by the famous Halley's Comet along its orbital path and we witness a meteor shower. The May encounter stokes the Eta Aquariid display, while October's produces the Orionids.

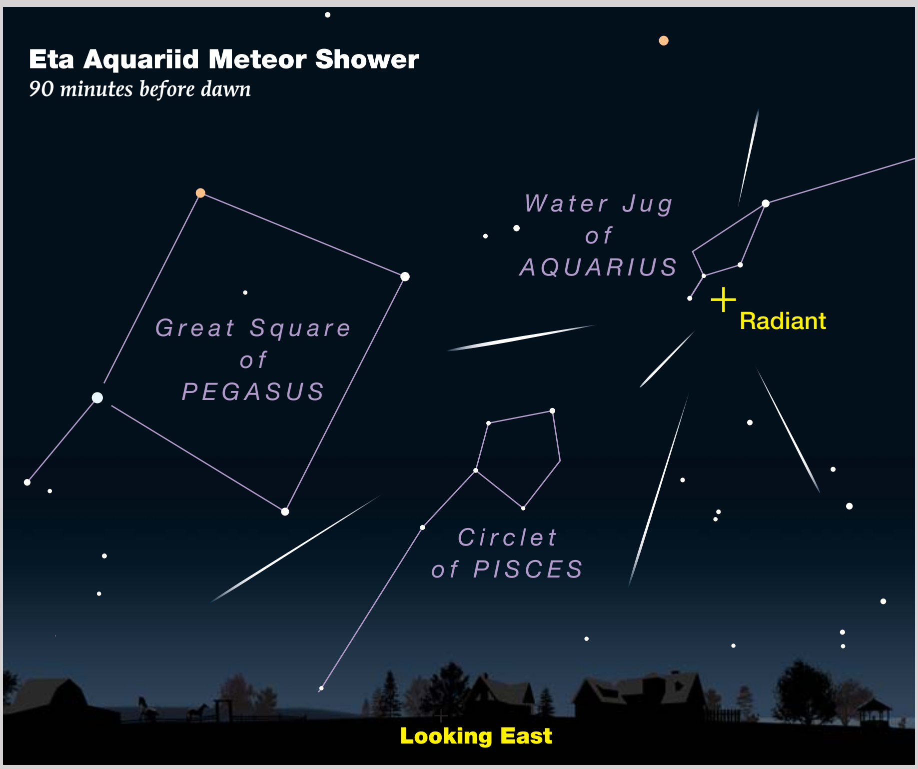
The Eta Aquariids are active from mid-April until late May but reach their peak on the night of May 4–5, with 10–30 meteors per hour visible from the Northern Hemisphere and 30–50 from the Southern. The two rates are due to the altitude of the radiant — it's low in the southeastern sky for northern observers but well-placed for those at tropical latitudes. Also, if you live at a mid-northern latitude, dawn begins early, quenching the display just as it begins to heat up.

This year the shower could be more active than usual. Gravitational nudging from Jupiter causes the Eta Aquariid peak rate to vary over a roughly 12-year cycle, with stronger activity possible from 2020 to 2022.

The Eta Aquariids are fast, often bright meteors that frequently leave persistent streaks of glowing, ionized air in their wake. That's the good news. Now for the bad. A 91%-full Moon in Virgo will cut the number of visible meteors by at least half.

Go out anyway. Twilight at mid-northern latitudes begins shortly after 4 a.m. local daylight-saving time, so plan your observing session for between 3:30 and 5 a.m. You'll know you're seeing a Halley fragment if you can mentally trace the meteor's path back toward the radiant, indicated in the chart below.

Comet Halley is one of the darkest objects in the solar system. If you hammered out a chunk of the comet it would look just like a piece of charcoal. What a wonderful twist then that these black fragments incandesce to light as they meet their demise.



Action at Jupiter

AS MAY BEGINS, Jupiter rises at about 1:30 a.m. local daylight-saving time and is high in the southeast at dusk. By the end of the month it transits the meridian during morning twilight. On May 1, the planet shines brightly at magnitude –2.3 and presents a disk 41″ diameter.

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

All the May interactions between Jupiter and its satellites and their shadows are tabulated on the facing page. Find events timed for dawn twilight in your time zone, when Jupiter is at its highest.

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

April 1: 1:51; 11:46; 21:42; **2**: 7:38; 17:33; **3**: 3:29; 13:25; 23:21; **4**: 9:16; 19:12; **5**: 5:08; 15:03; **6**: 0:59; 10:55; 20:50; **7**: 6:46; 16:42; **8**: 2:38; 12:33; 22:29; **9**: 8:25; 18:20; **10**: 4:16; 14:12; **11**: 0:07; 10:03; 19:59; **12**: 5:54; 15:50; **13**: 1:46; 11:42; 21:37; **14**: 7:33; 17:29; **15**: 3:24; 13:20; 23:16; **16**: 9:11; 19:07; **17**: 5:03; 14:58; **18**: 0:54; 10:50; 20:45; **19**: 6:41; 16:37; **20**: 2:32; 12:28; 22:24; **21**: 8:19; 18:15; **22**: 4:11; 14:06; **23**: 0:02; 9:58; 19:53; **24**: 5:49; 15:45; **25**: 1:40; 11:36; 21:32; **26**: 7:27; 17:23; **27**: 3:19; 13:14; 23:10; **28**: 9:06; 19:01; **29**: 4:57; 14:53; **30**: 0:48; 10:44; 20:40

May 1: 6:35; 16:31; **2**: 2:27; 12:22; 22:18; **3**: 8:14; 18:09; **4**: 4:05; 14:00; 23:56; **5**: 9:52; 19:47; **6**: 5:43; 15:39; **7**: 1:34; 11:30; 21:26; **8**: 7:21; 17:17; **9**: 3:13; 13:08; 23:04; **10**: 8:59; 18:55; **11**: 4:51; 14:46; **12**: 0:42; 10:38; 20:33; **13**: 6:29; 16:25; **14**: 2:20; 12:16; 22:11; **15**: 8:07; 18:03; **16**: 3:58; 13:54; 23:50; **17**: 9:45; 19:41; **18**: 5:36; 15:32; **19**: 1:28; 11:23; 21:19; **20**: 7:15; 17:10; **21**: 3:06; 13:01; 22:57; **22**: 8:53; 18:48; **23**: 4:44;

14:39; **24**: 0:35; 10:31; 20:26; **25**: 6:22; 16:18; **26**: 2:13; 12:09; 22:04; **27**: 8:00; 17:56; **28**: 3:51; 13:47; 23:42; **29**: 9:38; 19:34; **30**: 5:29; 15:25; **31**: 1:20; 11:16; 21:12

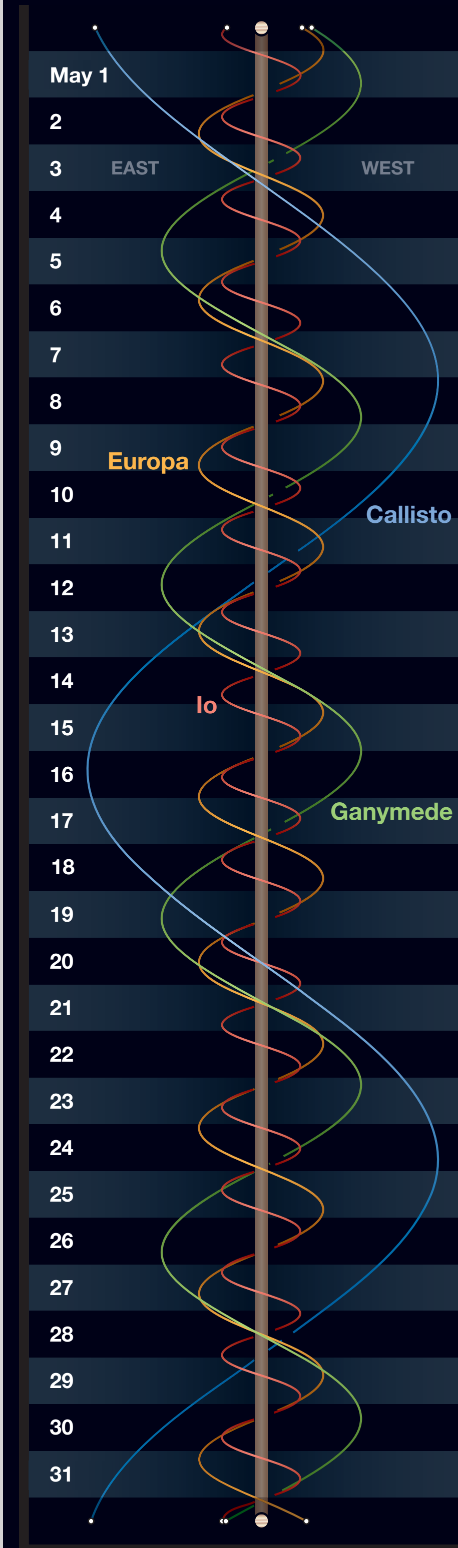
These times assume that the spot will be centered at System II longitude 332° on May 1. If the Red Spot has moved elsewhere, it will transit 1²/₃ minutes earlier for each degree less than 332° and 1²/₃ minutes later for each degree more than 332°.

Phenomena of Jupiter's Moons, May 2020

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

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

Jupiter's Moons



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

The Mountains of Mitchel

Glimpse the first discovery made at the oldest major observatory in the United States.

On August 26, 2003, the Hubble Space Telescope captured this image of Mars with the Mountains of Mitchel as they detached from the periphery of the south polar cap.

This year's favorable apparition of Mars presents an excellent opportunity to witness the development of a transient but recurring Martian feature known as the Mountains of Mitchel, discovered 175 years ago by the founder of the first major observatory established in the United States.

Ormsby MacKnight Mitchel was born in 1809 in Kentucky, then a rural outpost on America's western frontier. In 1825 he secured an appointment to the United States Military Academy at West Point, where the curriculum included surveying, civil engineering, and practical astronomy in addition to military subjects. After graduating, Mitchel remained at West Point as a mathematics instructor for three years. He resigned his commission in 1832 and moved to the thriving metropolis of Cincinnati, Ohio, where he studied law and was admitted to the bar. He was hired four years later by the newly established Cincinnati College to teach mathematics, engineering, and astronomy. (For more about Mitchel, see *S&T:* Nov. 2019, p. 30.)

Mitchel was a captivating orator who spoke without notes or visual aids. His series of public lectures about the solar system attracted audiences of as many as 2,000 Cincinnati residents, who packed into one of the city's largest churches. At the conclusion of the final lecture, Mitchel announced that he would devote his energies to establishing a major observatory in Cincinnati to be funded by the sale of 300 shares of stock at the price of $25 apiece. Shareholders in the Cincinnati Astronomical Society would be granted the privilege of viewing the heavens through the future observatory's powerful telescope.

Despite the price of a single share being equal to the monthly wages of a typical laborer, Mitchel generated such popular enthusiasm that all the shares were sold in less than a month. With the necessary funds in hand, he sailed off to visit Europe's preeminent observatories and telescope makers. He wisely selected the renowned Munich firm of Merz and Mahler to construct a refractor using a recently completed objective lens of 11.2 inches aperture.

In April 1845 the great telescope finally entered service. Unrivalled by

▶ The Cincinnati Observatory's 11.2-inch Merz and Mahler refractor is a painstakingly preserved masterpiece that continues to serve the public.

MARS: NASA / STSCI / J. BELL (CORNELL U.) / M. WOLFF (SSI); TELESCOPE: MARY STRUBBE any instrument in the Western Hemisphere, at the time it was the fourth largest refractor in the world.

While Mitchel was obliged to patiently endure frequent interruptions by shareholders wanting to look through the telescope, he proved to be an energetic and capable observer. He spent many hours at the eyepiece studying Mars, which in 1845 was approaching a close perihelic opposition similar to the one that will occur this October.

During perihelic apparitions the south polar region of Mars is tilted toward the Sun, allowing observers to monitor the rapid retreat of the polar cap during late Martian spring and early summer. Mitchel reported that on the evening of August 30 he observed ". . . a small bright spot . . . projecting out of the lower side of the polar spot." He went on to say:

> *. . . After the lapse of an hour or more . . . I was astonished to find a manifest change in the position of this small bright spot. It had apparently separated itself from the large spot and the edges of the two were now in contact, whereas when first seen they overlapped. . .. On the following evening I found a recurrence of the same phenomena. In the course of a few days the small spot gradually faded . . . and was not seen at any subsequent observation.*

Dubbed the "Mountains of Mitchel" in 1862 by the British artist and astronomer Nathaniel Green, this feature appears whenever the dwindling southern polar cap is favorably presented for observation. Occupying a swath of longitude from 300° to 330° at a latitude of 70° (almost 400 kilometers from the true pole), it follows a regular pattern of seasonal development, breaking up into discrete white dots before eventually vanishing. Green reasonably inferred that the lingering remnants were isolated snowfields on the summits of mountains that thawed long after snow at lower elevations.

When it appears as a brighter region within the polar cap or as a bulge or peninsula on its periphery, It is known as Novissima Thyle (Newest Thule) in Giovanni Schiaparelli's Latinized Martian nomenclature of ancient lands and mythologies introduced in 1877. Astronomer Eugène Antoniadi christened it Novus Mons (New Mountain) when it is completely detached from the retreating cap. He dubbed the dark rift that separates Novus Mons from the main body of the polar cap Rima Australis (Southern Fissure).

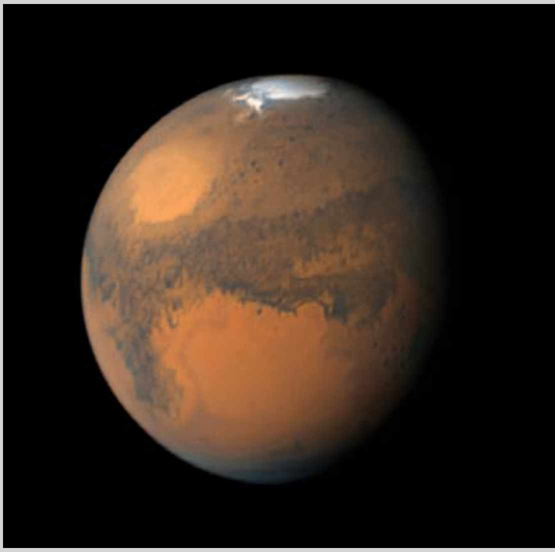
Mars expert Jeff Beish of the Association of Lunar and Planetary Observers (ALPO) predicts that Novissima Thyle will begin to protrude from the border of the polar cap early this June. About a month later the cap's retreat will leave the outlying "island" of Novus Mons. This, in turn, will contract into small patches early in August and may disappear completely by September, when summer solstice occurs on Mars.

A magnification of 200× or more and a telescope of at least 6 inches aperture is required to follow these developments. Use a red (Wratten 25 or 23A) or orange (Wratten 21) filter to penetrate any hazes that may be present over the polar region and sharpen the outlines of surface snows. Be on the lookout for the appearance of other dark rifts, notably Rima Angusta (Narrow Fissure), which may extend from 60° to 270° by mid-September.

Close-up inspection of the Mountains of Mitchel by orbiting spacecraft yields surprising results — even the very name has proven to be a misnomer. Two decades ago, the laser altimeter aboard NASA's Mars Global Surveyor revealed that the region's heavily cratered terrain is only moderately elevated.

Curiously, nearby areas at comparable elevations with similar topography do not retain frost. Although a portion of the Mountains of Mitchel includes an escarpment that may shade some frost from sunlight during late winter and early spring, the persistence of frost through late spring remains puzzling. For some still unknown reason, the frost covering the Mountains of Mitchel tends to be brighter and smaller in particle size than the frost on most other areas of the polar cap. Finer grains of frozen carbon dioxide reflect sunlight more efficiently and sublimate more slowly than the coarser frost, which may also contain more sunlight-absorbing dust.

Among the first astronomical discoveries made in the United States, the Mountains of Mitchel remain one of the Red Planet's few enduring mysteries accessible to backyard astronomers.



▲▲This sketch by Mitchel depicts a striking projection on the edge of the retreating south polar cap of Mars on August 30, 1845.

▲The Mountains of Mitchel seen while Mars was in a gibbous phase on September 17, 2018, during the planet's last apparition.

SKETCH: CINCINNATI OBSERVATORY CENTER; MARS: DAMIAN PEACH / CHILESCOPE

■ Contributing Editor **TOM DOBBINS** looks forward to observing the coming apparition of Mars with several instruments from his backyard in Gainesville, Florida.

Heavens Within Themselves

Five adjacent galaxies exhibit amazingly varied structures.

The vast sun clusters' gather'd blaze,
World-isles in lonely skies,
Whole heavens within themselves, amaze
Our brief humanities.

— Alfred, Lord Tennyson,
The Charge of the Heavy
Brigade at Balaclava

Although I've been writing monthly columns for *Sky & Telescope* for a dozen years, there are two objects from Charles Messier's famous catalog that I've never touched upon. This is the perfect time of year to correct that oversight by featuring these neglected galaxies, M88 and M91 in Coma Berenices.

M88 is one of the brightest spiral galaxies in the Virgo Cluster, which is centered about 54 million light-years away from us and contains at least 1,300 members. M88 is a Seyfert galaxy, defined by a brilliant nucleus of variable light intensity coupled with a spectrum indicating that it's powered by a supermassive object (probably a black hole) at the heart of the galaxy. Seyfert galaxies are named for the American astronomer Carl Keenan Seyfert, who, in the 1940s, found a number of galaxies presenting these features.

M88 is located roughly 2.9° south-southwest of 25 Comae, and it's yours for the taking through almost any telescope in a moderately dark sky. Admiral William H. Smyth found M88 quite charming through his 6-inch refractor. In his 1844 *Bedford Catalogue*, Smyth writes: "A long elliptical nebula, on the outer side of Virgo's left wing. It is pale-white in colour, and trends in a line bearing *np* [north preceding, or northwest] and *sf* [south following, or southeast]; and with its attendant stars, forms a pretty pageant."

M88 and 25 Comae share the field of view through 15×45 image-stabilized binoculars. From my semirural home, the galaxy is a faint oval with a dim star dangling from its southeastern end. M88 is easily visible and elongated through my 105-mm refractor at 28×. It runs southeast-northwest, and the star that was visible through binoculars now looks fuzzy. At 87× this unsharp star becomes a wide, unequal pair that makes a skinny triangle with a very dim star to the east. Closer to M88, another faint sun perches north of the galaxy's northwestern end. M88's halo cov-

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

▼ Messier 88 is one of the sky's brightest Seyfert galaxies. Like all Seyferts, it has a tiny, brilliant nucleus with exotic emission lines.

MASIL ASTRO-IMAGING TEAM

ers about 4½′ × 2′ and enfolds a small, brighter core with a stellar nucleus. I can see, but not quite hold constantly, an extremely dim star superposed on the galaxy's southeastern tip.

In my 10-inch reflector at 192×, M88 spans 5½′ × 2½′ and grows gradually brighter toward a small, oval inner core. Brightness variations in the halo suggest spiral arms that unwrap clockwise. The superposed star now accompanies a fainter companion to its south-southwest. Deep images show that the companion is a snug (1.9″) double star. It might take a very large telescope to separate its 15th-magnitude components. If you give it a try, please let me know how well you succeed.

The galaxy **M91** is only 50′ east of M88, with the two visible in the same binocular field of view. However, M91 is not an easy binocular object. The smallest binoculars through which I've spotted it are 18×50s with image stabilization. Even then it was simply a small, very faint smudge that took a little while to spot.

Through a telescope, you can follow part of Smyth's starry pageant from M88 to M91. The star hovering above M88's northwestern end is the first in an arc of three that curves northeast, each star brighter than the one before. Farther east, three more stars curve back down to M91, the final one lying off the galaxy's western side.

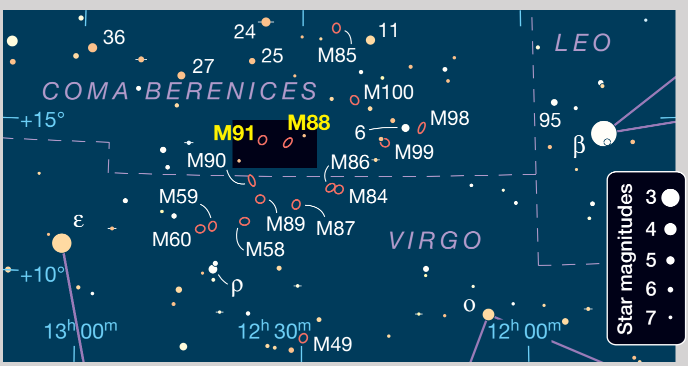
My 105-mm refractor at 28× shows M88 and M91 in the same field, with M91 as a faint spot. At 87× the galaxy grows a small round core with a stellar nucleus. The core has bar-like extensions that run east-northeast to west-southwest. M91 covers about 2′, and its core is less than half that.

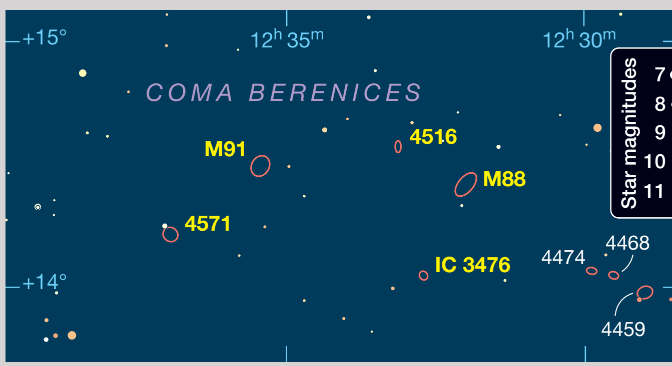
▲ Messier 91 is a classic example of a barred spiral galaxy.

My 10-inch scope at 192× reveals a faint wisp reaching north from the western extension of M91 and another reaching south from the opposite extension. The wisps quickly fade to a very faint halo that's somewhat oval and aligned perpendicular to the bar. The oval is about 2½′ wide, but its length is difficult to judge because the halo is rather dim. My 14.5-inch reflector at 170× makes the halo appreciably easier and puffs it out to about 5′ × 3½′.

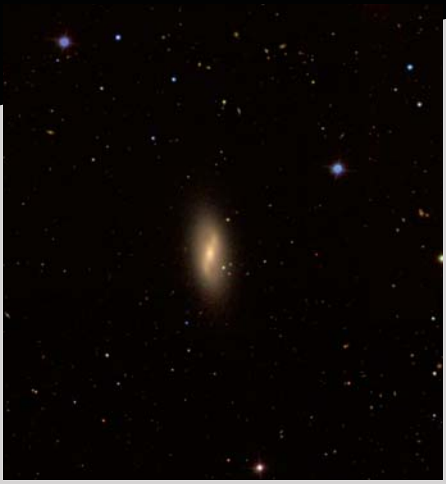
There's no object at the coordinates given for M91 by its discoverer, Charles Messier, so M91 was long considered "missing." Various hypotheses were put forward in a celestial version of a *Where's Waldo?* hunt. Astronomers and historians suggested that M91 might be NGC 4571, a passing comet, or a duplicate observation of M58. But it was an amateur astronomer from Texas who came up with the accepted solution to this puzzle, first published in this magazine's Letters column for December 1969. William C. Williams found that NGC 4548 fits Messier's description and position for M91 if you assume that Messier mixed up which object he'd used as his reference point. Thus, Messier's offsets should be applied to M88, not M58.

The little galaxy **NGC 4516** sits one-third of the way from M88 to M91 and 8′ north of an imaginary line connecting them. With my 105-mm scope at 87×, I can see NGC 4516 intermittently with averted vision as a very small glow





NOAO / AURA / NSF



▲ *Left:* NGC 4516 is a spiral with a pronounced S-shaped bar. *Center:* Blue stars suggest ongoing starburst activity in the irregular galaxy IC 3476. *Right:* NGC 4571 is an unusual ringed spiral galaxy.

elongated north-south. (Averted vision is the practice of looking a bit off to one side of a faint object to allow its light to fall on a more sensitive area of your eye's retina.)

The view through my 10-inch reflector at 192× is fascinating. At first glance, I was astonished when the galaxy's tilt seemed to change with averted vision. A more careful look showed a bright region about 1′ long and one-quarter as wide, tipped west of north, that spans a slender, larger oval running nearly north-south. Only the former stood out with direct vision. The bright area is a lovely sight and consists of a small core with a distinct nucleus at the center of a shallow S curve. Averted vision wraps it all in a delicate cocoon.

Let's drop 24′ south-southeast from M88 to a north-south pair of 12th-magnitude stars 2.7′ apart. The intriguing galaxy **IC 3476** rests 4.4′ east of the northern star. It's readily visible in my 105-mm refractor at 87× as a hazy blot about 40″ across. In the 10-inch scope at 192×, three faint suns join the 12th-magnitude pair to outline a candle snuffer ready to put out the light of IC 3476. The galaxy displays a lumpy brightness distribution and peculiar shape. IC 3476 is about 40″ wide at its northeastern end and tapers down toward the southwest, giving it a candle-flame profile 1¼′ long. The wide end contains a relatively large, blotchy, bright area, and some additional clumpy enhancements line the galaxy's southeastern side.

Galaxies in Southern Coma Berenices

Object	Mag(v)	Size	RA	Dec.
M88	9.6	6.9′ × 3.7′	12^h 32.0^m	+14° 25′
M91	10.2	5.4′ × 4.3′	12^h 35.4^m	+14° 30′
NGC 4516	12.8	1.9′ × 0.8′	12^h 33.1^m	+14° 35′
IC 3476	12.7	2.1′ × 1.8′	12^h 32.7^m	+14° 35′
NGC 4571	11.3	3.6′ × 3.2′	12^h 36.9^m	+14° 13′

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.

Strange little IC 3476 has been assigned a morphological type of IB(s)m — a barred, Magellanic-type irregular galaxy with traces of spiral structure. IC 3476 surprised astronomers with a supernova in 1970.

Our final target is **NGC 4571**, found 27′ southeast of M91. The galaxy has a 9th-magnitude star guarding its northeastern edge, and appears roundish, with a small brighter core in the 105-mm scope at 87×. Its low-surface-brightness halo improves with averted vision and is roughly 2′ to 2½′ across. Although NGC 4571 is more obvious in my 10-inch scope, it discloses no further secrets.

NGC 4571 is an unusual galaxy of type SA(r)c. Its fleecy spiral arms reach inward to a well-defined ring that closely circles the galaxy's core. Such ring structure is rare in a late-type spiral galaxy, that is, one that exhibits a small central bulge and loosely structured arms with prominent condensations.

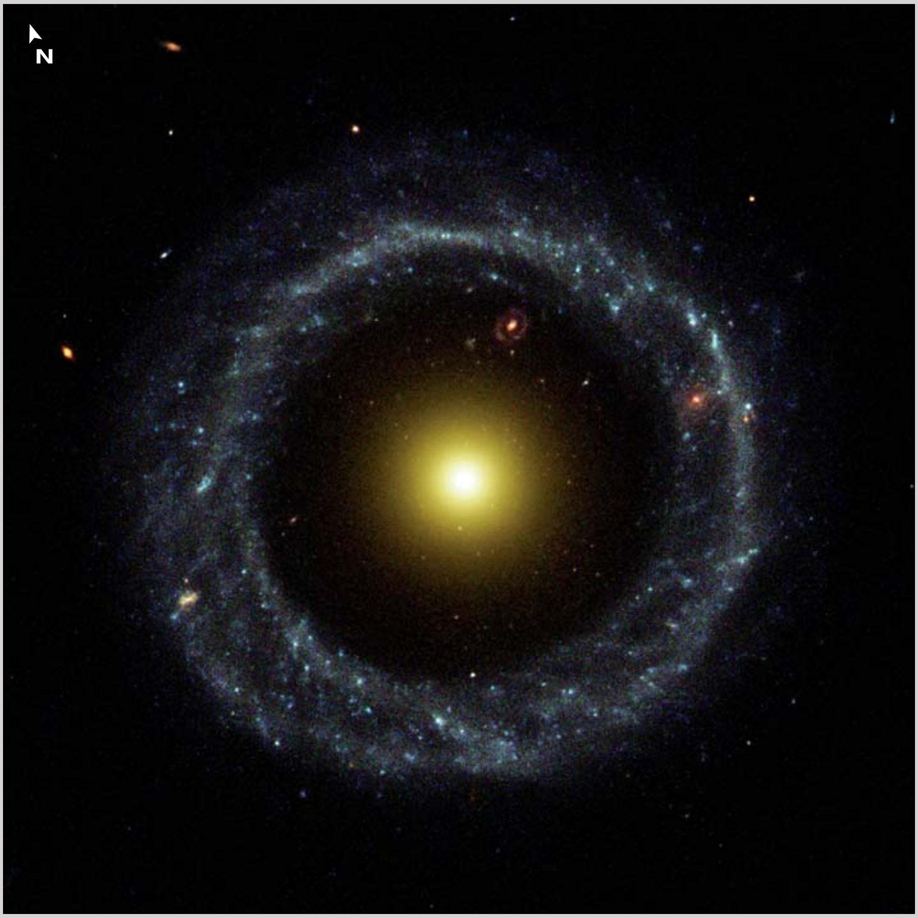
All these wonderful "world-isles" dwell in the core of the vast Virgo Cluster, possessing whole heavens within themselves that have long inspired the wondering skygazer's amazement. See page 22 for more interesting galaxies to observe.

■ Contributing Editor **SUE FRENCH** wrote this column for the May 2012 issue of *Sky & Telescope*.

SLOAN DIGITAL SKY SURVEY (3)

Hoag's Legacy

Ring galaxies are among some of the quirkiest objects in the sky — and one in particular piqued the author's curiosity.



▲ **RINGED SPLENDOR** Hoag's Object, named for its discoverer, is the prototype of a class of galaxies that display unusual morphologies involving ringlike structures. Incredibly, another ring galaxy (much farther away) peeks cheekily through the gap between the yellow core and the blue ring. Many consider this Hubble Space Telescope image to be one of its most iconic.

NASA / ESA / THE HUBBLE HERITAGE TEAM

If beauty is symmetry laced with mystery, then a discovery by a young doctoral student back in 1950 could be one of the most beautiful ever. His discovery has inspired not only generations of professional astronomers but has also intrigued amateurs drawn to arcana of the sky.

Arthur Hoag was born in 1921 and spent his early years in the New York City area. His childhood was marred by the tragic death of his mother and younger sister in a barge accident on the Hudson River when he was five. His father died when Arthur was 15, but the lad had the fortunate support of an extended family. Teachers, both in high school and at Brown University, where he graduated in 1942 with a degree in physics, stoked his interest in astronomy.

After World War II, Hoag attended Harvard University, where he was mentored by Bart Bok. He received his PhD in 1952, and then went on to become the first director of the U.S. Naval Observatory division in Flagstaff, Arizona. In the mid-1960s he headed the stellar division at Kitt Peak National Observatory in Tucson, and later returned to Flagstaff to serve as director of Lowell Observatory from 1977 until he retired in 1986.

Throughout his career, Hoag was particularly interested in developing and testing instrumentation. He performed early experiments with cooled photographic emulsions, and he also worked on versions of the grating prism, or *grism*, which he used to identify quasars in the 1970s.

Hoag's contributions to the amateur astronomy community include the discovery of a cluster of three quasars near M82, and an object that first featured in a brief, 21-line *Astronomical Journal* report in October 1950 entitled "A Peculiar Object in Serpens." He discovered this unique object on a photographic plate, initially taking it to be a "perfectly symmetrical" planetary nebula. But the size and nucleus weren't characteristic of planetary nebulae. Hoag also tentatively suggested gravitational lensing (which displayed remarkable forward thinking, for the first observation of a gravitational lens didn't happen until 1979). In the end, his most likely explanation — that it was a "new species among the 'pathological' galaxies" — gradually took hold, and the object would eventually bear his name.

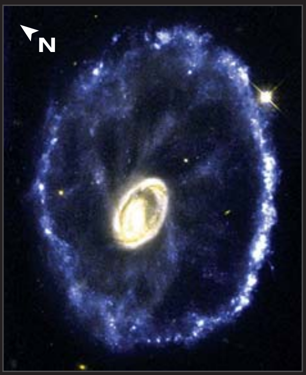
Texas Star Party Memories

As I write this on the first day of the 39th Texas Star Party, I am reminded of the TSP's influence on my early interest

Hoag's Objects

Object	Mag(v)	RA	Dec.
Hoag's Object	15.1	$15^h\ 17.2^m$	+21° 35′
Hoag 1 (Quasar)	19.5	$09^h\ 57.0^m$	+69° 39′
NGC 4650A	13.6	$12^h\ 44.8^m$	−40° 43′
Cartwheel Galaxy	15.2	$00^h\ 37.7^m$	−33° 43′

Right ascension and declination are for equinox 2000.0.

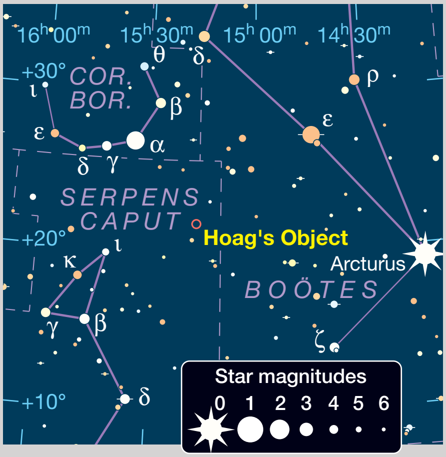


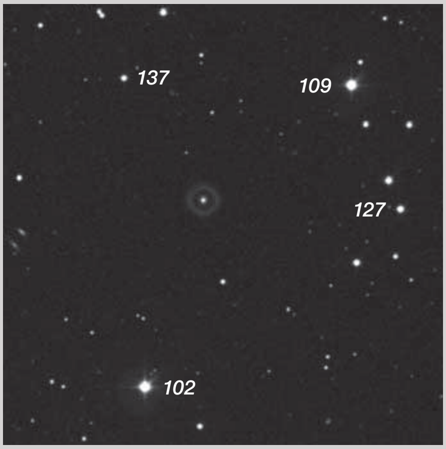
COSMIC CARTWHEEL The Cartwheel Galaxy, lying some 500 million light-years away in Sculptor, likely formed after a smaller galaxy plunged into a larger spiral around 200 million years ago. These events trigger spurts of star formation that can be seen in the ring-like structure surrounding the core.

in the deep sky. Attendees are drawn to the event to share their fascination for remarkable celestial objects with fellow observers. In the early 1990s I was still new to serious deep-sky observing and brought a large, heavy, and boxy 18-inch reflector to the 1992 TSP. I quickly learned of higher quality optical and mechanical options. So the following winter I traveled to Pennsylvania to pick up a 25-inch f/5 Tectron reflector housing a fine Galaxy Optics mirror. Then at the 1993 TSP, I was introduced to the fine art of visual sleuthing and to a host of intriguing objects, thanks to one of the best observers I've ever met.

Larry Mitchell of Houston, Texas, has been an avid observer of the deep sky for more than three decades. In the late 1980s he spent almost every clear night viewing with his 24-inch reflector, during which time, among many feats, he bagged all 2,400+ objects observed by William Herschel. Now best known for his challenging Advanced Observing Program at the TSP, a quarter century ago he and his observing partner Barbara Wilson were "sirens of the sky," calling out the names of unusual and seldom-observed (or never-observed) objects back and forth, drawing unsuspecting initiates into their lair.

▼ **BRIGHTER CORE, FAINTER RING** At 15th-magnitude, Hoag's Object can be a challenging target, and the fainter ring even more so. This 10′ × 10′ POSS-II blue-plate image enhances the ring. Magnitudes of nearby stars are marked.





My incipient interest in obscure and esoteric things in the sky was ignited by their contagious passion. I recall one object in particular that piqued my curiosity: a perfectly round galaxy with a gap between the core and outer ring. I had glimpsed **Hoag's Object**.

Hoag's Objects

Also known as PGC 54559, Hoag's Object is located in northwestern Serpens Caput, about 6.5° southwest of Alphecca, or Alpha (α) Coronae Borealis. The nearest "bright" star — at magnitude 5.6 — is 1° south-southeast of the galaxy. It's relatively isolated from nearby deep-sky objects, as the closest is 14th-magnitude NGC 5910 (one of two Hickson Compact Group galaxies) about 1° to the southeast.

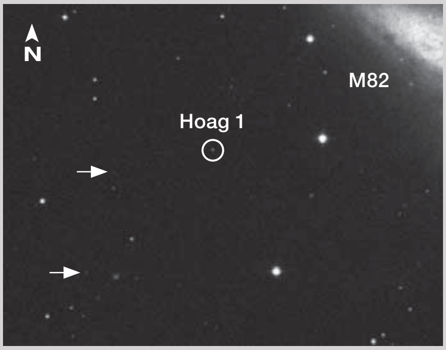
Hoag's Object as a whole has a B magnitude of 15.8 and a V magnitude of 15.1. Since the core is yellow and the fainter ring very blue, color must be taken into account when describing the galaxy. Observations indicate that this face-on ring galaxy is likely inclined to our line of sight by 19°. The outer circumference of the ring spans 45″, which corresponds to a diameter of some 130,000 light-years at a distance of a little more than 600 million light-years. The core spans 6″ in diameter. Most of the visible light from the galaxy is concentrated in this inner core, which appears 2 to 3 magnitudes brighter than the ring — this is especially evident in red photographic plates.

Coincidentally, another ring galaxy (SDSS J151713.93+213516.8) peeks through the dark gap between the core and the ring of Hoag's Object. This may be a "cartwheel"-type galaxy, as Hubble Space Telescope images hint at faint spokes inside its ring. What a remarkable tableau!

When I started observing this galaxy in the spring of 1993, it was one of the most exciting things I'd ever seen and sparked an abiding interest in unusual objects. I viewed it half a dozen times in the 25-inch throughout the following decade, noting the brighter center and hazy, outer ring. In 2004, the dark "gap" separating the ring from the core eluded me even at 908× and with the galaxy positioned near the zenith. It took the increased power of my 32-inch f/4 scope to be certain of seeing that feature. Despite the larger aperture, the background "Baby Hoag" ring galaxy at the one o'clock position within the gap remains elusive. I plan to keep trying.

Arthur Hoag researched many things, but his other eponymous finds, as noted, were three closely clustered quasars southeast of M82 in Ursa Major. The brightest is **Hoag 1** with a V mag-

CARTWHEEL GALAXY: CURT STRUCK / PHILIP APPLETON / KIRK BORNE / RAY LUCAS / NASA / ESA; ZOOM IMAGE: POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY



▲ **CHALLENGING TRIPLET** Hoag 1 appears as a faint dot southeast of M82 in this 7′ × 10′ blue POSS-II image. The arrows indicate the positions of Hoag 2 and Hoag 3.

nitude of 19.5 and a redshift of 2.05. I viewed this object's ten-and-a-half-billion-year-old light on the night of May 13, 2017, with my 32-inch reflector at 650× in seeing of 4/10 and transparency of 6–7/10. It was stellar, of course, and difficult in those conditions. At the eyepiece there was no hint of the two fainter, nearby Hoag quasars. I plan to try for those two on a better night.

Several Kinds of Rings

After the *National Geographic Society — Palomar Observatory Sky Survey* (*POSS*) was completed in 1958, astronomers trawled this jewel of a resource for previously unknown objects. The Russian astronomer Boris Vorontsov-Vel'yaminov searched systematically for interacting and unusual galaxies. His *Atlas and Catalog of Interacting Galaxies*, published in 1959 and later expanded in the 1970s to 852 items, listed many ring-type galaxies, including a category of "detached-ring" objects similar to Hoag's find. Three of Halton Arp's peculiar galaxies (numbers 146, 147, and 148) have ring structures. During the past seven decades reports of new ring galaxy discoveries have trickled in. Proliferation can foster confusion until organizing principles of formation and evolution are established. The field appears to be without consensus, but agreement is simmering in some areas. In a paper published in 2017, Burçin Mutlu Pakdil of the University of Minnesota and her collaborators nicely summarize the four main categories of galaxy rings: *polar*, *collisional*, *accretion*, and those arising from *secular evolution*.

Polar-ring galaxies are likely formed when a smaller galaxy is gravitationally captured by a larger lenticular or elliptical galaxy, and waves of star formation ensue. I've observed **NGC 4650A**, NGC 660, and NGC 2685, which are examples from this category. On a recent trip to Chile I was thrilled to also spot NGC 5128 (Centaurus A) with my unaided eye. It's arguably the most famous galaxy in this group.

Galaxies sporting collisional rings are perhaps best exemplified by the **Cartwheel Galaxy** (ESO 350-40) in Sculptor. In this case, an interloper has collided head-on with another galaxy, giving rise to nearly symmetric density waves of gravitational disruption that trigger star formation. I have viewed the 15th-magnitude Cartwheel with my 32-inch reflector at the Okie-Tex Star Party, but I couldn't distinguish the "spokes." On the *POSS* plates and in the eyepiece, the Cartwheel appears reverse to Hoag's Object: The ring is brighter than the core.

▲ **RING AROUND A GALAXY** A prime example of a polar-ring galaxy, NGC 4650A lies around 130 million light-years away in Centaurus. As the category name implies, the ring rotates around the poles of the central galaxy.

IC 2006 in Eridanus is a good example of a galaxy with a ring that formed through accretion processes. In these cases, an early-type galaxy accreted external matter — possibly through interactions at a distance with other galaxies — that went into structuring the ring. IC 2006 is ephemeral at best on the red *POSS* plates, and on the blue plates it's large (4′ in diameter), circular, and ghostly faint. I have yet to observe this galaxy.

The most common ring galaxies are likely forged via secular evolution through slow, steady interaction with their environment. This class is largely composed of barred spirals, although non-barred spirals have also been observed to sport rings. These galaxies morph over time via internal processes, which include star formation induced by spiral density waves and bulge growth through the funneling of gas into the core in barred spirals (which could also contribute to starburst activity).

So, into which of these ring-forming scenarios does Hoag's Object fit? Although consensus hasn't been reached, observational clues largely point to a major accretion event some 2 to 3 billion years ago onto the core of the central elliptical galaxy, likely triggered by interaction with another galaxy.

Epilogue

The prolific science and sci-fi writer Isaac Asimov is credited with the phrase "That's odd!" in reference to a moment of discovery. The legacy of Arthur Hoag's finds will live on if we pursue our personal and collective dreams of exploring outliers in the sky. Beauty — even when it's "odd"— is in the eyepiece of the beholder.

■ **DAVE TOSTESON** enjoys searching the literature and news outlets for unusual and yet-to-be-explained objects to observe.

HOAG 1: POSS-II / STSCI / CALTECH / PALOMAR OBSERVATORY; NGC 4650A: THE HUBBLE HERITAGE TEAM / NASA / ESA

Seventy-nine and Counting: Finding Jupit

The discovery of the Jovian satellites enhanced our understanding of the solar system and changed the course of history.

In the hierarchy of the sky, Jupiter has always enjoyed a front-row seat. With its prominence exceeded only by the Moon, Venus, and occasionally Mars, Jupiter is usually the third brightest object in the night sky. It's little wonder that the Romans named it the king of the gods.

On January 7, 1610, Jupiter's eminence surged when Galileo Galilei aimed his newly built telescope at it and observed what at first appeared to be three nearby stars hugging the regal planet. Then, on January 11th, he saw four. Documenting the first planetary moons other than our own, Galileo vaulted to lasting fame. The discovery of these four worlds was one of the most momentous turning points in astronomical history, challenging the established belief that Earth was the center of Creation around which all heavenly bodies revolved. Suddenly there was another system — one in which our planet didn't occupy the exclusive focus of the firmament.

In March 1610, Galileo published his findings in a pamphlet, *Sidereus nuncius* (*The Starry Messenger*), an account of his observations of Jupiter's satellites, the mountains and craters of the Moon, and the myriad stars visible in his telescope. His immediate intent was to honor his patron, Cosimo II de Medici, the Grand Duke of Tuscany, by naming the four satellites the "Medicean Stars." It wasn't until the mid-1800s that they were officially named Io, Europa, Ganymede, and Callisto, all characters from myths associated with Jupiter. Simon Marius proposed this nomenclature following a suggestion by fellow German astronomer Johannes Kepler (best known for determining that the planets describe elliptical orbits around the Sun — an accomplishment that ranks as one of the greatest intellectual achievements in history).

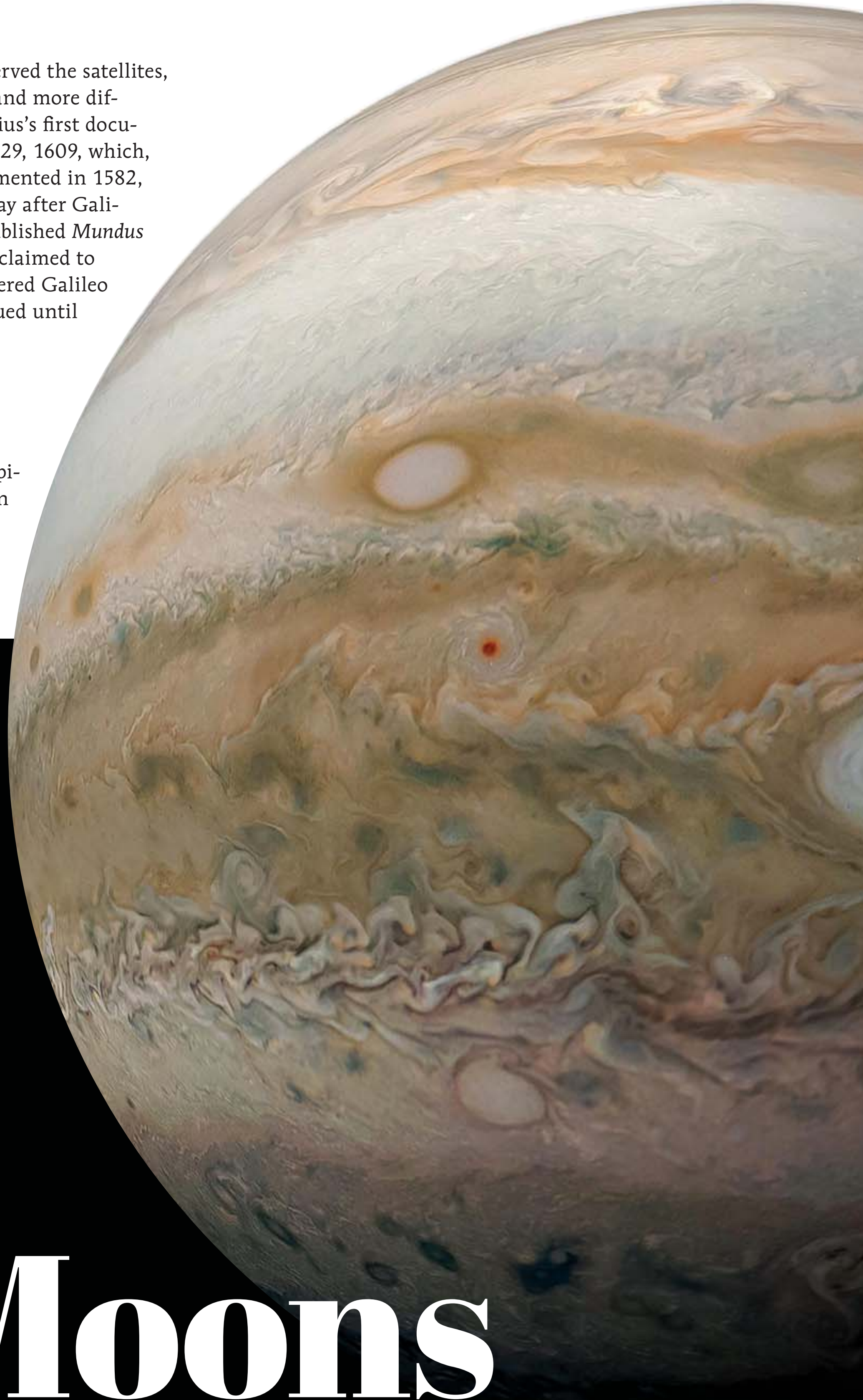
However, digging deeper, it's apparent that Marius deserves credit for more than just the naming of

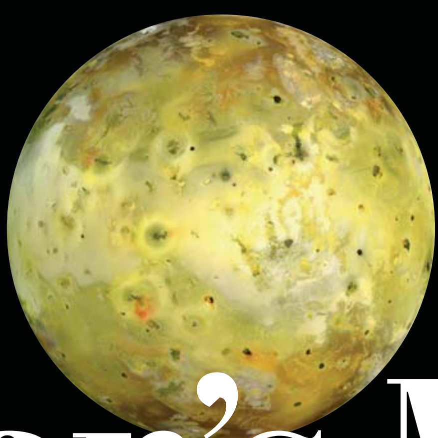
CALLISTO, EUROPA: NASA / JPL / DLR; GANYMEDE: NASA / JPL the moons. In fact, he independently observed the satellites, but records of his work are less complete and more difficult to verify than those of Galileo. Marius's first documented observations are dated December 29, 1609, which, after adjusting for calendar reform implemented in 1582, translates to January 8, 1610 — just one day after Galileo's first observations! In 1614 Marius published *Mundus Iovialis* (*The World of Jupiter*) in which he claimed to have observed the satellites first. This angered Galileo and triggered a bitter conflict that continued until Marius's death in 1625.

IO: NASA / JPL / UNIVERSITY OF ARIZONA; JUPITER: NASA / JPL-CALTECH / SWRI / MSSS / KEVIN M. GILL

Through the Looking Glass

As anyone who observes Jupiter regularly knows, the four Galilean satellites aren't always all visible. They can hide behind Jupiter's disk or traverse through eclipse within the planet's shadow. This happens most often for Io and Europa, which never journey far from the planet. Ganymede





◄▼ **GALILEO'S MOONS** This composite family portrait shows (from left to right) Callisto, Ganymede, Europa, Io, and Jupiter. The individual images were recorded by these spacecraft: Galileo (Ganymede, Europa, and Io), Voyager 2 (Callisto), and Juno (Jupiter). Images not to scale.

er's Moons

and Callisto, on the other hand, are almost always visible. The Galilean moons have orbits that are virtually perfectly circular and, consequently, veer as far to the east of Jupiter as they do to the west. Although the four moons orbit in nearly the same plane aligned with Jupiter's equator, from our Earthly perspective we usually view the Jovian system from slightly above or below the planet's equator, so the satellites rarely appear strung out in a straight line.

Galileo's telescopes were optically poor by today's standards — his observations we can accomplish with modern binoculars. Indeed, under favorable conditions, Galileo's satellite worlds are bright enough to be discerned with the unaided eye were it not for their proximity to Jupiter and its overpowering luminosity. Ganymede, at magnitude 4.6 and a diameter of 5,262 kilometers, is the brightest and largest, while 4,821-km-diameter Callisto is the dimmest at magnitude 5.7. Europa has a diameter of only 3,122 km, making it the smallest of the four, but its relatively high albedo allows it to shine at magnitude 5.3. Closest to Jupiter in distance is magnitude-5.0 Io, which spans 3,643 km.

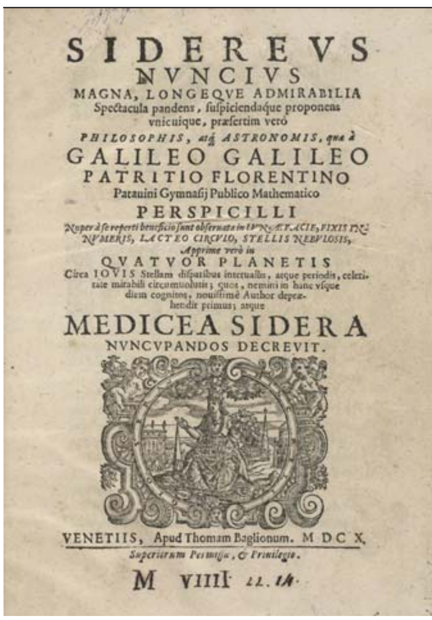
Are there any confirmed naked-eye sightings of the Jovian moons? There is one recorded pre-telescopic observation from the 4th century BC. Chinese astronomer Gan De recorded "a small reddish star" next to Jupiter, which the 20th-century Chinese astronomer and historian Xi Zezong has interpreted as a possible sighting of Ganymede. This magazine has received a few reports over the years, but the very nature of such observations makes them difficult to verify.

◀ **BY ANY OTHER NAME** In a bid to curry favor, Galileo initially named the four new Jovian moons Cosmica Sidera ("Cosimo's stars"), but Cosimo de Medici graciously suggested he refer to the newly discovered objects simply as Medicea Sidera ("the Medician stars"). In this illustration, Galileo is depicted showing Cosimo the Jovian moons.

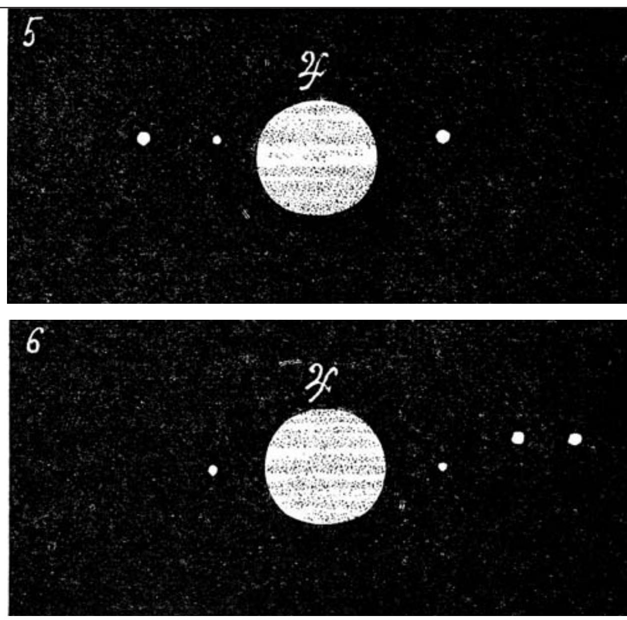
Moving Heaven and Earth

As is well known, Galileo's discoveries and the inevitable implication that Earth no longer occupied a special place in the cosmos prompted consternation within the formidable Catholic establishment. In the early decades of the 16th century, Nicolaus Copernicus labored over a lengthy exposé on heliocentricity, a Sun-centered scenario that opposed the prevailing Earth-centered model that the ancient Greeks, particularly Aristotle and later Ptolemy had promulgated. Heliocentrism also contradicted Catholic dogma, and as such was considered heresy. Copernicus's ideas are spelled out in detail in a six-part book, *De revolutionibus orbium coelestium* (*On the Revolutions of the Heavenly Spheres*), issued at the time of his death in 1543.

While Copernicus was hesitant about publishing his ideas, Galileo was confident his own observations had conclusively verified that the universe was not Earth-centered. He traveled to Rome in 1611 and invited ecclesiastical authorities to view Jupiter through his telescope. Some readily accepted the valid-



SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS INNVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeritate mirabili circumuolutis; quos, nemini in hanc vsque diem cognitos, nouissimè Author depræhendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.
VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.
M VIIII 22. 14



◀◀ **A NEW VIEW** In 1610, Galileo published *Sidereus nuncius* (*The Starry Messenger*), the title page from which is reproduced here. This slender volume contained his pioneering telescopic observations, including drawings of Jupiter's satellites. Although a scientific triumph, *Sidereus nuncius* also set Galileo on a collision course with the Church.

◀ **NEW MOONS** Galileo's drawings depicting Jupiter's four largest moons first appeared in *Sidereus nuncius*. His efforts provided important observational support for the Copernican model of a Sun-centered solar system.

GALILEO AND COSIMO DE MEDICI: CHRONICLE / ALAMY STOCK PHOTO; SIDEREUS NUNCIUS: PUBLIC DOMAIN / WIKIMEDIA COMMONS; JOVIAN MOON DRAWINGS: SPL / SCIENCE SOURCE ity of what appeared to be a miniature analog to the solar system. Others struggled to find reasons to deny what was clearly obvious, appealing to the word of Scripture, which espoused a centralized, motionless Earth. Still others conjectured that the instrument was faulty and didn't portray reality.

However, Jesuit priest and astronomer Christopher Clavius was an early endorser of Galileo's assertions. Clavius was also responsible for much of the analysis behind the 1582 reform of the calendar, which more accurately synchronized it with the length of the year, thus keeping holy days (particularly Easter) in step with the seasons. Ironically, Clavius adhered to the geocentric view, yet he didn't turn a blind eye to the reality presented by Galileo's telescope.

◀ **GALILEO'S NEMESIS** Simon Marius not only gave the Galilean moons the names they now bear, but he also proved to be a thorn in the great scientist's side by claiming to have discovered the satellites first and publishing a book to bolster his assertion.

Galileo's observations and scientific musings triggered years of dispute with the Church, resulting in his eventual trial and subsequent lifetime house arrest. Multiple factors played a part in this outcome, including the overt bluntness of the books Galileo authored, coupled with his sometimes abrasive personality. Teaching and writing about Copernicanism was forbidden, and *Revolutions* was placed on the "Index" — a list of books Catholics were prohibited from reading.

Down-to-Earth Matters

While Galileo's observations ultimately validated a Sun-centered view, observations of Jupiter's moons contributed to other advancements of the era, particularly for determining longitude, essential for navigation and cartography.

Although latitude is easy to reckon by measuring the altitude of stars above the horizon, no equivalent technique existed for determining longitude. In the 1670s Danish astronomer Ole Rømer devised a method of calculating longitude by timing the eclipses of Jupiter's satellites. He made his observations from Uraniborg, Tycho Brahe's observatory near Copenhagen, in concert with Giovanni Domenico Cassini, who documented the same events from Paris. By comparing their results the two could calculate the difference in longitude between the two locations. Although a valid procedure, it proved unworkable from the deck of a ship navigating turbulent oceans. Many other scientists and inventors toiled over the puzzle using various means, but it wasn't until the late 1700s when John Harrison and others built accurate chronometers that a truly reliable method for determining longitude at sea existed.

After relocating to Paris in 1672 to become Cassini's assistant, Rømer continued to observe Jupiter's satellites, which led him to conjecture that the speed of light is finite. This position was counter to the prevailing view that light propagated instantaneously from a source. Both he and Cassini recognized that as Earth and Jupiter move apart in their respective orbits, the interval between eclipses of the satellites increases, and when they approach each other, it decreases. Rømer primarily monitored Io, which, being closest to Jupiter, orbits more frequently and therefore provides more data points. His conclusion was that a finite speed of light accounted for the observed differences, although at the time methods sufficiently accurate for determining the speed of light were unavailable.

More and More Moons

In 1892, American astronomer E. E. Barnard discovered Jupiter's first post-Galilean satellite. Barnard detected the dim little moon (listed at magnitude 14.1) with the newly commissioned 36-inch refractor at Lick Observatory on Mount Hamilton in California. This was to be the last visual discovery of a planetary satellite. At 167 km in diameter, Amalthea (as it was formally named in 1976) is only 3% percent the size

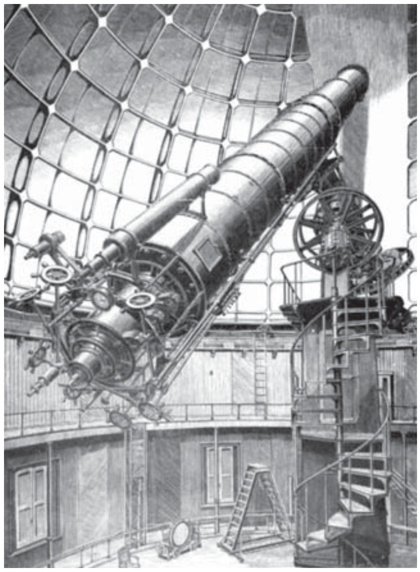
▶ **COPERNICAN REVOLUTION** Polish astronomer Nicolaus Copernicus is credited with having first described a heliocentric solar system in detail in his book *De revolutionibus orbium coelestium* (*On the Revolutions of the Heavenly Spheres*), published in 1543, the year of his death.

PUBLIC DOMAIN / WIKIMEDIA COMMONS (2)

of Ganymede, and orbits much nearer to Jupiter than its four larger siblings do. Consequently, Amalthea is a virtually impossible target through amateur telescopes, regardless of size or quality — Jupiter is roughly 6 million times brighter than Amalthea, but only about 1,500 times brighter than the Galilean moons.

Jupiter's sixth satellite, Himalia, was discovered in 1904 by Charles Dillon Perrine on photographic plates taken with the 36-inch Crossley reflector telescope at Lick Observatory. Although slightly fainter than Amalthea, Himalia orbits far from Jupiter's overpowering brightness and is more easily visible. Nevertheless, at least a 10-inch telescope and optimal viewing conditions are required for this 14.2-magnitude object. Additionally, one would need to separate it from the multitudes of nearby field stars of similar appearance. Perrine also discovered Jupiter's seventh moon, Elara, a year later.

In subsequent decades, discoveries trickled in, but the dam finally broke in 2000 when highly sensitive ground-based detection methods came online. The vast majority of Jupiter's currently known, 79 satellites have been discovered in the past two decades, mostly by a team lead by Scott S. Sheppard at the Carnegie Institution for Science. These are tiny objects, generally only a few kilometers in diameter. However, in 2019 Sheppard's team announced the discovery of 20 new satellites orbiting Saturn, bringing the ringed planet's total to 82, thus crowning it the reigning moon king — at least for now.



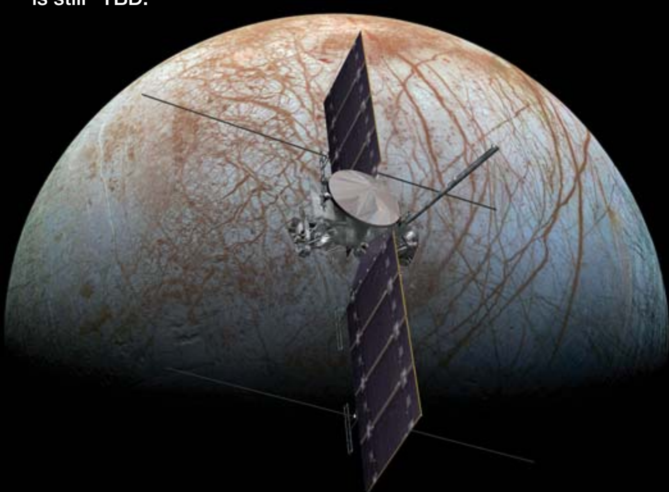
◀ **BIG GLASS** It's easy to imagine how stunned Galileo would have been had he been able to utilize the Lick Observatory's 36-inch behemoth telescope. This refractor was the instrument E. E. Barnard used to make the last visual discovery of a planetary satellite.

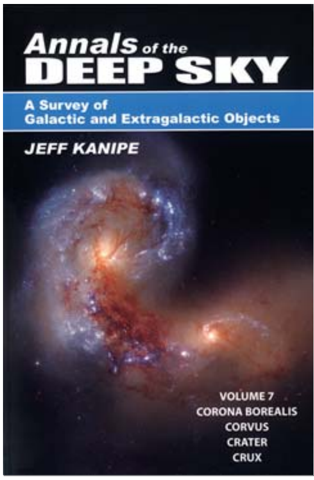
But of all the satellites orbiting Jupiter the only ones that we can accurately describe as "worlds" are the four Galileo discovered. In the 1970s, Io, Europa, Ganymede, and Callisto returned to the forefront of scientific interest as the Pioneer, Voyager, and Galileo spacecraft returned scores of detailed close-up photographs of each one. These images established the distinct personalities of the Galilean moons. Io is a multicolored volcanic wonderland; Ganymede features grooved water-ice terrain; Callisto's ancient surface is pockmarked with impact craters; and Europa is a world covered with a water-ice crust encasing a silicate rock surface, sporting the smoothest surface of any solar system body. Could there be an ocean residing beneath Europa's surface — one that might harbor primitive microorganisms? Enthusiastic scientists are discussing plans for satellite missions to learn more about this exciting world. What began with a small spyglass more than 400 years ago continues unabated to this day.

■ **MIKE WITKOSKI** volunteers at Muddy Run Observatory (located approximately 100 miles west of Philadelphia), where the Galilean satellites are a big hit on public viewing nights.

LICK REFRACTOR: PUBLIC DOMAIN / WIKIMEDIA COMMONS; EUROPA CLIPPER BASE IMAGE: NASA / JPL-CALTECH / SETI INSTITUTE; EUROPA CLOSE-UP: NASA / JPL-CALTECH / UNIVERSITY OF ARIZONA

MYSTERY MOON What lurks below the intricate icy surface of Europa? The proposed Europa Clipper orbiter is designed to help scientists find out. The launch date of the mission, however, is still "TBD."





◀ CONTINUING COMPENDIUM

Willmann-Bell announces the latest volume of its popular series *Annals of the Deep Sky: A Survey of Galactic and Extragalactic Objects* by Jeff Kanipe ($24.95). Volume 7 covers the constellations Corona Borealis, Corvus, Crater, and Crux, providing the most up-to-date and comprehensive information on the prominent stars, deep-sky objects, and other celestial exotica within each region. This richly illustrated volume details the latest findings in astrophysics and cosmology, combined with extensive historical and observational information for each object. Volume 7 is softbound and includes 223 illustrations. The book is 6 by 9 inches and has 394 pages. ISBN 978-1-942675-13-6.

Willmann-Bell
P.O. Box 35025, Richmond, VA 23235
804-320-7016 or 1-800-825-STAR (7827); willbell.com

▶ OFF-AXIS AUTOGUIDER

Diffraction Limited announces the SBIG StarChaser series of Off-Axis Guider Cameras. These unique guide cameras both feature a 1.3-megapixel CMOS detector with 4.8-micron-square pixels in a thin off-axis guider housing with an adjustable pick-off mirror. The StarChaser SC-2 ($999) attaches to most SBIG STF or Aluma cameras and filter wheels, while the larger StarChaser SC-3 ($1,299) works with the SBIG STX and STXL-series cameras and compatible filter wheels. Both models operate in conjunction with the company's Adaptive Optics high-speed correctors for their respective models. Each camera is powered with an included 12V power supply and connect to a computer via a 6-foot USB 2.0 cable. A copy of *MaxIm LT* is also included with purchase.

Diffraction Limited
59 Grenfell Crescent, Unit B
Ottawa, ON K2G 0G3, Canada
613-225-2732; diffractionlimited.com

◀ ENHANCED OBSERVING

At long last, Unistellar Optics unveils the eVscope ($2,999). This integrated telescope system promises to change your observing experience. The system combines a 4½-inch f/4 reflector with a permanently mounted Sony IMC224 color CMOS detector, an enhanced-vision OLED screen "eyepiece," and a powerful alt-az Go To mount controlled by your smartphone. The system's patent-pending Autonomous Field Detection feature automatically recognizes star fields, self-aligns, and is ready to observe within 10 seconds of powering up. Its track-and-accumulate imaging with automated intelligent image-processing produces colorful "live" images of 4,800 deep-sky targets from its internal database within minutes of pointing at each subject. The eVscope weighs 19.8 lbs assembled and comes with a collapsible tripod, an internal rechargeable battery that powers the unit for up to 10 hours, and a free iOS or Android control app.

Unistellar
unistellaroptics.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.org. Not all announcements can be listed.

Orion's Premium Linear BinoViewer

This binoviewer has unusual features that could change any opinions you may have about using one.

Orion Premium Linear BinoViewer for Telescopes

U.S. Price: $449.99

Telescope.com

What We Like

Works with any telescope fitted for 1¼-inch eyepieces

Very solidly built

Collet-style eyepiece holders

What We Don't Like

Observing experiences with binoviewers can vary from person to person, and this unit works differently than "conventional" models, so it has different pros and cons that need to be considered. But this isn't a bad thing.

SURF THE INTERNET FOR information about observing with a binoviewer and you'll find lots of superlatives. "Awesome," "like floating in space," "OMG," "things [may] never be the same again," and the list goes on. It makes sense after all. Humans evolved with two eyes, so why wouldn't it be better to look through a telescope with both at the same time rather than just one? That said, I suspect the reason binoviewers aren't wildly popular is because all the ones I've tried have advantages that are offset by some notable disadvantages.

In that regard, the Orion BinoViewer is similar. It has pros and cons. But there are some very significant differences that set it apart from others. Foremost is its ability to work with any telescope that accepts 1¼-inch eyepieces, even Newtonians with low-profile focusers that have limited travel. If your scope comes to focus with a given 1¼-inch eyepiece, you can add the Orion BinoViewer and still be in focus without changing the magnification or field of view. No exceptions. The Orion BinoViewer does not require additional back focus.

Some of the binoviewers I've tried skirt the back-focus issue with a Barlow-like lens to extend a telescope's focus point. But for a given eyepiece, this

▼ Orion's Premium Linear BinoViewer comes with a quality, waterproof carrying case, which has plenty of additional space for the optional pentaprism diagonal and at least one pair of eyepieces. The foam lining is pre-cut into cubes that are easily removed to make room for accessories.

ALL PHOTOS BY THE AUTHOR

significantly changes the telescope's magnification and field of view. And while popular Schmidt- and Maksutov-Cassegrain telescopes that focus with moving primary mirrors can extend their back focus far enough to accommodate a conventional binoviewer, doing this also increases the telescope's effective focal length and thus changes the magnification and field of view of a given eyepiece.

There are other ways the Orion BinoViewer is different from conventional models, so let me start with the day the unit we borrowed for this review arrived. I was doing routine maintenance in my backyard observatory when the UPS truck rumbled up to the driveway. Something as straightforward as the Orion BinoViewer doesn't need a mandatory study of its instruction manual before a first look, so I swung the 4-inch refractor I'd been using the night before toward a neighbor's flowerbed about 700 feet away and visible through a scattering of tree branches. Using the scope "straight through," I racked the focuser out until a 24-mm eyepiece was sharply focused on the flowers. I removed the eyepiece from the focuser, replaced it with the Orion BinoViewer, and slipped the eyepiece into its left eyepiece holder. The image was perfectly focused and the field looked the same, just as advertised, and rather impressive at that. I repeated this test with a handful of other 1¼-inch eyepieces, including modern wide-field designs, all with the same result. (Careful tests later showed that the Orion BinoViewer does introduce a small increase in magnification with a corresponding reduction in the field of view. It could easily go unnoticed.)

Over the years, telescopes have come and gone in my life, but eyepieces seem to flow in only one direction. Nevertheless, on that first day the only "matched" pair I could find suitable for a binoviewer were two of the ubiquitous Meade 26mm Super Plössls that ship with many of the company's telescopes. They were of different vintages, but the same mechanically and optically.

My first two-eyed look through the Orion BinoViewer was shocking — the scene appeared truly three-dimensional, even being enhanced by a squirrel scampering around the flowerbed. This, I thought, had to be an extreme example of the power of suggestion since I was looking through a telescope with a single objective. The scene couldn't possibly be real 3D the way it is in binoculars that have separate optical systems for each eye. But before I had time to marvel at this lesson in eye-brain gymnastics, things got really weird.

As I moved my head, shifting my gaze through the Orion BinoViewer's eyepieces, there was clearly visible parallax. The nearby tree branches and shrubs behind the flowerbed appeared to be at different distances. And, to make matters even more confusing, the distances seemed inverted — the nearby branches appeared to be behind the flowers. This was simply nuts! I couldn't think of any reason why this was happening.

The problem is, I wasn't thinking hard enough, since the answer

▶ Rather than pivoting on a central axis to vary the spacing of the eyepieces, the Orion BinoViewer's eyepieces slide linearly outward from a center position. The scale shows the eyepiece separation, which ranges from 58 to 74 millimeters. Eyepieces are held in place with solid, locking collets, and the right eyepiece has a precision helical focuser to compensate for any variations between an observer's eyes.

▲ As detailed in the accompanying text, the Orion BinoViewer is unusual because it divides a telescope's aperture into two halves, putting the light collected by each half into the separate eyepieces. For this photograph a bright green light was placed into one of the Orion BinoViewer's eyepiece holders and projected "backward" through a 12-inch f/5 Newtonian onto a wall, showing a silhouette of half of the secondary mirror and spider vanes.

▲ The Orion BinoViewer gives a right-side-up and correct-reading view (like conventional binoculars) when used straight through on refractors and Cassegrain telescopes. To have the same field orientation with a 90° star diagonal requires a pentaprism diagonal such as this one from Orion. Note that this style of diagonal requires more back focus than conventional mirror or prism models. The total back focus for the Orion Pentaprism is 4½ inches.

was obvious the instant I turned the telescope toward the stars after dark. Out-of-focus star images appeared like quarter moons rather than circular diffraction disks.

Unlike binoviewers that employ beamsplitters to deliver 50% of the light collected by a telescope to each eye, the Orion BinoViewer optically splits the aperture in half. Each eye gets all of the light collected by a physical half of the aperture. Furthermore, in the straight-through refractor setup I used earlier in the day, the light collected by the right half of the objective comes out of the left eyepiece and vice versa. With that nearby scene, even the small separation afforded by each half of a 4-inch objective was enough to render a 3D view, and the right-to-left swap caused the inverted sense of depth. On later days of terrestrial viewing I could often coax my brain into perceiving depths properly, but your mileage may vary.

◀ Because the Orion BinoViewer works with any Barlow lens and eyepiece combination that already reaches focus with a telescope, it's easy to vary magnifications without having to own multiple sets of matched eyepieces. As described in the text, the author used this pair of 26-mm Plössl eyepieces with 2×, 3×, and 5× Barlow lenses to observe with the effective magnifications offered by eyepiece sets having 26-, 13-, 8.6-, and 5.2-mm focal lengths.

For astronomical observing none of this really matters. Regardless of telescope aperture, the distances are too great to show real 3D. And the Orion BinoViewer still delivers half of the light gathered by a telescope to each eye. I did note, however, that the half-moon diffraction pattern seemed to make me more sensitive to even slight differences in focus between the left and right eyepieces. Fortunately, the Orion BinoViewer has a very precise and smooth-operating helical focuser on one eyepiece holder, making it very easy to keep the focus of both eyepieces critically in sync.

Orientation is often an issue for people looking through telescopes. Think how many times you've had to explain the "upside-down" view in a telescope eyepiece to first-time observers. For the record, here's what you get with the Orion BinoViewer. In a straight-through refractor or Cassegrain the view is right-side up and right-reading just as it is with a standard binocular. With a regular 90° star diagonal the view is upside down and mirror-reversed (the included manual is wrong on this point, saying the view is "non-reversed"). With an image-correcting star diagonal the view through the Orion BinoViewer is still upside down, but right reading (again, contrary to the manual). If you want to use a diagonal that gives a right-side up and right-reading view, you need a pentaprism diagonal, such as the one Orion offers as a $149.99 option. But be aware, this diagonal consumes about 4½ inches of back focus.

The Orion BinoViewer's internal relay-lens system that makes it work without additional back focus is very good. I didn't notice any internal reflections, and star images were sharp across the field. During daytime observing there was a slender blue fringe circling the extreme edge of the field. It wasn't objectionable, and it varied somewhat depending on the eyepieces I tried.

There was one issue that cropped up during daytime observing of terrestrial scenes and when viewing the Sun (with a proper solar filter) and Venus during daylight. The Orion BinoViewer's aperture-splitting optics produce an unusual exit pupil emerging from each eyepiece. Only half of the circular exit pupil is image-forming light from the telescope's aperture. The other half shows any light entering the Orion BinoViewer's other eyepiece. At night this isn't an issue, but during daytime light "leaking" into the eyepieces from around my eyes diluted the contrast of the scene. The solution was to use eyepieces with close-fitting rubber eye guards, or to use a black cloth over my head — a common practice for solar observers.

One complaint about binoviewers in general is the expense of requiring matched sets of eyepieces, especially if you like to use different magnifications, as most of us do. Here's where the Orion BinoViewer once again differs from any I used in the past. Because of the way its internal optics work, if you have any Barlow lens that works with your scope and eyepiece, you can simply add the Orion BinoViewer to the system. In other words, putting the Orion BinoViewer between a Barlow and eyepiece had no effect on the focus, nor did it change the magnification that came from using the Barlow and eyepiece alone. I already own Barlows that produce 2×, 3×, and 5× magnification increases, which effectively turned my lone pair of 26-mm eyepieces into matched sets with effective focal lengths of 26, 13, 8.6, and 5.2 mm. Barlow lenses are generally much less expensive than matched sets of eyepieces.

The more I used the Orion BinoViewer, the more I enjoyed it. It worked extremely well for me once I got the hang of carefully setting the distance between the eyepieces and adjusting the focusing eyepiece so that it matched my eyes' needs. This was especially true for high-magnification views of the Sun and Venus during the daytime, when it was important to have the exit pupils from the eyepieces align with the small pupils of my eyes — this adjustment is more relaxed at night when my eyes' pupils are dilated.

There is one aspect of binoviewing that intrigues me, and it's independent of anything special about the Orion unit. Each eye is getting only half the light collected by the telescope. Common sense suggests that this will reduce the limiting magnitude of stars visible in an eyepiece. But somehow using two eyes, even though each is getting only half the light, makes up for the loss. I observed a number of open and globular star clusters, carefully noting the faintest star that I could comfortably hold in steady view with just an eyepiece alone in the scope. I could still see the same star with the Orion BinoViewer setup.

▲ For daytime observing with the Orion Linear BinoViewer it's important to have eyepieces with tight-fitting rubber eye guards or to employ the technique solar observers often use of covering their heads with a black cloth. This is because the optical design of the Orion BinoViewer allows any light entering one eyepiece to reduce the contrast of the view seen in the other eyepiece.

▼ Here are just some of the 1¼-inch eyepieces that the author tested with the Orion BinoViewer. Each showed virtually the same field of view and magnification when focused in a telescope alone and when the Orion BinoViewer was added to the setup. But even with a matching mate, not all 1¼-inch eyepieces are suitable for binoviewers in general since large ones can have a minimum separation that is still too wide for an observer's eyes.

I tested the Orion BinoViewer with 2.4-, 4-, and 6-inch refractors, 12-inch f/5 and 18-inch f/4 Dobsonians, 8- and 16-inch f/10 Schmidt Cassegrains, a 6-inch f/12 Maksutov-Cassegrain, and an 8-inch f/3 Newtonian (with and without a coma corrector on the reflectors). The Orion BinoViewer worked well on all of them.

If you've ever wanted a binoviewer but were put off by the need for lots of back focus or the expense of sets of matched eyepieces, then now might be the time to consider the Orion BinoViewer. It certainly changed my concerns about these issues.

■ **DENNIS DI CICCO** really enjoys testing equipment that doesn't come weighted down with an extensive owner's manual.

The Optolong L-eNhance Filter

This dual-bandpass filter permits deep-sky imaging of nebulae with color cameras even under light-polluted conditions.

The L-eNhance filter from Chinese manufacturer Optolong passes the light from hydrogen beta (Hβ), doubly ionized oxygen (O III), and hydrogen-alpha (Hα) radiation while blocking most sources of light pollution and strong moonlight.

Optolong L-eNhance Filter

U.S. Price: $229

Available in the U.S. from optcorp.com

What We Like

High-contrast images of emission nebulae in full light pollution

Works well in bright moonlight

What We Don't Like

Blocks most reflection nebulosity

ONE OF THE FIRST ITEMS to check on one's list of preparations for imaging emission nebulae is the phase of the Moon. Bright moonlight typically washes out all but the brightest emission nebulae, so most imagers simply wait for moonless nights to shoot these colorful objects. The typical exception to this rule is to image them using monochrome cameras and special narrowband filters that isolate specific regions of the visible spectrum where these ionized gasses emit light. Narrowband filters also block most moonlight, as well as many sources of light pollution, so amateurs equipped with these setups could shoot pretty much any clear night. But astrophotographers with one-shot color (OSC) cameras were left to wait for the Moon to leave the scene.

That is, until recently. The new L-eNhance filter from Optolong Optical allows for narrowband imaging with OSC cameras and results that show a palette similar to natural-color (RGB) images. This dual-passband filter allows light from two astronomically important regions of the spectrum to pass through almost uninhibited while blocking most sources of light-pollution. The first passband encompasses a 24-nm slice of the spectrum where hydrogen-beta and the dual emission lines of doubly ionized oxygen emit light at 486.1, 495.9, and 500.7 nm, respectively. Its second bandpass is 10-nm wide centered at 656.4 nm where hydrogen-alpha glows. Outside of these two bands, the filter blocks 99% of all light between 300 nm and 1000 nm. Holding the filter up to your eye and examining a daylight scene reveals a blue-green cast.

The 2-inch filter with 48-mm threads makes it convenient to install on a camera's 2-inch nosepiece, coma corrector, focal reducer, or extension tubes that are threaded for standard 48-mm filters. A 1¼-inch-format filter is also available.

For my first imaging test, I targeted NGC 7000, the North America Nebula, using a William Optics 71-mm f/4.9 apochromatic refractor paired with a ZWO ASI071MC Pro color CMOS camera on a night with a bright gibbous Moon. The first 60-second exposure clearly showed the shape of the nebula with very little fogging from the nearby Moon. I then took a series of 300-second exposures. The stacked result rendered the nebula in its familiar reddish color though with a slight yellowish hue. For comparison, an unfiltered exposure just 15 seconds long on the same night was hopelessly drowned out by moonlight, with no sign of the nebula at all.

Using the same setup, I turned the scope toward M8 and M20 sinking low in my southwestern sky. The emission nebulosity of both objects stood out well in 10-minute exposures despite the pair being smack-dab in the most light-polluted region of my sky. The only minor disappointment was the weak visibility of M20's blue reflection nebulosity due to the filter blocking most of its wavelengths.

On a different night I set my sights on NGC 7635, the Bubble Nebula in Cassiopeia, shooting with a 14-inch Meade ACF telescope at f/6.7 and the same camera. Again, a bright Moon was in the sky. My 60-second exposures

ALL IMAGES COURTESY OF THE AUTHOR

used to frame the subject easily revealed the Bubble's brightest arc and a few knots of nebulosity. A series of 10-minute exposures displayed high-contrast reddish Hα throughout the small field.

While the L-eNhance filter does a great job producing rich Hα and O III nebulosity in images, stars recorded through the filter were generally colorless dots, with the exception of red stars. Images of M27, the Dumbbell Nebula, showed more faint red stars than I recall from previous images of the object taken without any filtration.

The L-eNhance filter proved particularly useful in pulling out contrast and detail in emission objects that never reach high altitudes above my horizon. This was helpful when I imaged NGC 7293, the Helix Nebula, which culminates at about 34° from my backyard in southeastern North Carolina.

It's worth noting that the L-eNhance filter is best suited for astronomical cameras — its performance is greatly diminished when paired with DSLR and mirrorless cameras. Test exposures through my stock Nikon D750 DSLR with its IR blocking filter showed that while the filter blocked light pollution and moonlight, the camera's poor Hα sensitivity resulted in images with lots of white stars and occasional O III in select targets, and a general lack of hydrogen-alpha nebulosity. Modified DSLRs and mirrorless cameras, as well as the few models designed specifically for astrophotography (such as Canon's Mirrorless EOS Ra reviewed in the April issue, p. 64) should greatly benefit from use with the filter.

▲ The above photographs display the strength of the L-eNhance filter. The top picture of NGC 7000 is a stack of 12 unfiltered, 3-minute exposures through moderate light pollution — the longest exposure possible from the author's location. The image below it consists of 12 filtered, 5-minute exposures. Adding the filter permits longer exposures before sky fog washes out the intended target.

Though the general look of an emission nebula imaged through the filter closely resembles typical RGB shots of the same object, there are subtle differences such as a warmer color of red nebulosity and the general diminishing of star colors. And as my M20 testing shows, reflection nebulae are noticeably diminished with the filter. I encountered no troublesome reflections from the filter surface during my tests.

At $229.00, the 2-inch L-eNhance filter is pretty good value in an urban imager's battle against light pollution, particularly those of us who reside under moderately light-polluted urban skies and can't always travel to dark-sky sites for astrophotography. The convenience of convenient backyard imaging rather than packing the car and driving a considerable distance to dark skies makes the L-eNhance filter extremely attractive.

And even from a dark site, the filter's performance under bright moonlight permits users to capture useful color images whenever the sky is clear, freeing up more nights for deep-sky imaging. That alone may be worth the filter's price for some.

Perhaps the most dramatic moment of using the filter comes when a detailed color image of your target appears on a computer screen while a nearly full Moon illuminates the sky and surrounding landscape.

■ Contributing Editor **JOHNNY HORNE** is always on the lookout for gear that can improve his backyard astrophotography.

▲ *Left:* Planetary nebulae such as NGC 7293, the Helix Nebula in Aquarius, display vivid reds from Hα and a rich teal core due to the presence of O III. This image was shot under strong moonlight with a 14-inch Meade ACF telescope at f/7. Total exposure was 3⅓ hours with a ZWO ASI071MC Pro CMOS camera. *Right:* The Dumbbell Nebula, M27, displays excellent cloud detail as well as some of its outer halo in this 100-minute stacked image, though most stars throughout the field appear colorless and fainter stars have a notable red cast.

Pipe-Fitting Mounts

An old idea is still going strong.

Drew Sorenson can haul and set up his portable pier mount as easily as he can a truss Dobsonian.

IOWA AMATEUR DREW SORENSON is a refractor nut. He's also an amateur telescope maker. So, not surprisingly, he's made several refractors, his largest being a 6-inch f/10 with lenses he ground himself.

But I'm not here to tell you about his telescopes. I'm writing about his mount!

Drew contacted me after he read my article on "Hobby Killers" (*S&T:* Dec. 2019, p. 36). He said, "I am very frustrated to hear so often that people don't consider larger refractors because they would need a mount that would cost over $1,000. I think the hobby is at least 'stunted' (maimed?) when people don't think they can enjoy what refractors can contribute visually because of lack of an expensive mount." He proceeded to show me a mount that costs about $75 in parts and works like a charm even for a large refractor.

To fully appreciate this mount you need a little history. Back in the early days of amateur telescope making, nearly every scope was placed on a German equatorial mount. Commercial mounts of any sort were rare, however, and expensive, so most ATMs built their own mounts as well as their own scopes. They used the easiest, simplest materials that would do, which more often than not meant pipe fittings.

Pipe fittings work great for equatorial mounts, especially for people living around latitude 45°N. You can use a simple 45° elbow to angle the polar axis, and a tee off that for your right ascension and declination motion. The screw threads act as your bearings: With a little grease and tightened until they're just snug, they provide plenty of motion — and smooth motion at that — to aim a telescope anywhere in the sky.

With the advent of the Dobsonian mount, however, since most ATMs were making reflectors, they abandoned pipe-fitting mounts in favor of plywood altitude-azimuth (alt-az) mounts, with the result that you don't see many pipe-fitting mounts today.

Drew is an exception to that rule. He has been using the same pipe-fitting mounts for more than 30 years, and they still work beautifully after all this time. Where Drew parts way with tradition, however, is in the "equatorial" part. He went alt-az from the beginning, preferring the intuitive up-down, left-right motion and the simple construction of an alt-az mount.

▶ The permanent mount is solid as a rock . . . because it pretty much *is* a rock, with a pipe in the top.

And because he likes looking straight through his telescopes (no mirrors!), that means getting them high off the ground, so he built his mounts into piers. He has two that he uses all the time: a permanent concrete installation and a portable PVC-and-plywood one.

The permanent one is a two-step pier, with a vertical pipe embedded in the top. A simple 90° elbow atop the pipe provides the azimuth motion, and a nipple in the other end of the elbow provides the altitude motion. Drew welded the nipple to a chunk of wide channel iron, but a person without a welder could bolt a pipe flange to it just as well. The telescope is held to the channel iron with a simple rubber-coated cable.

The portable pier uses 2″ × 8″ legs and an 8-inch-diameter PVC tube. Notches in the tube keep it from twisting, and guy-wires keep it stable. The upright iron pipe at the top screws into

DREW WITH SCOPE: A.J. SORENSON; MOUNT: DREW SORENSON

▲ *Top:* The upright pipe fits into a flange bolted to plywood disks. The tee pipe fitting provides smooth altitude-azimuth motion. *Bottom:* The base of the portable mount is simply a pair of 2″ × 8″s crossed over each other, with the pipe notched so it won't slip and guy-wires to hold it steady.

TOP END OF MOUNT: TOLLEF SORENSON; BASE OF MOUNT: DREW SORENSON

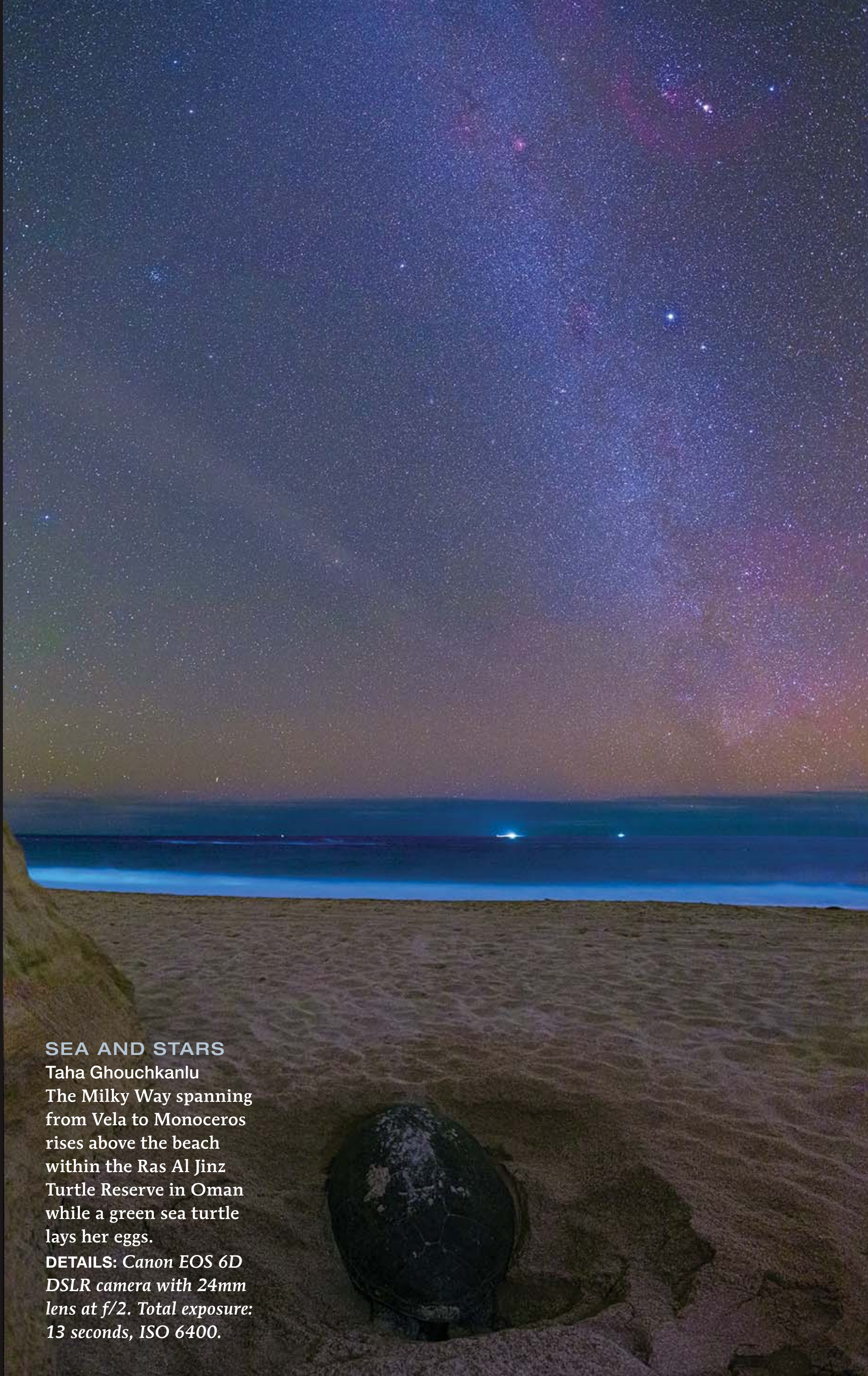
a pipe flange screwed to a wooden disk that's screwed in turn to the PVC. Drew used a tee rather than an elbow, thinking he might want to add a counterweight to the side opposite the scope and use it equatorially, but he never did.

So how does it all work? In a word: beautifully. The motion is smooth and vibration-free. And the portable pier is truly portable. Drew has hauled it to star parties for decades in the back of a series of Mazda cars — not the largest of vehicles.

And why should you consider building one? I'll let Drew have the last words:

"It's a shame people don't feel they can support larger refractors! I know 'aperture rules,' but I think a lot of rules need asterisks. Refractors don't have to be budget killers!"

■ Contributing Editor **JERRY OLTION** is a big fan of simple, functional astronomy equipment. Like Drew, he doesn't much care what something looks like so long as it works.



SEA AND STARS

Taha Ghouchkanlu

The Milky Way spanning from Vela to Monoceros rises above the beach within the Ras Al Jinz Turtle Reserve in Oman while a green sea turtle lays her eggs.

DETAILS: *Canon EOS 6D DSLR camera with 24mm lens at f/2. Total exposure: 13 seconds, ISO 6400.*

COLORFUL IMPRESSION

Mark Seibold

This excellent drawing of the Moon accurately depicts dozens of major craters, rays, and even the subtle color differences that reveal themselves through careful inspection at the eyepiece.

DETAILS: *Dry pastel on 100% cotton black paper. Based on more than 4 hours of observations and photographs from July 8, 2009.*

◁ **WIDE SPIRAL**

Fernando Menezes

Residing about 30 million light-years away in the southern constellation of Pavo, spiral galaxy NGC 6744 is thought to look very similar to our home galaxy, the Milky Way.

DETAILS: *Sky-Watcher Esprit 150ED refractor with QHY16200A CCD camera. Total exposure: 10.3 hours through Baader Planetarium LRGB filters.*

▽ **HEART AND SOUL**

Ron Brecher

This colorful nebulae complex along the western border of Cassiopeia consists of IC 1848, the Soul Nebula, at left, and the combination of IC 1805 (right) and NGC 896 (top right) together making up the Heart Nebula.

DETAILS: *Takahashi FSQ-106ED astrograph at f/3.6 with a QHY367C color CMOS camera. Total exposure: 20⅓ hours through an Optolong L-eNhance filter* *(see review on page 70).*

Gallery showcases the finest astronomical images that our readers submit to us. Send your best shots to gallery@skyandtelescope.org. See **skyandtelescope.org/aboutsky/guidelines**. Visit **skyandtelescope.org/gallery** for more of our readers' astrophotos.

SKY & TELESCOPE

Market Place

Your essential source for astronomical products

CAMERAS (cont.)

MISCELLANEOUS

MOUNTS

skyandtelescope.org

OBSERVATORIES/DOMES

OPTICS

SOFTWARE

TELESCOPES

TRAVEL

CLASSIFIEDS

SOUTHWEST NEW MEXICO: Casitas de Gila Guesthouses. Dark skies, great accommodations; power, wifi, and pads available. casitasdegila.com/astronomy.html. 575-535-4455.

FOR RENT: 3BR/2BA furnished home in ARIZONA SKY VILLAGE PORTAL, AZ. Specatcular observing/birding! irkitzman@gmail.com www.arizona-dreaming.com 520-203-8500

FOR SALE: 2 Building Lots in Portal, AZ next to Arizona Sky Village. Spectacular views day and night. https://www.landandfarm.com/property/7_6_Acres_in_Cochise_County-9630605/ andhttps://www.landandfarm.com/property/8_45_Acres_in_Cochise_County-9630608/ Contact Joan: 520-204-0459 JOANGALANIS@TIERRAANTIGUA.COM

FOR SALE: 14 and ½ Telescope, Equatorial Mount Setting Circles, Good Optics, 2" Eyepieces. Call 740-654-7713.

Classified ads are for the sale of noncommercial merchandise or for job offerings. The rate is $1.75 per word; minimum charge of $28.00; payment must accompany order. Closing date is 10th of third month before publication date. Send ads to: Ad Dept., Sky & Telescope, 90 Sherman Street, Cambridge, MA 02140.


Stargazing
REIMAGINED
GIOVALE OPEN DECK OBSERVATORY
One of the finest collections of telescopes available for public observing
LOWELL
OBSERVATORY
125 YEARS | 1894 - 2019
lowell.edu/sky


TRAVELQUEST
international
The leader in astronomy-themed travel
800-830-1998
TravelQuestTours.com


NEAF
NORTHEAST ASTRONOMY FORUM™
29TH ANNUAL
NORTHEAST ASTRONOMY FORUM & SPACE EXPO
APRIL 4-5, 2020
WORLD'S LARGEST ASTRONOMY, TELESCOPE & SPACE EXPO!
OVER 120 VENDORS, PRO/AM & ASTRONOMY WORKSHOPS,
SOLAR OBSERVING & WORLD-CLASS SPEAKERS FEATURING:
JERRY ROSS NASA ASTRONAUT & SPACEWALKER
TOM MULDER BOEING STARLINER
SAMUEL D. HALE EXEC. DIR., MT. WILSON, GRANDSON OF GEORGE ELLERY HALE
DIANNA COLMAN PRES. YERKES FOUNDATION, SAVING YERKES
EDWARD GUINAN VILLANOVA UNIV., THE DIMMING OF BETELGEUSE
JANI RADEBAUGH PLANETARY SCIENTIST, DRAGONFLY MISSION
JPL MARS 2020 MISSION, PLUS ISS 20TH ANNIVERSARY
PLUS MUCH, MUCH MORE!
SHOW HOURS: SAT 9-6 PM, SUN 10-5 PM
SUNY ROCKLAND COMMUNITY COLLEGE SUFFERN, NY (ONLY 30 MINS FROM NYC)
NEAFEXPO.COM FOR TICKETS, INFO, HOTEL ROOMS
Presented by
RAC
ROCKLAND ASTRONOMY CLUB™
Sponsored by
SKY & TELESCOPE
skyandtelescope.org
NEAIC
NORTHEAST ASTRO IMAGING CONFERENCE™
DON'T MISS THE NORTHEAST ASTRO IMAGING CONFERENCE
APRIL 2-3, 2020 AT NEAF
FEATURING IMAGING WORKSHOPS, LECTURES & VENDOR EXHIBITS
Andy Campbell
Alan Friedman
John O'Neill
Steve Mazlin
Alex McConahay
Dr. Ron Brecher
Stephanie Anderson
Jim Moronski
Kerry-Ann Hepburn
TJ Connelly
John Hayes
Rachel Freed

INSIDE This Issue

Specialty astronomy equipment dealers and manufacturers are an important resource for amateur and professional astronomers alike — patronize our advertising dealers in this issue and enjoy all the benefits of their expertise.

Product Locator

BINOCULARS

Sky-Watcher USA (Page 3)
SkyWatcherUSA.com
310-803-5953

CAMERAS

QHYCCD /
Light Speed Vision CO. Ltd (Page 77)
www.QHYCCD.com

Sky-Watcher USA (Page 3)
SkyWatcherUSA.com
310-803-5953

EYEPIECES

Sky-Watcher USA (Page 3)
SkyWatcherUSA.com
310-803-5953

Tele Vue Optics, Inc. (Cover 2)
TeleVue.com
845-469-4551

FILTERS

Astro-Physics (Page 80)
Astro-Physics.com
815-282-1513

Tele Vue Optics, Inc. (Cover 2)
TeleVue.com
845-469-4551

MISCELLANEOUS

nimax GmbH (Page 5)
universe2go.com

MOUNTS

Astro-Physics (Page 80)
Astro-Physics.com
815-282-1513

iOptron (Page 77)
iOptron.com

Sky-Watcher USA (Page 3)
SkyWatcherUSA.com
310-803-5953

MOUNTS (continued)

Software Bisque (Cover 4)
Bisque.com
303-278-4478

Tele Vue Optics, Inc. (Cover 2)
TeleVue.com
845-469-4551

TELESCOPES

iOptron (Page 77)
iOptron.com

Sky-Watcher USA (Page 3)
SkyWatcherUSA.com
310-803-5953

Stellarvue® (Cover 3)
Stellarvue.com
530-823-7796

Tele Vue Optics, Inc. (Cover 2)
TeleVue.com
845-469-4551

To advertise on this page, please contact Tim Allen at 773-551-0397, or Ads@skyandtelescope.org

AD INDEX

Astro Haven Enterprises 79
Astro-Physics, Inc. 80
Diffraction Limited. 73
DiscMounts, Inc.. 79
Finger Lakes Instrumentation, LLC. 79
Flo Tours 80
iOptron. 77
Irene Kitzman 80
Knightware. 79
Lowell Observatory 81
Lunatico Astronomia 78
Metamorphosis Jewelry Design 79
Michael G. Grelle, Sr.. 80
Michael P. O'Connor 80
Morrow Technical Services 78
NEAF - Northeast Astronomy Forum. 81
NexDome 79
nimax GmbH (Omegon) 5
Optic Wave Laboratories 79
Orange County Telescope, LLC 78
PreciseParts 78
QHYCCD/Light Speed Vision Co., Ltd.. . . . 77
Sky & Telescope 1, 73
Sky-Watcher USA 3
Software Bisque C4
Stellarvue C3
Technical Innovations 78
Tele Vue Optics, Inc. C2
Telescope Live 13
Town of Tonopah Nevada Tourism 80
TravelQuest International 81
Willmann-Bell, Inc. 78

Event Calendar

Here's the info you'll need to "save the date" for some of the top astronomical events in the coming months.

NEAL HERBERT / NPS

April
GLOBAL ASTRONOMY MONTH
Everywhere!
https://is.gd/astronoborders

April 4–5
NORTHEAST ASTRONOMY FORUM
Suffern, NY
rocklandastronomy.com/neaf.html

April 19–26
INTERNATIONAL DARK SKY WEEK
Everywhere!
darksky.org/dark-sky-week-2020

April 22–25
MID-SOUTH STAR GAZE
French Camp, MS
rainwaterobservatory.org/events

April 23–26
SOUTHERN STAR
Little Switzerland, NC
https://is.gd/southernstarcon

April 24–26
MICHIANA STAR PARTY
Vandalia, MI
michiana-astro.org/index.php/msp12

May 2 (also September 30)
ASTRONOMY DAY
Events across North America
https://is.gd/AstronomyDay

May 17–24
TEXAS STAR PARTY
Fort Davis, TX
texasstarparty.org

June 5–7
RASC GENERAL ASSEMBLY
Vancouver, BC, Canada
ga2020.rasc-vancouver.com

June 13–20
GRAND CANYON STAR PARTY
Grand Canyon, AZ
https://is.gd/GCSP2020

June 17–20
BRYCE CANYON ASTRO FESTIVAL
Bryce Canyon National Park, UT
https://is.gd/brca_astrofest

June 17–21
ROCKY MOUNTAIN STAR STARE
Gardner, CO
rmss.org

June 18–20
WISCONSIN OBSERVERS WEEKEND
Hartman Creek State Park, WI
new-star.org/index.php?Itemid=82

June 18–21
CHERRY SPRINGS STAR PARTY
Coudersport, PA
cherrysprings.org

June 20–24
GOLDEN STATE STAR PARTY
Bieber, CA
goldenstatestarparty.org

July 16–18
ALCON 2020
Albuquerque, NM
alcon2020.info

• For a more complete listing, visit **https://is.gd/star_parties**.

A Night of Déjà Vu

A curious sensation while observing the Great Cluster in Hercules triggers back-to-back familiar memories.

SOMETIMES A NIGHT OF casual observing can lead to unexpected revelations.

Recently, while observing the globular cluster M13 with my modest telescope, I noticed an interesting phenomenon as I increased the magnification. Within the eyepiece, the cluster became a lively assemblage of tiny flashing lights. It was as if the lights from a dozen Christmas trees blinked on and off for my amusement.

The flashing lights came from faint stars within the cluster that shone at the very boundary of my perception. These stars appeared to continuously jump in and out of view as my eye/brain briefly recognized them and then lost them again to background "noise." Such a dramatic visual show is well known to deep-sky observers. In fact, Sue French often noted this effect in her "Deep-Sky Wonders" column.

While enjoying this spectacle, I suddenly realized that I'd seen these "dancing lights" before, sans telescope. But where?

It then came to me that I'd witnessed a remarkably similar sight many years ago while using a *spinthariscope* to observe radioactive decay. This device consists of a fluorescent screen that produces a momentary point of light wherever an atomic particle impacts its surface. Placed near a radioactive source, it displays a significant number of continuous flashes, each caused by interaction with a single emitted alpha particle. The resulting display is nearly identical to the one M13 provided through my telescope.

I'd no sooner made this connection between visual perceptions at the atomic and astronomical levels when I was struck by another moment of déjà vu. I recalled that I'd seen the same "dancing lights" at yet another level of human perception.

I live near a wetland dominated by a large open field. During summer evenings this field comes alive with flashing lights, each generated by a solitary firefly seeking a mate. Some summers, conditions are just right for the firefly population to explode. At such times, thousands of "dancing lights" are visible at any given moment.

The display is so mesmerizing that I've often spent hours watching this natural light show. It's as if I'm observing a boundless multiverse, with endless numbers of local universes magically popping into existence from some cosmic Neverland, each announcing its arrival via a mini "Big Bang."

My overactive imagination aside, I'm amazed that unrelated phenomena, occurring in three different domains of existence — atomic, macro, and astronomical — can appear so similar to an anonymous observer.

Is the universe trying to tell us something?

■ **FRANK RIDOLFO** is a retired nuclear engineer who lives in Bloomfield, Connecticut.

JEFF DAI / SCIENCE SOURCE

Omne Trium Perfectum

You deserve the best, right now. And, if not now, when?

Paramount robotic telescope systems combine precision mechanics, advanced control-system electronics, and the world's most capable software suite to achieve unmatched performance, reliability, and productivity.

Its unrivaled TPoint™ telescope modeling software helps optimize your efficiency and productivity while its ProTrack™ assisted tracking ensures pinpoint stars with long exposures.

Whether you choose the portable MYT, the transportable MX+, or the legendary observatory-class ME II, make a Paramount the foundation of your digital imaging pursuits.

And thanks to our state-of-the-art manufacturing facility, we can typically deliver the model you want, without the long wait. Make the Paramount yours today.

SOFTWARE BISQUE

Superior imaging solutions for discriminating astronomers.