Telescopes for **KIDS** p. 60 | **OCEAN WORLDS** of the solar system p. 24

NOVEMBER 2017

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A pair of black holes spiral together, unleashing a torrent of gravitational waves that eventually will sweep across the universe.

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PLUS

Why **DARK MATTER** matters p. 30

OBSERVE WITH BOTH EYES WIDE OPEN p. 58

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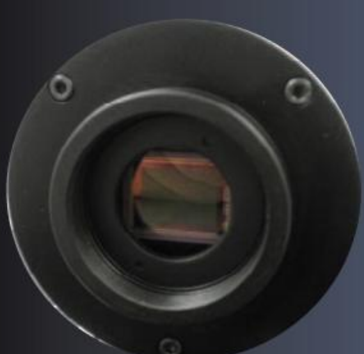

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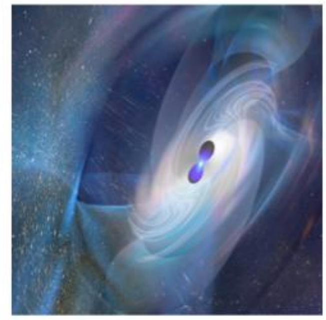

DON DIXON FOR *ASTRONOMY*

ON THE COVER

In 2017, a third gravitational wave detection by LIGO revealed the collision and merger of two distant black holes.

FEATURES

COLUMNS

QUANTUM GRAVITY

IN EVERY ISSUE

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Picture of the Day
Gorgeous photos from our readers.

BY DAVID J. EICHER

Making light of galaxies

The gorgeous face-on spiral galaxy NGC 6946 in Cygnus makes a beautiful sight through backyard telescopes on early autumn evenings. TONY HALLAS

We live in a world completely saturated by images, 24/7. You wanna see the universe? Just wait a minute and a wash of cosmic images will move down through your social media feed, dozens per day. And that's great. That we have the tools to share our interests so completely, so nonstop, is pretty neat.

But I suggest that you might not want to live in a bubble all the time.

Trust me, I've been in the astronomy game for a long time, and there's no alternative to seeing the real thing. Live photons that have traveled for millions of years, only to strike your eye as you peer into a telescope? There's no substitute for that. Photos are very cool, but there's nothing like the real deal.

This month, Steve O'Meara writes about some of the greatest galaxies you can observe in his story "Fall into autumn galaxies" (p. 46). If you look carefully, observing from a dark sky, galaxies can reveal much about the nature of the universe. These islands of stars, gas, and dust are the basic building blocks of the cosmos, which contains perhaps 1 trillion of them. And the variety, some of which you can see in telescopes, is nearly endless.

In Steve's story, you can read about many incredible objects aside from obvious autumn galaxies like M31, M33, and M74. How about NGC 157, which is easy to find because it lies a mere 4° east of the bright star Iota Ceti? This spiral appears as a comet-like glow sandwiched between two 9th-magnitude suns.

You can also explore unusual, high-energy galaxies like M77 in Cetus. This object is a so-called Seyfert galaxy, a type studied by the American astronomer Carl Seyfert for its active core, which acts as a low-energy quasar, spewing out radiation that escapes the grip of its central black hole.

Move over to Pisces, and you can locate NGC 488, a multiple-armed spiral that shows rings of star formation bursting forth along its concentrically shelled spiral arms. You'll also spot a soft, starlike nucleus within the galaxy's central glow. And nearby you can find NGC 524, a lenticular, or lens-shaped galaxy. This class of objects is marked by a loss of gas, which has left behind a rather ghostly footprint, as Steve describes it, of the formerly pronounced spiral structure.

You can also witness interaction between galaxies in this great big universe. In Pegasus, the group called Stephan's Quintet consists of five galaxies, the brightest of which, NGC 7320, is a foreground object, much closer than the others and simply projected against them. But the four fainter galaxies are locked in a tidal embrace, traveling together through space due to their mutual gravity. And they lie some 300 million light-years away. To see that in a backyard telescope, for real? Are you kidding me? I'll take that anytime, and get back to my pictures in the social media feed when the sky clouds up. There's just nothing else quite like it.

Yours truly,

David J. Eicher
Editor

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EVERYTHING YOU NEED TO KNOW ABOUT THE UNIVERSE THIS MONTH . . .

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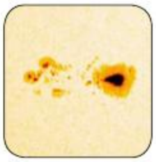
TRENDING TO THE TOP

HOLEY WHEELS
A new software algorithm should help reduce wear and tear on the Curiosity rover's wheels by controlling their speed to adjust traction.



GIANT SPOT
A sunspot bigger than our planet recently rotated into view of NASA's Solar Dynamics Observatory.

SCIENCE START
NASA's new Neutron star Interior Composition Explorer (NICER) has begun studying pulsars from aboard the International Space Station.

SNAPSHOT

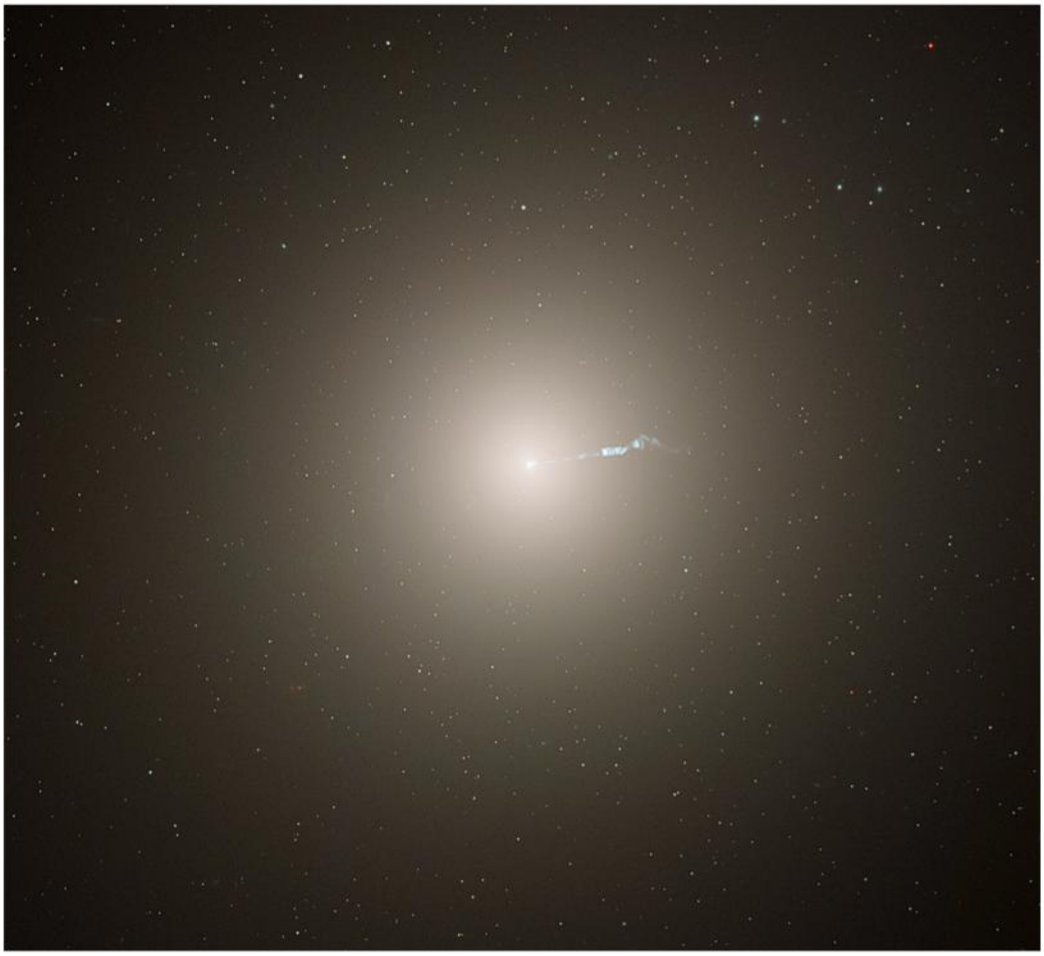
Portrait of a giant

In the local universe, galaxy M87 is as huge as they come.

When it comes to galaxies, the big ones rule the roost. The largest galaxies we know, called cD galaxies, exist in the hearts of rich galaxy clusters. They have grown substantially over the eons by devouring their neighbors, using gravity to inexorably pull in the nearby smaller galaxies one by one.

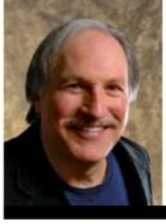
Thinking of galaxies, it's easy to start with the Milky Way, our own. We live in a barred spiral galaxy with a bright disk that stretches some 100,000 light-years across, and it contains about a trillion times the mass of our Sun. By comparison, the cD galaxy M87 spans 120,000 light-years. But instead of being a flattened disk, M87 is a huge elliptical football of stars, gas, and dust. The result is that it contains six times as much mass as our galaxy, with a ferocious black hole in its center. The Milky Way hosts a relatively quiet supermassive black hole harboring 4.3 million solar masses. But M87's black hole is quite active, as witnessed by the superluminal jet of matter flying outward from its accretion disk. M87's black hole tips the scales at a whopping 3.5 billion solar masses — some 800 times more mass than the Milky Way's.

Galaxies like M87 cast off enormous amounts of high-energy emission. It's probably better for us that we live in a more normal, smaller, and less energetic galaxy. Galactic monsters can be dangerous places. Living in an ordinary barred spiral, halfway out from the center, gives us a peaceful place from which to view the cosmos. — **David J. Eicher**



Supermassive elliptical galaxy M87 lies in the core of the Virgo Cluster and is one of the greatest galaxies in the local universe. Its central black hole "weighs" 3.5 billion solar masses, and the galaxy's spherical glow spans 120,000 light-years. A slightly bluish jet consists of material being flung away from the black hole at very high speeds.

NASA, ESA, AND THE HUBBLE HERITAGE TEAM (STScI/AURA); TOP FROM LEFT: NASA/JPL-CALTECH/MSSS; NASA'S GODDARD SPACE FLIGHT CENTER/SDO/JOY NG; NASA



STRANGE**UNIVERSE**

BY BOB BERMAN

Love affair with a saros

Saros 136 is responsible for long, history-making totalities, and it's approaching the United States.

The great eclipse is over. Millions are probably hooked. The word *saros*, which may have previously sounded like a Middle Eastern snack, is now a familiar term. It's the time period, usually 18 years, 11⅓ days, separating a repeat of the same eclipse conditions, such as type, time of year, and duration; each has its own three-digit number.

At parties, eclipse fanatics like to name-drop particular saroses. Let me join that chorus to sing a love song for one extraordinary saros that keeps doing amazing things.

We'll begin with the famous totality of May 29, 1919, sometimes called the Einstein or Eddington eclipse. It confirmed general relativity theory. You know the story. Einstein said massive objects can warp space. British physicist Arthur Eddington realized this could be confirmed by observing stars near the Sun during a total eclipse. The upcoming 1919 event was suitable: The Sun would be in Taurus, embedded in the famous Hyades star cluster.

Beloved by backyard astronomers, the Hyades is best seen not when the Sun is near it, but now, this very month. At 150 light-years away, it's the nearest star cluster, conspicuously surrounding the famous bright-orange luminary Aldebaran. The stars form a V shape, and just for extra fun, the V points precisely to the little star Lambda (λ) Tauri, which intriguingly loses half its light every four days. This Algol-like eclipsing binary is easy to track by comparing its brightness to Gamma (γ) Tauri, the star at the V's point. You know Lambda is in eclipse if it's dimmer than Gamma. Easy as can be. And the Pleiades, over twice as distant, hovers to the right of the Hyades. Taurus is a lot of fun.

What you may not have known is that same eclipse, one of the century's longest at 6 minutes, 51 seconds, was a member of Saros 136. If that number rings a bell, you're a genuine eclipse fanatic. This is the only saros that delivers truly long totalities in the 19th, 20th, and 21st centuries.

F. W. DYSON, A. S. EDDINGTON, AND C. DAVIDSON

The 6 minute, 51 second eclipse of May 29, 1919, provided proof of Einstein's theory of general relativity. It was also part of Saros 136.

Since Eddington's long eclipse crossed Brazil, if you add 54 years to that 1919 event and look a bit north, you'd see that in 1973 Colombia and Panama got a superlong totality that crossed the Atlantic and maxed out in Africa as one of the lengthiest totalities in recent human generations.

At parties, eclipse fanatics like to name-drop particular saroses.

Moreover, Saros 136's eclipses are shifting northward over time, and their paths conveniently cross the mid-northern countries where most of us live.

That ⅓ day business means each successive eclipse in the same saros happens 120° of longitude west of the previous one. So you need three eclipses for the world to have rotated a full turn to bring the event back to the starting region. Three saroses roughly equals 54 years and 1 month, a period called the exeligmos. It's the lion's share of an average human life span.

The next event in that saros, 18 years later, was the Baja, Mexico, totality of July 11, 1991 — a 6 minute, 40 second duration that won't be equaled in our lifetimes. If you were there, and it felt historic, that's because it happened in the same saros as the Einstein eclipse!

It was followed 18 years later by the long Chinese totality of 2009. Add another 18 years, look one-third of the globe westward, and get psyched for the superlong totality of August 2, 2027, on Egypt's Nile River under likely clear skies. Let's hope the political situation is OK, because the Egyptians are extraordinarily friendly and hospitable, and totality for this eclipse is the longest for the remainder of the century.

We can't help adding another 18 years and looking 120° west because that takes us to a noteworthy U.S. eclipse. After this summer's 2½-minute totality, we get a 4-minute event April 8, 2024, over Texas, the Midwest, and the Northeast. (That's one exeligmos after the 1970 Virginia Beach totality from Saros 139.) The very next totality for the mainland U.S., on August 12, 2045, will be the longest in U.S. history! The 6 minutes of darkness will happen over Walt Disney World and West Palm Beach, Florida.

That's our beloved Saros 136 again. It's still at it, delivering superlong historic events. For the weathered alumni of the 1991 Baja event, perhaps watching with grandkids in hand, one splendid exeligmos will have elapsed.

Contact me about my strange universe by visiting **http://skymanbob.com.**

BROWSE THE "STRANGE UNIVERSE" ARCHIVE AT **www.Astronomy.com/Berman.**

ASTRO**LETTERS**

A family discussion

I want to recognize Jeff Hester for his article "A Dunning-Kruger universe" in the June 2017 issue. I am a research scientist and do understand the concepts of proving a scientific theory. Also, my daughter is a psychology major, and I am discussing your article in depth with her. I truly enjoy your interpretation of concepts and the way you look at things around us. It reminds me to not only look but to see, and to be more diligent in my thought process. Thank you, Jeff, for your refreshing viewpoints, and keep up the good work. **— Tom Rusek,** Aberdeen, MD

Inspiring the beginners

As a person who enthusiastically watched the heavens through my 50mm refractor in the early '60s and tried to take pictures, I really appreciated Glenn Chaple's article in the June issue about photographing the Moon with a smartphone. Because he held the device in his hands — as my friends and I did with a camera back then — he inspires the most basic amateur with no money (as I was as a kid) to give it a try. After all, even if you want to take good astroimages, you have to start somewhere, and Glenn introduces the path.

One night, my friends and I tried to photograph the Moon through a star diagonal on a small refractor with a camera that had a viewfinder only. As my friend pointed the camera down, we eyeballed the alignment with the eyepiece and instructed him how to move and hold the camera. When we developed the pictures in his darkroom, we had 16 pictures of his feet! Oops! Kudos to Mr. Chaple for encouraging beginners.
— Robert Walty, Stephens City, VA

Honoring the Hooker telescope

Ronald Voller's article, "Mount Wilson's famous telescope celebrates a century," in the May 2017 issue raises the age-old question about who determines history: men or events. This most excellent article is well documented and wonderfully written, and it describes the men and events surrounding the creation of the 100-inch Hooker telescope on Mount Wilson. Although larger telescopes were to come, this was the first "great eye" that gave answers to hungry researchers. The discussion of George Ellery Hale and the events in his life are enlightening and form a very human portrayal of the difficulties he faced in making important decisions at a critical time.

The 100-inch (2.5 m) Hooker Telescope was the world's biggest telescope from 1917 until 1949. Edwin Hubble used the famous telescope to prove that the universe expanded past the Milky Way galaxy. KEN SPENCER

Events in astronomical discovery were converging at this time regarding the nature and size of the universe. The existing theories were lacking in observable data, which could answer these questions. Enter Edwin Powell Hubble and his use of the Hooker telescope to research and discover the observable data. Without either Hubble or the Hooker, there would have been considerable delay in advancing our knowledge of the nature of our universe.

The picture on page 33 of the article is an amazing historical document. It shows Albert Einstein, Hubble, and Walter Adams at the Hooker Telescope in 1931 — Einstein the theorist, Hubble the astronomical scientist, and Adams the director of the Mount Wilson Observatory and researcher in stellar spectra. Each one of these men greatly changed our understanding of the universe. It is also interesting to see the view of Los Angeles from Mount Wilson; Hubble referred to it as the "Los Angeles Nebula."

Congratulations to Voller and to *Astronomy* for a truly outstanding article.
— Donald I. Craig, Jr., Indianapolis, IN

We welcome your comments at Astronomy *Letters, P. O. Box 1612, Waukesha, WI 53187; or email to letters@astronomy.com. Please include your name, city, state, and country. Letters may be edited for space and clarity.*

BUILDING BLOCKS. Researchers at the Murchison Widefield Array successfully detected radio emissions from organic molecules originating in variable stars in our galaxy.

OUR MOON'S MANTLE IS WETTER THAN WE THOUGHT

For decades, scientists believed the Moon contained little water. But a new study published July 24 in *Nature Geoscience* indicates that the Moon's mantle may be relatively water-rich.

Ralph Milliken of Brown University and Shuai Li of the University of Hawaii reviewed data from the Moon Mineralogy Mapper on the Indian Space Research Organisation's Chandrayaan-1 lunar orbiter and found widespread evidence for water just below the crust of the Moon.

Water content similar to basalts on Earth has been seen previously in volcanic samples from the Apollo missions. But these samples were small and from isolated areas.

"The key question is whether those Apollo samples represent the bulk conditions of the lunar interior or instead represent unusual or perhaps anomalous water-rich regions within an otherwise 'dry' mantle," Milliken said in a press release.

To answer this question, the team looked at data from Chandrayaan-1, which observed sunlight reflected by large-scale volcanic features called pyroclastic deposits. But solar heating of the Moon's surface can mask water's signature. The team first combined the existing Apollo samples with additional data on surface heating of the Moon to model and subtract this effect from the Chandrayaan-1 observations.

They found water "spread across the surface, which tells us that the water found in the Apollo samples isn't a one-off. Lunar pyroclastics seem to be universally water-rich, which suggests the same may be true of the mantle," Milliken said.

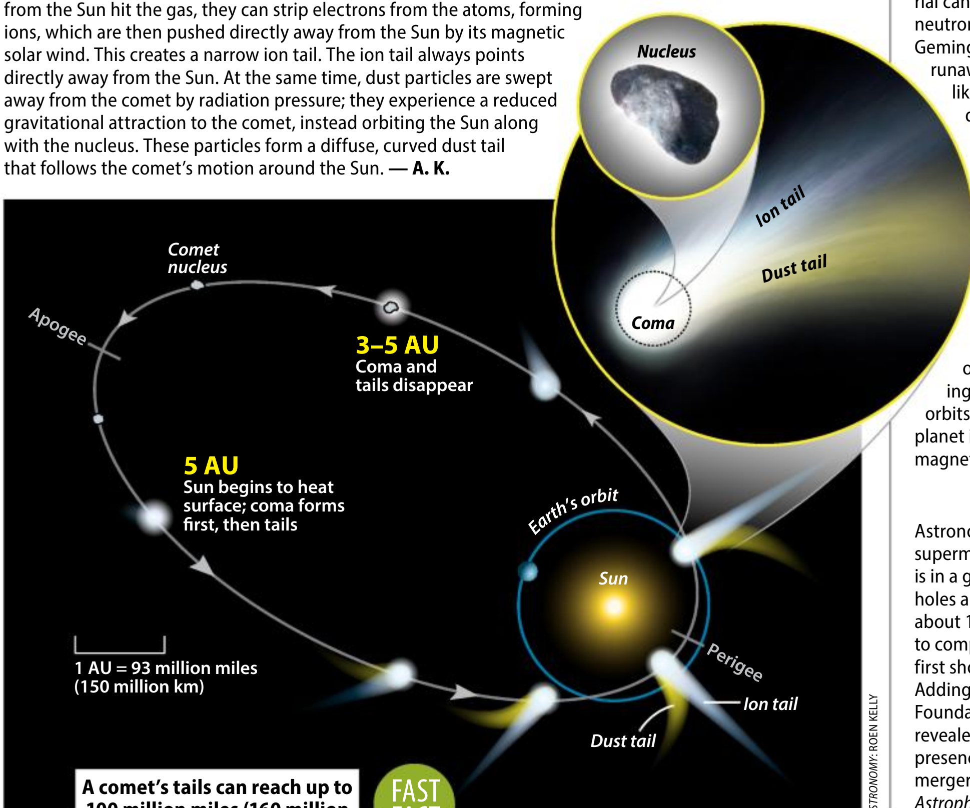
The collision that created the Moon was hot enough to destroy the hydrogen required to form water as the debris condensed, so little water should have been created as a result. "The growing evidence for water inside the Moon suggests that water did somehow survive, or that it was brought in shortly after the impact by asteroids or comets before the Moon had completely solidified," Li said. "The exact origin of water in the lunar interior is still a big question." — **Alison Klesman**

NASA/GSFC/ARIZONA STATE UNIVERSITY

WATER EVERYWHERE? Some volcanic features on the Moon show evidence of higher water content than expected. This crater is one of many that formed in an area containing volcanic material.

A TALE OF TWO TAILS

BIG CHANGES. Comets spend most of their time in the outer solar system without their trademark tails. As a comet approaches the inner solar system on its way to perigee (the closest point to the Sun in the comet's orbit), ices on its surface begin to vaporize, forming a coma of gas around the nucleus. As ultraviolet photons from the Sun hit the gas, they can strip electrons from the atoms, forming ions, which are then pushed directly away from the Sun by its magnetic solar wind. This creates a narrow ion tail. The ion tail always points directly away from the Sun. At the same time, dust particles are swept away from the comet by radiation pressure; they experience a reduced gravitational attraction to the comet, instead orbiting the Sun along with the nucleus. These particles form a diffuse, curved dust tail that follows the comet's motion around the Sun. — **A. K.**



ASTRONOMY: ROEN KELLY

A comet's tails can reach up to 100 million miles (160 million km) or more in length. FAST FACT

BRIEFCASE

SECOND CHANCES

Some planets may be a second family to their home stars. When a star goes supernova, the resulting material can accrete into planets around the newly formed neutron star. British researchers studying the pulsar Geminga, which is 800 light-years away, found that the runaway pulsar drags material behind it as a comet-like tail. This bow shock pulls material toward the dense stellar remnant, which can in turn accrete into "zombie" planets. Geminga seems to be in the process of forming one or more planets a few times the mass of Earth.

TOPSY-TURVY

Uranus' magnetic field can switch-hit in a pinch. The seventh planet spins on its side, which has an unusual effect: Its magnetosphere comes and goes throughout the day, flickering on and off. The east-west orientation of the magnetic field gives it a bit of a tail, causing reconnection to occur "behind" the planet as it orbits the Sun. This also means that at times the planet is bathed in solar winds, while at other times, the magnetic fields fortify it against them.

BLACK HOLE DANCE

Astronomers have spotted for the first time a pair of supermassive black holes orbiting each other. The pair is in a galaxy 750 million light-years away, and the black holes are 24 light-years apart, with a combined mass of about 15 billion Suns. It takes them about 30,000 years to complete a single orbit. The galaxy, called 0402+379, first showed two "core" regions in 2003 and 2005. Adding new data taken with the National Science Foundation's Very Long Baseline Array in 2009 and 2015 revealed two distinct supermassive black holes. Their presence indicates the galaxy has recently undergone a merger. The discovery was published June 27 in *The Astrophysical Journal*. — **John Wenz, A. K.**

STAR STUFF. The Spitzer Adaptation of the Red-sequence Cluster Survey found more molecular gas, a building block of new stars, in distant early galaxies than in nearby objects.

Our fastest stars could be runaways

GALACTIC CANNON. The Large Magellanic Cloud, a big, fast-moving satellite of the Milky Way, potentially spews out runaway stars that infiltrate our own galaxy as hypervelocity stars. ESO

Hypervelocity stars have puzzled astronomers since their discovery in 2005. Several ideas exist to explain this small population of about 20 strange stars, but none can account for one key characteristic: Hypervelocity stars are found in only one region of the sky, near the constellations Leo the Lion and Sextans the Sextant.

Astronomers at the University of Cambridge now think they've uncovered these stars' mysterious origin and explained this grouping effect: They believe the Milky Way's hypervelocity stars are runaway stars from our largest satellite galaxy, the Large Magellanic Cloud (LMC).

This finding, published in the August *Monthly Notices of the Royal Astronomical Society*, was born of the lead author's dissatisfaction with current explanations. To address that frustration, Douglas Boubert, a Ph.D. student at Cambridge's Institute of Astronomy, and his co-authors combined data from the Sloan Digital Sky Survey with computer simulations to show how these stars could originate in the LMC and end up in the Milky Way.

In this scenario, hypervelocity stars, which are blue giant stars, were once members of binary systems. When its binary companion exploded as a supernova, the remaining star had nothing to hold it in orbit. Instead, it continued moving in a straight path at the speed at which it had been orbiting. Because the LMC is small, containing only about 10 percent of our galaxy's mass, many of these stars would be moving fast enough to easily escape the dwarf galaxy's gravitational pull and end up in the Milky Way.

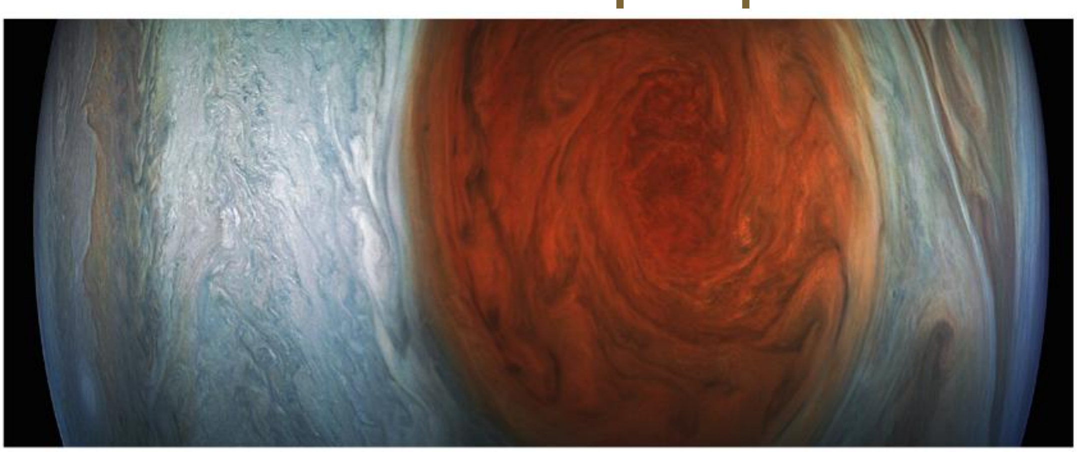
Furthermore, because the LMC is moving so quickly (nearly 250 miles per second [400 km/s]), the speed of the star combined with the speed of the dwarf galaxy for an even bigger boost. "These stars have just jumped from an express train — no wonder they're fast," Rob Izzard, a co-author on the paper, said in a press release. "This also explains their position in the sky, because the fastest runaways are ejected along the orbit of the LMC toward the constellations of Leo and Sextans."

The researchers are the first to model such a possibility. They predict there could be up to 10,000 such runaway stars from the LMC throughout the Milky Way. Because giant stars are the progenitors of compact objects and have short life cycles, many more runaway stars may "die" in transit between the two galaxies. As a result, the researchers also predict up to 1 million runaway neutron stars and black holes flying through the Milky Way in addition to the hypervelocity stars we do see.

Unlike many other predictions, these can be put to the test in short order. When the European Space Agency's Gaia satellite reports its findings next year, "there should be a trail of hypervelocity stars across the sky between the Leo and Sextans constellations in the north and the LMC in the south," Boubert said. If this trail is found, it will be a smoking gun pointing back at the LMC as the origin of these stars.

You can learn more about hypervelocity stars in our March 2017 feature article, "How high-speed stars escape the galaxy." — **A. K.**

Juno sees the Great Red Spot up close



NASA/JPL-CALTECH/SwRI/MSSS/GERALD EICHSTÄDT

IN THE RED. NASA's Juno spacecraft returned dazzling pictures of Jupiter's Great Red Spot on July 10. But all of the spacecraft's eight additional instruments also studied the storm. Combining the multiwavelength data from these state-of-the-art instruments, scientists can create a more complete model of the storm than ever before. This image was taken 6,100 miles (nearly 10,000 kilometers) above the cloud tops. It has been enhanced and illumination-adjusted to bring out the color and structure inside and around the Spot. — **A. K.**

QUICK TAKES

TINY HITS
Small meteorite impacts change Mercury every day, vaporizing parts of its crust and ejecting volatiles into its tenuous atmosphere.

CAT'S CRADLE
Stanford University researchers vaporized a diamond over compressed water to create Ice VII, an isotope found deep within Titan and the ice giants.

COSMIC BULLIES
Uniform iron concentrations in galaxy clusters show that the element likely was created before the clusters formed rather than after, indicating that the first galaxies led violent lives.

KICK-START
Ultraviolet radiation may have been the catalyst for iron-and-sulfur clusters, compounds vital for amino acid formation.

MUDDY MIX
Early Earth-like protoplanets may start as muddy balls that contain both ice and rock.

MISBEHAVING COMET
The comet-like centaur 174P/Echeclus appears devoid of carbon monoxide, unlike other comets with similar orbits. Researchers aren't sure why.

YOUR NEW GO-TO
The Gravitational-wave Optical Transient Observer (GOTO) was inaugurated in La Palma, Canary Islands, to look for optical effects from gravitational waves.

NOT-SO-IMAGINARY FRIENDS
JPL researchers suggest gas giants could be mistaken for rocky worlds if an unseen binary companion to their sun affects density measurements.

THEY COME IN PAIRS
Astronomers discovered two possible planets orbiting each other without a home star. The objects likely came from the TW Hydrae association.

BIGGER THAN BIG
Indian astronomers announced the discovery of Saraswati, a galaxy megacluster 4 billion light-years away that spans 600 million light-years and has the mass of 20 million billion Suns. — **J. W.**

OBSERVING**BASICS**

BY GLENN CHAPLE

Priceless royalty

A small scope reveals many deep-sky wonders lurking in Andromeda the Princess.

Approximately 60 stars scatter loosely across the face of the bright open star cluster NGC 752. ANTHONY AYIOMAMITIS

Earlier this year, I decided to have a little fun tracking down some deep-sky objects in Andromeda with the smallest telescope I own: a 2.4-inch (60mm) f/12 refractor. Many serious backyard astronomers might consider a scope of this size nothing more than a child's toy, but I know better.

The scope I used was an upgrade from the poor-quality 2.4-inch units that pervaded the market a few decades ago. No need to struggle with a rickety alt-az mount or squint through a cheap plastic finder scope or subpar 0.975" eyepiece. My current model is supported by a sturdy go-to mount (though I opted to use the manual mode and star-hop to each target), comes equipped with a red-dot finder, and accepts standard 1¼" eyepieces.

Here's a summary of my small-scope Andromeda adventure. I show the notes I took that night in italics.

Almach (Gamma [γ] Andromedae)

A double star with magnitudes of 2.3 and 5.0, a separation of 9.8", and a position angle of 63°.

Nicely split at 67x. Colors — rich yellow and soft blue — well-seen at 117x.

This colorful pair is one of my favorites. In fact, I prefer it to the more-heralded Albireo in Cygnus. The hues are comparable, and Almach's components are more than three times closer than Albireo's. I'm always blown away by the crisp star images a refractor delivers, and this little scope doesn't disappoint.

Pi (π) Andromedae

A double star with magnitudes of 4.4 and 7.1, a separation of 35.6", and a position angle of 174°.

Required averted vision to see companion at 67x. Well-seen at 117x. Primary whitish, perhaps off-white.

A nearly three-magnitude difference in brightness between the main star and its partner makes this a challenging pair. The solution was to separate the two with the highest practical magnification (around 120x for a 2.4-inch refractor).

59 Andromedae

A double star with magnitudes of 6.1 and 6.7, a separation of 16.6", and a position angle of 37°.

Pretty pair, somewhat faint. Split at 67x, but best seen at 117x.

Although it lacks the visual splendor of Almach, this pair has a uniquely delicate beauty. These closely matched hot stars (spectral classes B9 and A1) both appear white.

56 Andromedae

A double star with magnitudes of 5.8 and 6.1, a separation of 203", and a position angle of 298°.

Wide pair, both white. Easy at 27x. Nearby is open cluster NGC 752.

As a football referee might say, "I call 'em as I see 'em." Through the 2.4-inch scope, the component stars of this optical pair didn't show any distinct color, so I called them "white." The online edition of the *Washington Double Star Catalog*, however, lists the spectral classes as K0 and M0, which should lead to golden yellow to orange-red hues. What colors do you see?

NGC 752

An open star cluster that glows at magnitude 5.7 and spans 60'.

Best seen at 44x. Triple star in center (mag 7 primary). Surrounded by two dozen fainter stars. Fills field. Large and sparse.

The notes I made when observing this cluster with a 3-inch reflector in 1978 mirror what I wrote this time. Low power is the way to go with NGC 752, especially if you want to include 56 Andromedae.

The Andromeda Galaxy

The spiral galaxy also known as M31 shines at magnitude 3.4 and spans 3° by 1°.

Only the nucleus of M31 was visible. M32 was visible as a small circular patch at 44x; best seen at 117x. No sign of NGC 205.

Admittedly, the magnificent Andromeda Galaxy isn't so magnificent when viewed through a 60mm refractor — at least under the moderately light-polluted skies where I live, 40 miles northwest of Boston. All I could see for certain was the bright nucleus: a hazy oval less than a degree in length. Knowing where to look (I made a right-to-left reverse chart to help), I had little trouble finding the galaxy's companion, M32, but struck out with the larger, fainter companion, NGC 205. If you're observing from a dark-sky site, see if you have better luck with NGC 205 than I did.

Questions, comments, or suggestions? Email me at gchaple@hotmail.com. Next month: Why I'm reluctant to recommend a particular restaurant or movie — or telescope. Clear skies!

The Blue Snowball (NGC 7662) shows its distinctive color in photographs, but observers with small scopes will find it challenging to see the subtle hue. DEREK SANTIAGO

Blue Snowball

A planetary nebula also known as NGC 7662; it glows at magnitude 8.3 and spans 32" by 28".

Found by star-hopping, using a right-to-left reverse chart to match the view through a refractor and star diagonal. Visible at 117x as an out-of-focus star — grayish in color; no blue.

This object's starlike appearance at low power makes it a tough customer for small-aperture scopes. My finder chart allowed me to star-hop from Iota (ι) to 13 Andromedae, which is less than a degree northeast of NGC 7662. Once I located the little planetary and centered it in the eyepiece field, I was able to switch to higher magnification.

Glenn Chaple has been an avid observer since a friend showed him Saturn through a small backyard scope in 1963.

BROWSE THE "OBSERVING BASICS" ARCHIVE AT **www.Astronomy.com/Chaple.**

ASTRO**NEWS** **URSA MAJOR MINOR.** Astronomers are watching NGC 3359 consume the Little Cub dwarf galaxy. The smaller galaxy is considered "pristine" in its chemical makeup, offering a unique look at a process called galaxy quenching.

HIDDEN COUNTERPARTS. The central portion of the star-forming region RCW 38 is home to many massive stars and protostars — and, apparently, brown dwarfs. ESO

Brown dwarfs might be as plentiful as stars

A recent international study found that the Milky Way may be home to 100 billion brown dwarfs — equal to the projected number of stars in our galaxy.

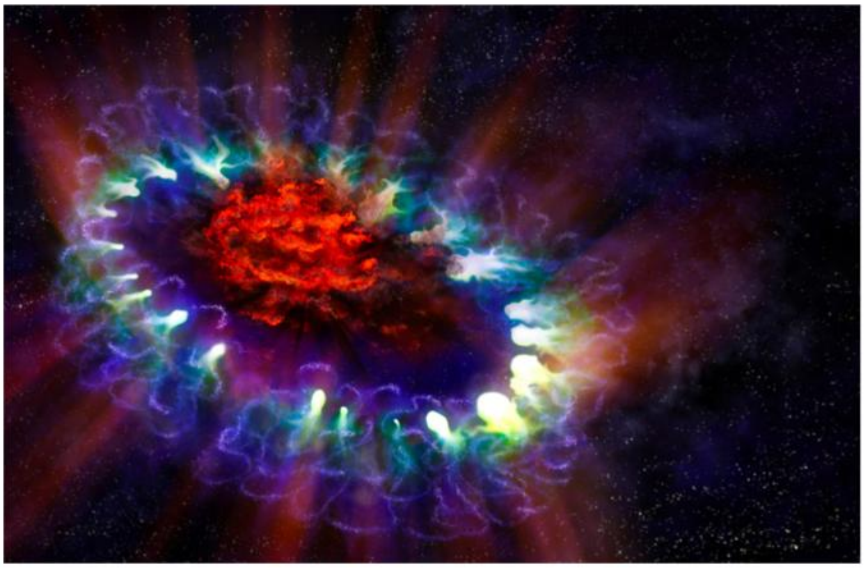
A brown dwarf is called a failed star because it cannot fuse hydrogen into helium. They typically are gaseous objects about 13 Jupiter masses or more, and they form like stars rather than planets.

The researchers surveyed RCW 38, an ultra-dense star-forming cluster about 5,500 light-years away. They found the same ratio of brown dwarfs as in five other surveyed clusters going back to 2006, many without the same extreme conditions as RCW 38. In other words, brown dwarfs seem fairly uniformly distributed in the galaxy, regardless of environment.

"We've found a lot of brown dwarfs in these clusters. And whatever the cluster type, the brown dwarfs are really common," Alex Scholz, an astronomer at University of St. Andrews, said in a press release. "Brown dwarfs form alongside stars in clusters, so our work suggests there are a huge number of brown dwarfs out there."

The bare minimum estimate is that there are 25 billion brown dwarfs in the galaxy. Further studies of brown dwarfs and low-mass stars could help determine what causes some stars to thrive and others to fail. **— J. W.**

Supernovae may leave dust behind



A DUSTY HEART. Supernova 1987A, envisioned in this artist's concept, is composed of an inner region (red) containing the progenitor star's remains, and an outer shell (white and blue) that represents the interface between the shock wave from the explosion and the envelope of gas the star ejected prior to its death. The inner region contains the dust molecules detected by ALMA. ALMA (ESO/NAOJ/NRAO)/ALEXANDRA ANGELICH (NRAO/AUI/NSF)

While it's known that supernova explosions produce the heavy elements that are incorporated into the next generation of stars, astronomers previously thought these explosions destroyed materials such as molecules and dust within the dying star. Now, a team led by astronomers at the University of Cardiff has uncovered evidence that supernova remnants can create environments that foster dust and molecule production as well, further facilitating the birth of new stars. Their results were published in August's *Monthly Notices of the Royal Astronomical Society*.

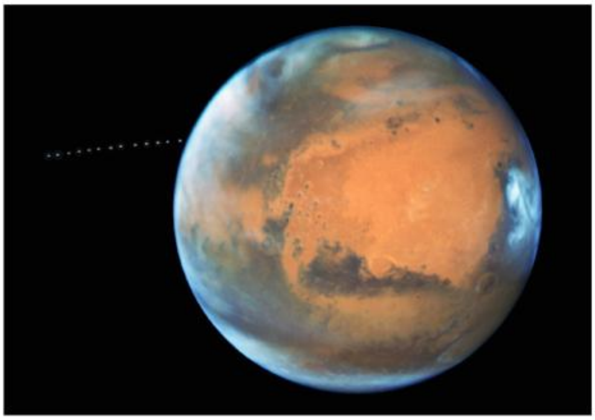
The team used the Atacama Large Millimeter/submillimeter Array (ALMA) to observe Supernova 1987A, a supernova remnant 163,000 light-years away in the Large Magellanic Cloud. The detail achievable with ALMA allowed them to identify molecules such as formylium (HCO+) and sulfur monoxide (SO) in the cooling supernova remnant. Previous studies have identified carbon monoxide (CO) and silicon oxide (SiO) there, too.

The discovery of these molecules was unexpected. "This is the first time that we've found these species of molecules within supernovae, which questions our long-held assumptions that these explosions destroy all molecules and dust that are present within a star," lead author Mikako Matsuura of Cardiff University's School of Physics and Astronomy said in a press release.

Based on findings that the cooling supernova remnant is allowing these molecules to form, she explained, "What is most surprising is that this factory [the area around the remnant] of rich molecules is usually found in conditions where stars are born. The deaths of massive stars may, therefore, lead to the birth of a new generation," as that dust is later incorporated into forming stars. Thus, it appears that supernovae not only form the heavy elements that make up future stars and planets, but some of their dust as well. **— A. K.**

50
trillion

The intensity (in electron volts) of the gamma-ray glow in the Milky Way's center.



Hubble captures a bonus shot

PHOTOBOMB. While photographing Mars on May 12, 2016, the Hubble Space Telescope got a bonus when Phobos appeared. The telescope captured 13 images of the tiny martian moon in 22 minutes, allowing astronomers to create a time-lapse of Phobos' orbital path. At just 16.5 by 13.5 by 11 miles (26.5 by 21.7 by 17.7 kilometers), Phobos is one of the smallest moons in the solar system. It orbits Mars three times over the course of one martian day. These photos were taken when Mars was 50 million miles (80.5 million km) from Earth, just a few days before it reached its closest approach to Earth in 11 years. **— Nicole Kiefert**

NASA, ESA, AND Z. LEVAY (STScI), ACKNOWLEDGMENT: J. BELL (ASU) AND M. WOLFF (SPACE SCIENCE INSTITUTE)

SECRET**SKY**

BY STEPHEN JAMES O'MEARA

A fishy tale in the fall sky

Pisces will never be the same.

Pisces is a sprawling constellation composed mainly of faint stars. It ranks 14th in size but only 68th in overall brightness among the 88 constellations. TONY HALLAS

Pisces the Fish is a peculiar constellation. At least it's odd in the way star charts depict it in a connect-the-dots fashion.

Most show the famous western Circlet of stars (easily imagined as a fish), attached to a wide V-shaped cord with a dim kink of stars on the northeastern end. That part resembles a diamond-shaped fish halved lengthwise. Such a depiction just doesn't cut it because something seems missing.

Al-Sufi's fishes

The problem with modern depictions of constellations is they show us, as best they can, figures that fit within established boundaries imposed by an international committee. This forces celestial cartographers to "stay within the lines." But constellations were imagined long before these boundaries existed and without any constraints.

Take the eastern fish of Pisces. Anyone looking at it can imagine a full "circlet" of stars; it's just that you have to borrow some from a neighboring constellation to complete it. So, combine Phi (ϕ), Nu (ν), Tau (τ), 68, and 65 Piscium with Zeta (ζ) and Eta (η) Andromedae. This fish even has a tail: Chi (χ) Piscium and its neighboring chain of three stars Psi^1 (ψ^1), Psi^2 (ψ^2), and Psi^3 (ψ^3) Piscium.

Actually, the stars mentioned above belong to two fishes imagined by the 10th-century Persian astronomer Abd al-Rahman al-Sufi and recorded in *The Book of the Images of the Fixed Stars*, which he completed around A.D. 964. The small fish is superimposed on a larger fish (both swimming north), which, in turn, is superimposed on Andromeda's upper body.

What's more, in a recently discovered copy of al-Sufi's star atlas (dated A.D. 1125 and referred to as the Doha Manuscript, as it is displayed at the Museum of Islamic Art in Doha, Qatar), we see yet another fish. This one is swimming south out of the Milky Way in far eastern Andromeda near Perseus.

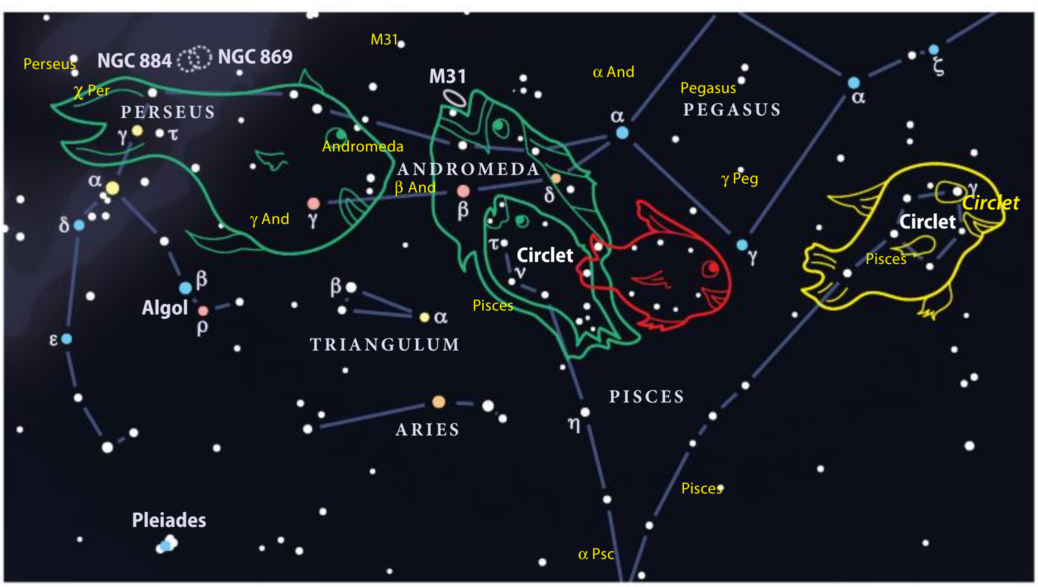
To find this third fish's lower jaw and underside, locate the stars Tau, 55, Gamma (γ), 60, 62, 64, and 65 Andromedae. For its upper jaw, use Upsilon (υ), Chi, 51, and 54 Andromedae, before extending to the Double Cluster (NGC 869 and NGC 884). All three of al-Sufi's fishes were Bedouin constellations.

A modern addition

When we add the western fish of Pisces to the picture, we get a clear stream of fish extending from the western boundary of the Milky Way "river" to the eastern boundary of Aquarius the Water-bearer, who pours another stream of water into the mouth of Piscis Austrinis the Southern Fish. As seen through the eyes of the ancients, our culminating stars of autumn were a veritable water world filled with fishes.

But as I peruse the stars in this region, I am captured by yet another circlet in Pisces — one visible to the unaided eyes under dark skies. It lies roughly midway between the two classical fishes tied by the cord, and is composed of the stars 52, 53, 54, 55, 57, 64, 67, and TV Piscium.

It's OK to see the stars in new ways. We have the freedom of imagination, so let's use it for our enjoyment. As always, let your thoughts flow to sjomeara31@gmail.com.



The three fish with green outlines are the ones created by 10th-century astronomer Abd al-Rahman al-Sufi; the western fish of Pisces is in yellow; and the modern fish is in red. RICHARD TALCOTT AND ROEN KELLY, AFTER STEPHEN JAMES O'MEARA

Stephen James O'Meara is a globe-trotting observer who is always looking for the next great celestial event.

BROWSE THE "SECRET SKY" ARCHIVE AT **www.Astronomy.com/OMeara.**

ASTRO**NEWS** **ENCELADUS' GUNK.** Methanol was spotted in the vicinity of Enceladus' icy plumes. However, researchers believe it may form from interactions with other particles in space, rather than in the moon's interior.

Titan's lakes are calm

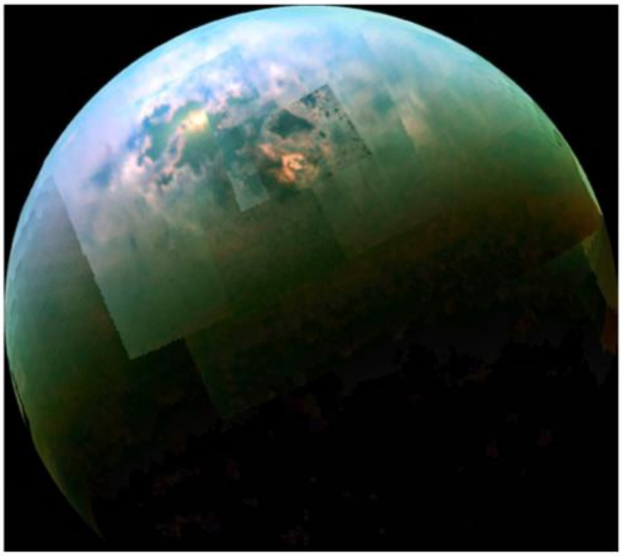
The hydrocarbon seas on Saturn's moon Titan are relatively calm, which might make landing a future probe there much easier, according to research led by the University of Texas at Austin. Cornell University, the Johns Hopkins University Applied Physics Laboratory, and NASA's Jet Propulsion Laboratory also collaborated on the study, which appeared in *Earth and Planetary Science Letters* on June 29.

Cyril Grima, a research associate at the University of Texas Institute for Geophysics, created a technique called radar statistical reconnaissance to measure surface roughness in minute detail from radar data. It's been used to measure snow density and surface roughness in Antarctica and the Arctic, and it is set to help select the landing site for NASA's Mars lander, InSight, scheduled for launch next May.

Research using this technique on Saturn's moon showed that the lakes of liquid methane on Titan create waves that don't get much more than 0.4 inch (1 centimeter) high and 8 inches (20cm) across.

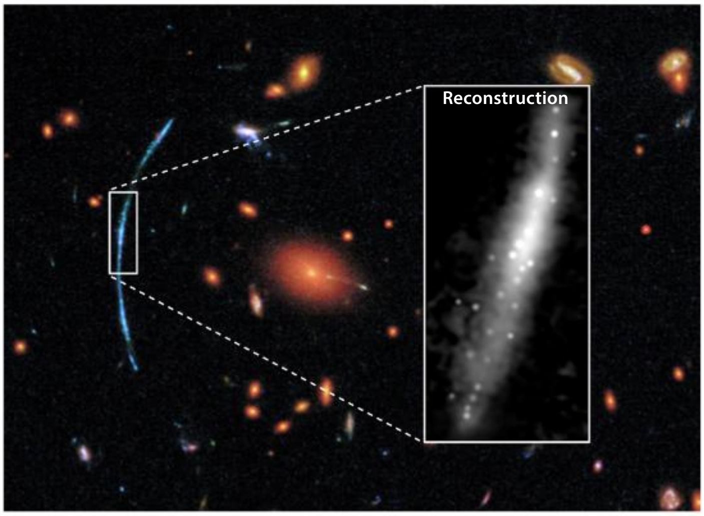
Saturn's largest moon has long been an area of interest for researchers thanks to its methane and ethane rain, cryovolcanoes, and the icy crust that could be a sign of an ocean below the surface.

The three biggest areas of interest are Kraken Mare, Ligeia Mare, and Punga Mare, lakes in the moon's northern hemisphere. Mission concepts exist, but there are no current plans to send a probe to Titan. It's comforting to know, though, that should a mission come to fruition, its probe would likely have a smooth landing. — **N. K.**



SMOOTH SAILING. The methane seas of Saturn's moon Titan are visible in the northern hemisphere of this mosaic photo, compiled using images from NASA's Cassini spacecraft. NASA/JPL/UNIVERSITY OF ARIZONA/UNIVERSITY OF IDAHO

11 The number of days this year NASA can't send commands to Mars missions due to alignment of Mars, the Sun, and Earth.

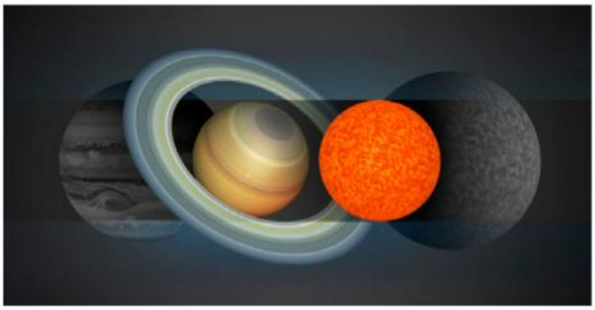


NASA, ESA, AND T. JOHNSON (UNIVERSITY OF MICHIGAN)

Gravity magnifies distant star formation

STAR-STUDDED. Gravitational lenses act like a telescope, magnifying the images of background objects as light bends around areas of high mass, such as galaxy clusters. One such lens has essentially "sharpened" the Hubble Space Telescope's image quality by 10 times, showing a distant galaxy in magnificent detail. Astronomers reconstructed the image of the galaxy, which is smeared out in an arc by the lens. The galaxy shows numerous intense areas, or knots, of star formation. Based on its distance of 11 billion light-years, the galaxy itself exists at a time when the universe was just 2.7 billion years old. Without the massive galaxy cluster SDSS J1110+6459 sitting a mere 6 billion light-years away between it and Earth, this distant galaxy would appear as a smooth edge-on disk galaxy without any visible knots. Thanks to the magnification boost provided by the galaxy cluster, astronomers can now study star formation in the early epochs of the universe. — **A. K.**

The smallest star ever



A BOETTICHER ET AL, 2017

SMALL BUT STELLAR. This artist's rendering compares the smallest star found to date, EBLM J0555–57Ab, to Jupiter, Saturn, and TRAPPIST-1.

A team of astronomers at the University of Cambridge was on the lookout for new exoplanets when they accidentally discovered the smallest star currently measured.

The tiny star, EBLM J0555–57Ab, is located about 600 light-years from Earth and has a mass (85 Jupiter masses) comparable to the estimated mass of TRAPPIST-1, but a radius about 30 percent smaller. Like TRAPPIST-1, EBLM J0555–57Ab is likely an ultracool M-dwarf star.

The team was originally searching for exoplanets and used data from an exoplanet experiment called WASP (the Wide Angle Search for Planets). During their studies, they noticed a consistent dimming of EBLM J0555–57Ab's parent star, which signified an object in orbit. Through further research to measure the mass of any orbiting companions, they discovered the object they'd detected was too massive to be a planet — it was instead a tiny star.

Although EBLM J0555–57Ab is incredibly small, it still has enough mass for hydrogen fusion, which powers the Sun and provides Earth with energy. Just barely bigger than Saturn, the star has a gravitational pull 300 times stronger than Earth's. If the star were much less massive, it wouldn't exert enough pressure in its center for fusion to occur, and it would instead have formed as a brown dwarf, rather than a star.

The team plans to use this newly discovered star to better understand planets orbiting stars. Details of this discovery were published in the August issue of *Astronomy & Astrophysics*. — **N. K.**

GRAVITATION

From novelty to science

The mergers of at least three binary black holes opened a window into an exotic new realm of astrophysics.

by Robert Naeye

Gravitational waves pour from a black hole binary system just 0.1 second before the two objects merge. As the waves radiate outward at the speed of light, they distort the appearance of distant stars. DON DIXON FOR *ASTRONOMY*

AL WAVES

On September 14, 2015, the international LIGO collaboration accomplished the seemingly impossible. Its twin laser interferometers in Louisiana and Washington made the first direct detection of gravitational waves, long-sought deformations in the fabric of space-time predicted a century earlier by Albert Einstein in his general theory of relativity.

LIGO (the Laser Interferometer Gravitational-wave Observatory) caught the final half-second inward spiral and merger of two black holes containing the masses of 29 and 36 Suns. In a fleeting moment, the smash-up created a 62-solar-mass black hole and converted the remaining 3 solar masses into pure gravitational wave energy, a cosmic tsunami that barreled outward at the speed of light. The wave's peak power briefly exceeded the total energy output of the entire visible universe 50 times over, but none of this energy was in any form of light.

As the wave radiated 1.3 billion light-years in all directions, an infinitesimally tiny portion of its energy passed through Earth. It alternately stretched and compressed the two 2.5-mile-long (4 kilometers) arms in each LIGO facility by 1/1,000 the width of a proton. With their powerful lasers, both LIGO facilities caught these deformations with a precision equivalent to measuring the 4.2-light-year distance to Proxima Centauri *to the width of a human hair.*

LIGO's scientific and technical breakthrough was so astounding that its February 11, 2016, announcement managed to briefly steal the media limelight from the U.S. presidential election.

LIGO followed up this Nobel-worthy discovery with a second detection on December 25, 2015. This event involved the cataclysmic coalescence of 8- and 14-solar-mass black holes at a distance similar to the first event. LIGO also detected a possible merger October 12, 2015, between black holes of about 13 and 23 solar masses. The team is about 90 percent confident that this event is real, but refrained from claiming it as an official detection.

After shutting down LIGO for 11 months for a series of upgrades, the team began a new science run in late November 2016. Five weeks later, on January 4, 2017, the observatory caught waves from a third black hole coalescence, with objects of 19 and 31 solar masses.

Just two years ago, astronomers had no direct evidence that stellar-mass black holes paired up in binary systems. Now they know for certain that such binaries exist, and that they have finite lifetimes. "The key thing to take away from this third highly confident event is that we're really moving from novelty to a new observational science, a new astronomy of gravitational waves," LIGO spokesman David Shoemaker said at the May 31 discovery press conference.

Analyzing the waves from the three mergers has yielded crucial information about black hole masses and spins. But the field is still in its infancy. In the years ahead, we can expect profound discoveries that would be impossible to make any other way. We'll learn about black hole formation, whether some neutron stars are made of exotic matter, and whether general relativity breaks down in nature's most extreme laboratories.

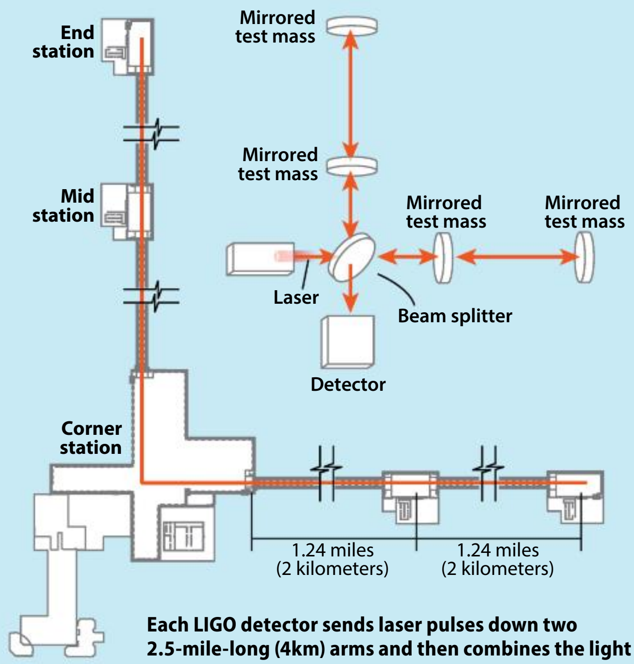
"After personally working endless hours on LIGO for 18 years, 16 of those seeing nothing, it's nice to live in a world where gravitational wave astronomy is a real thing," says Amber Stuver of Villanova University. "And there is still so much more out there to discover."

Heavy black holes

LIGO's latest discovery delighted scientists for several reasons. Like LIGO's first detection, it involves a new class of black holes considerably more massive than the stellar-mass black holes previously detected in binary systems with normal stars. Those earlier known black holes range from about 5 to 15 solar masses, and they presumably formed when the cores of massive stars collapsed and triggered supernovae, which ejected most of their stars' envelopes into space.

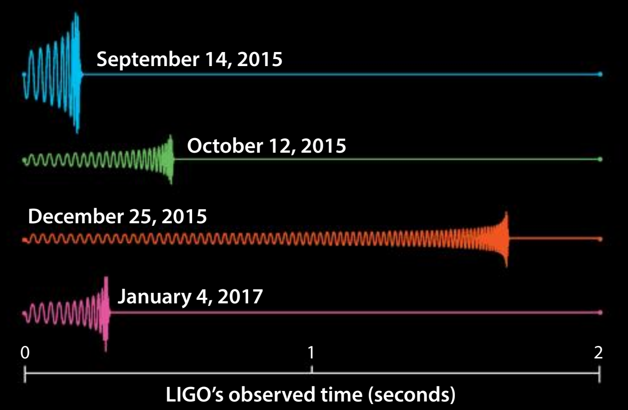
Some members of the heavier class that LIGO detected probably arose from prior black hole mergers, but most presumably formed from the deaths of massive stars. Theorists have predicted that heavier black holes can form if their progenitors were deficient in elements heavier than hydrogen and helium. These so-called "low-metallicity" stars were common in the early

How LIGO works



Each LIGO detector sends laser pulses down two 2.5-mile-long (4km) arms and then combines the light beams to create an interference pattern. By analyzing these patterns, scientists can deduce minuscule changes in the distance the light travels caused by a passing gravitational wave. *ASTRONOMY*: ROEN KELLY

Black hole mergers revealed



LIGO has detected gravitational waves from three black hole mergers as well as one likely merger (on October 12, 2015). The systems with more mass produced stronger signals and also occurred more quickly. Still, LIGO observed the longest event for less than 2 seconds. *ASTRONOMY*: ROEN KELLY; AFTER LIGO/CALTECH/MIT/UNIVERSITY OF CHICAGO (BEN FARR)

universe. They produce weaker stellar winds, so their envelopes retain a high fraction of their mass as the stars age.

When a massive low-metallicity star dies, its core collapses into a neutron star. But sometimes the supernova engine proves too weak to blow off a massive envelope, so the explosion fizzles. The neutron star accretes infalling material for several seconds and collapses into a black hole. A black hole formed in one of these "failed supernovae" could gobble up several dozen solar masses.

Coincidentally, just a week before the third LIGO announcement, the Space Telescope Science Institute issued a press release touting a possible failed supernova. Using the Hubble Space Telescope and the Large Binocular Telescope, a team led by Ohio State University astronomers observed a highly luminous star in spiral galaxy NGC 6946 vanish from sight with no supernova. This star apparently collapsed into a black hole — possibly in the heavy mass range seen by LIGO.

LIGO's merged black holes are also highly significant. The heavier two contain about 62 and 49 solar masses, falling into an intermediate mass range between stellar-mass black holes and the supermassive black holes in the centers of galaxies.

Astronomers have identified several binaries that consist of two supermassive black holes weighing millions or billions of solar masses. These monstrous systems, which arise when galaxies merge, radiate gravitational waves with wavelengths far too long for LIGO to detect. But teams of radio astronomers in the United States, Europe, and Australia are monitoring pulsars — rapidly spinning neutron stars that emit precisely timed pulses — to catch these waves. When gravitational waves from these supermassive binaries cross the space between Earth and these distant pulsars, they slightly affect the arrival time of pulsar pulses. Because pulsar timing is so precise, it's likely these teams will detect long-wavelength gravitational waves in the next several years.

Forming black hole binaries

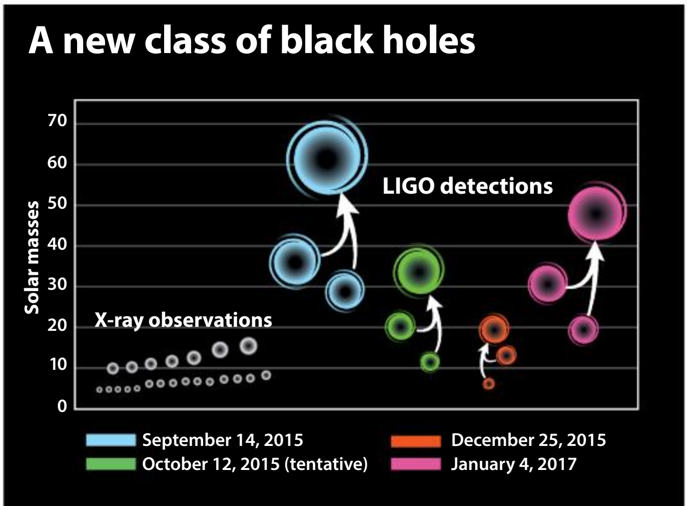
LIGO's recently announced merger also sheds light on the fascinating question of how black holes pair together in binaries. One possibility is that the progenitor stars were always gravitationally bound. The two stars eventually collapsed and left behind black hole corpses that remained locked together. Gravitational waves slowly drained the binary's orbital energy, inexorably closing the gap between the black holes over billions of years. But only in the final seconds before they collided were the waves powerful enough and in the right wavelength band to be detected from Earth.

But the third LIGO event offers evidence for a different scenario. Just like stars and planets, a black hole spins on its axis. If the black hole progenitors formed together in a binary system, their spin axes should be aligned with their orbital plane. According to relativity, the two couldn't merge until they draw extremely close and shed some of the system's rotational energy. But the LIGO data doesn't show this slight delay, indicating that the spin axis of one or both black holes was tilted with respect to the orbital plane.

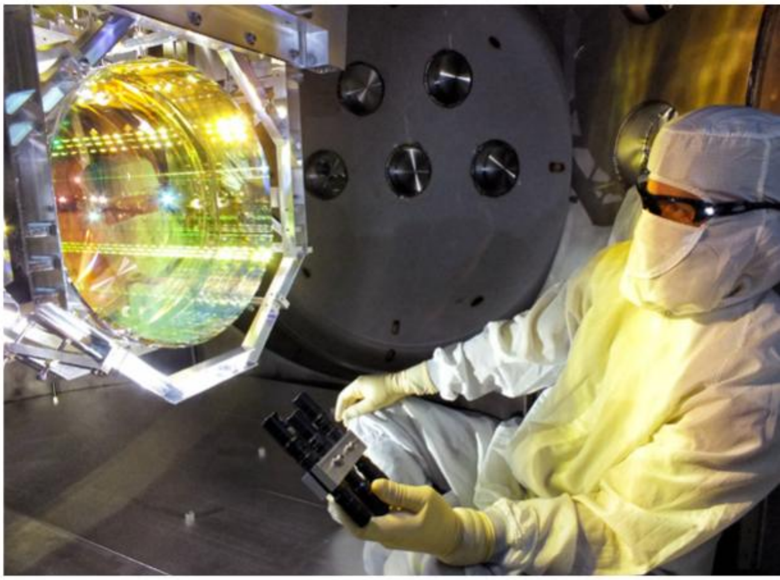
"This finding likely favors the theory that these two black holes formed separately in a dense stellar cluster, sunk to the core of the cluster, and then paired up, rather than being formed together from the collapse of two already-paired stars," says LIGO team member Laura Cadonati of Georgia Tech University.

As the LIGO team ramps up the interferometers' sensitivities in the coming years, the instrument will see deeper into space, bringing millions of new galaxies into view. Although black hole mergers are extremely rare events in any given galaxy, extending LIGO's reach means the two facilities will catch hundreds of black hole mergers each year. By analyzing the statistics of dozens and eventually hundreds of mergers, scientists should be able to determine which mode of black hole binary formation predominates.

Because astronomers don't expect black hole binaries to radiate much light in any part of the spectrum, there is no other way to observe these incredible systems. As West Virginia University physicist Paul Baker explains, "Studying black hole binaries was one of LIGO's great selling points. LIGO is probing something that no other instrument has probed before."



LIGO has discovered a novel group of black holes with masses a few dozen times that of the Sun. These new objects dwarf the stellar-mass black holes typically found in X-ray observations of binary systems, but fall far short of the supermassive black holes that lurk in the hearts of most large galaxies. *ASTRONOMY*: ROEN KELLY; AFTER LIGO COLLABORATION



LIGO's precise measurements would be impossible if contaminants marred any of its optical surfaces. Here, an optics technician illuminates one of the instrument's mirrors to search for imperfections. MATT HEINTZE/CALTECH/MIT/LIGO LAB

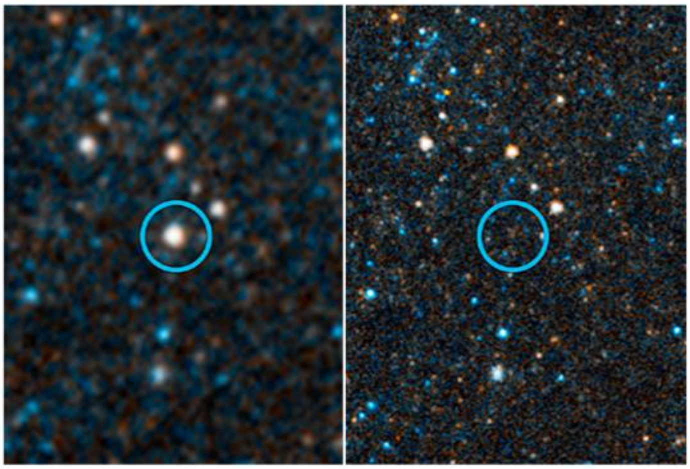
Testing general relativity

The most recent LIGO event was also noteworthy for the relative weakness of its gravitational waves considering the black holes' high masses. The signal's faintness yields an estimated distance of 3 billion light-years, more than twice that of the first two detections.

The greater distance gave the LIGO team a golden opportunity to test a key prediction of general relativity: that gravitational waves don't disperse, meaning all frequencies travel at exactly the same velocity (the speed of light). If gravitational waves disperse, slower frequencies will arrive at the detectors after the faster ones. And the farther away the source, the greater the time lag.

"Our measurements are very sensitive to minute differences in the speeds of different frequencies," says Bangalore Sathyaprakash of Penn State and Cardiff universities. "But we did not discover any dispersion, once again failing to prove that Einstein was wrong."

Just as photons transmit the electromagnetic force, hypothetical quantum particles known as gravitons convey the force of gravity. Quantum theory predicts that gravitons should have zero rest mass, just like photons. Any hint of dispersion would indicate that gravitons have mass, so dispersion would contradict quantum theory as well as relativity. The most recent LIGO detection tightened the limits on a possible graviton mass by 30 percent.



In 2007, the Hubble Space Telescope captured a normal, 25-solar-mass star in spiral galaxy NGC 6946 (left). Two years later, the star's brightness soared to more than a million times the Sun's luminosity. But the star disappeared without a trace by 2015 (right). Astronomers suspect it was a "failed supernova" that collapsed to form a black hole. NASA/ESA/C. KOCHANEK (OSU)

Despite the more than $1 billion the National Science Foundation and its international partners have spent on LIGO, the project remains a work in progress. When it ramps up to its final design sensitivity sometime after 2020, LIGO will start detecting hundreds of black hole mergers a year, with many of them at even greater distances. And because the farther the source, the better the chances of seeing any dispersion, scientists should be able to tell whether gravitational waves deviate at all from general relativity's predictions. Einstein has passed every test so far.

"Black hole mergers are an incredibly dynamic and strong regime to test general relativity. I don't think anybody is expecting any crazy differences, so any deviations will be subtle," Penn State astrophysicist Chad Hanna says.

Any such detection would rock the foundations of science, but it could guide physicists toward a long-sought unification of general relativity and quantum theory. As Penn State physicist Abhay Ashtekar says, "I don't think general relativity is the final word on gravitation because it ignores quantum physics."

Virgo joins the search

On August 1, less than a month before LIGO closed for about a year for more upgrades, a new partner joined the search: the European Virgo interferometer near Pisa, Italy. With 1.9-mile-long (3km) arms, Virgo will be considerably less sensitive than LIGO at first, but like its sibling, it will undergo improvements over time to extend its range.

Adding a third interferometer will take gravitational wave science to new heights. Most importantly, Virgo will enable scientists to locate a gravitational wave source more precisely, giving astronomers a better chance of catching an electromagnetic signal from the event itself, or from its afterglow. Although expected to be incredibly faint, any kind of electromagnetic counterpart to a gravitational wave source would usher in a revolutionary new era of multi-messenger astronomy. It would allow scientists to

The 1.9-mile-long (3km) arms of the Virgo interferometer nestle in the countryside near Pisa, Italy. The instrument came online August 1 and will help scientists locate future gravitational wave sources. THE VIRGO COLLABORATION

Japan's underground Kamioka Observatory houses the KAGRA gravitational wave detector, which should begin observations in 2018. This view shows one of the interferometer's arms. WIKIMEDIA COMMONS/CHRISTOPHER BERRY (UNIVERSITY OF BIRMINGHAM)

compare the signals and extract detailed information about the physics of the event.

With just the two LIGO detectors, scientists use the slight difference in a wave's arrival time between Louisiana and Washington to narrow down the location of a source to roughly 100 square degrees. But as amateur astronomers know, that's a huge area of sky. Finding an afterglow is essentially hopeless. Scientists would feel confident they had seen an electromagnetic counterpart to a LIGO detection only if they detected a simultaneous supernova or gamma-ray burst (GRB) in the same area. Adding a third interferometer will enable scientists to triangulate some sources to about 10 square degrees. This smaller patch of sky would give astronomers a fighting chance to spot an afterglow.

The LIGO team currently sends out alerts to about 70 astronomical partners only after it has studied a candidate gravitational wave and feels confident it's not an instrumental glitch, a process that takes several minutes. But once the LIGO and Virgo teams have built up confidence with more detections, they will issue public alerts more quickly after they register a promising signal.

Two additional laser interferometers currently under construction will enable researchers to pin down the location of some sources to only 1 square degree. Japan is building its KAGRA interferometer under a mountain. With two 1.9-mile-long (3km) arms, it features some cutting-edge technology, such as cryogenically cooled mirrors that should reduce instrument noise. After a series of significant delays, scientists expect KAGRA — short for Kamioka Gravitational Wave Detector — to join LIGO and Virgo next year.

A clone of the LIGO interferometers will be built in Maharashtra, India, using hardware initially built for LIGO's Washington facility. LIGO-India is scheduled to begin science operations around 2024, with a sensitivity similar to the two U.S. instruments.

Sky map of mergers

With two detectors, LIGO can't pinpoint its observed black hole mergers. This map plots the likely locations of the four events, including the uncertain one seen October 12, 2015. The outer contour of each represents 90 percent confidence; the innermost contour signifies 10 percent confidence.
LIGO/CALTECH/MIT/LEO SINGER; MILKY WAY IMAGE: AXEL MELLINGER

Neutron star stuff

Scientists may need the more robust capabilities of an expanded network to go beyond black hole mergers. While black hole binaries were only theorized prior to LIGO's first detection, astronomers were 100 percent certain that neutron star binaries existed. In fact, radio astronomers have detected 20 such pairs. And in every case where they can make high-precision measurements, the binary's orbit is shrinking exactly in accordance with Einstein's predictions of how gravitational waves carry away orbital energy. In other words, neutron star binaries are also destined to merge.

LIGO has yet to see any such mergers because neutron stars have lower masses than black holes, so their mergers produce weaker gravitational waves. The observatory can detect neutron star mergers only out to about 290 million light-years. But as the team ramps up LIGO's sensitivity and extends this range to 1.4 billion light-years, it will start catching these rare but highly significant events.

Astronomers suspect that neutron star mergers initiate most GRBs lasting less than two seconds, although some of them might come from mergers between black holes and neutron stars. A simultaneous gravitational wave event and GRB would be immensely important because it would reveal the nature of the progenitor. It also would help answer burning questions about the energy source that powers GRBs, how the merger ejects mass, the angle at which matter gets beamed in jets, and how that material produces gamma rays.

Perhaps even more important: As the two neutron stars draw close, each star's gravity tidally distorts its partner, which, in turn, affects how fast they spiral inward in the final milliseconds prior to merging. Any detection of gravitational waves from this tug-of-war will yield valuable information about the highly compressed nuclear material inside each neutron star.

Recent computer simulations show that the merger itself produces a hypermassive neutron star with a density several times higher than atomic nuclei. Such an object spins rapidly, producing a centrifugal force that briefly prevents it from collapsing into a black hole. These extraordinarily dense objects shed rotational energy by emitting gravitational waves. LIGO will be challenged to detect these waves, but if scientists luck out and catch a neutron star merger within 100 million light-years, they could gain precious insights into matter as it is compressed to almost unimaginably high densities. "We would be able to witness the final victory of gravity over nuclear forces as the star collapses to form a new black hole," says Princeton University theorist David Radice.

LIGO also could discover the first known binary consisting of a black hole orbiting a neutron star. Although scientists think such systems are extremely rare, they almost certainly exist. In these systems, the black hole would tidally rip apart the neutron star just before they coalesce, producing strong gravitational waves that would reveal vital information about the neutron star's composition.

Even solitary neutron stars could give off gravitational waves. With their incredibly high densities, neutron stars should be perfectly symmetrical about their rotation axes. But neutron stars with bulges just a couple of inches high would radiate gravitational waves continuously. LIGO might catch these waves if any of these neutron stars reside in our corner of the Milky Way. Such detections would yield critical evidence about whether neutron star cores are made of conventional nuclear matter or exotic material, such as strange quarks. You can participate in this search by visiting https://einsteinathome.org and letting your computer sift through LIGO and other data while you're away.

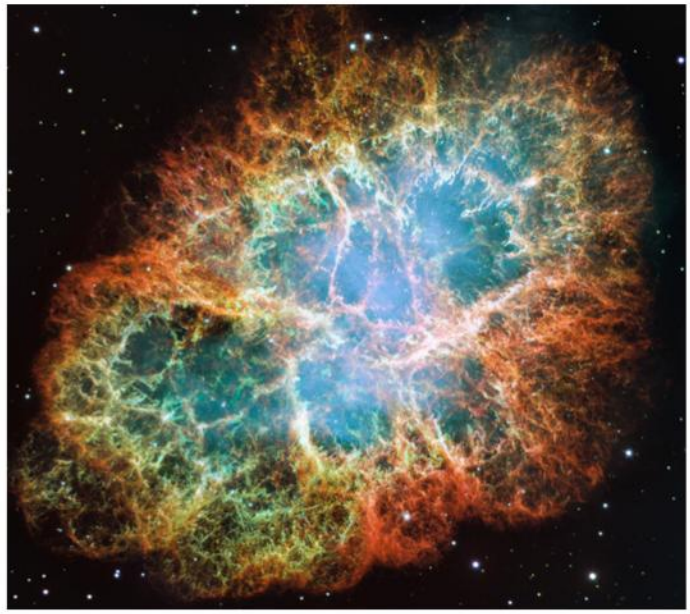
The ultimate cosmic messenger

While LIGO has already identified several black hole mergers, another type of event could prove even more valuable. Our Milky Way is long overdue for a supernova. A galactic event triggered by the collapse of a massive star's core would be an astrophysicist's dream come true — a cosmic Rosetta stone of multi-messenger astronomy. Although a core collapse would be phenomenally bright across much of the electromagnetic spectrum, it also would produce on the order of 10^{58} neutrinos representing 99 percent of the supernova's energy. The world's various neutrino detectors would register tens of thousands of hits, giving precious insights into the explosion mechanism. And under certain conditions, a collapsing stellar core will unleash gravitational waves that could be detected from Earth.

"The gravitational waves would be emitted at almost exactly the same time as the neutrinos, so you could correlate the two events," says Princeton astrophysicist Adam Burrows. "If we could get all that information from the signal, we'd really have a window on exactly what was happening in real time." Theorists would learn about the core's rotation, density, and mass, and how turbulence and asymmetries affect the explosion.

But how close would that supernova have to be? The mass involved in a collapsing stellar core is tiny compared with that in a binary merger, so the gravitational waves are much weaker. And, Burrows notes, a spherical core collapse wouldn't produce gravitational waves.

According to Shunsaku Horiuchi of Virginia Tech, the detectable range depends on the symmetry of the collapsing core as well as other factors. A highly asymmetric collapse would produce stronger waves, so LIGO might have an outside shot at hearing such a supernova in a nearby galaxy. But if the collapse is nearly



The Crab Nebula holds the remains of a supernova that lit up Earth's sky nearly 1,000 years ago. Astronomers hope that a similarly close supernova in the future will light up gravitational wave detectors and give them new insights into how stars explode. NASA/ESA/J. HESTER AND A. LOLL (ARIZONA STATE UNIVERSITY)

symmetric, it would be a challenge for LIGO even if the explosion occurred well within the Milky Way.

Horiuchi also points out another intriguing possibility: If a massive star in our galaxy collapses into a black hole and fails to produce a supernova, it could be a detectable gravitational wave source with little or no corresponding electromagnetic signal.

The exotic and the unknown

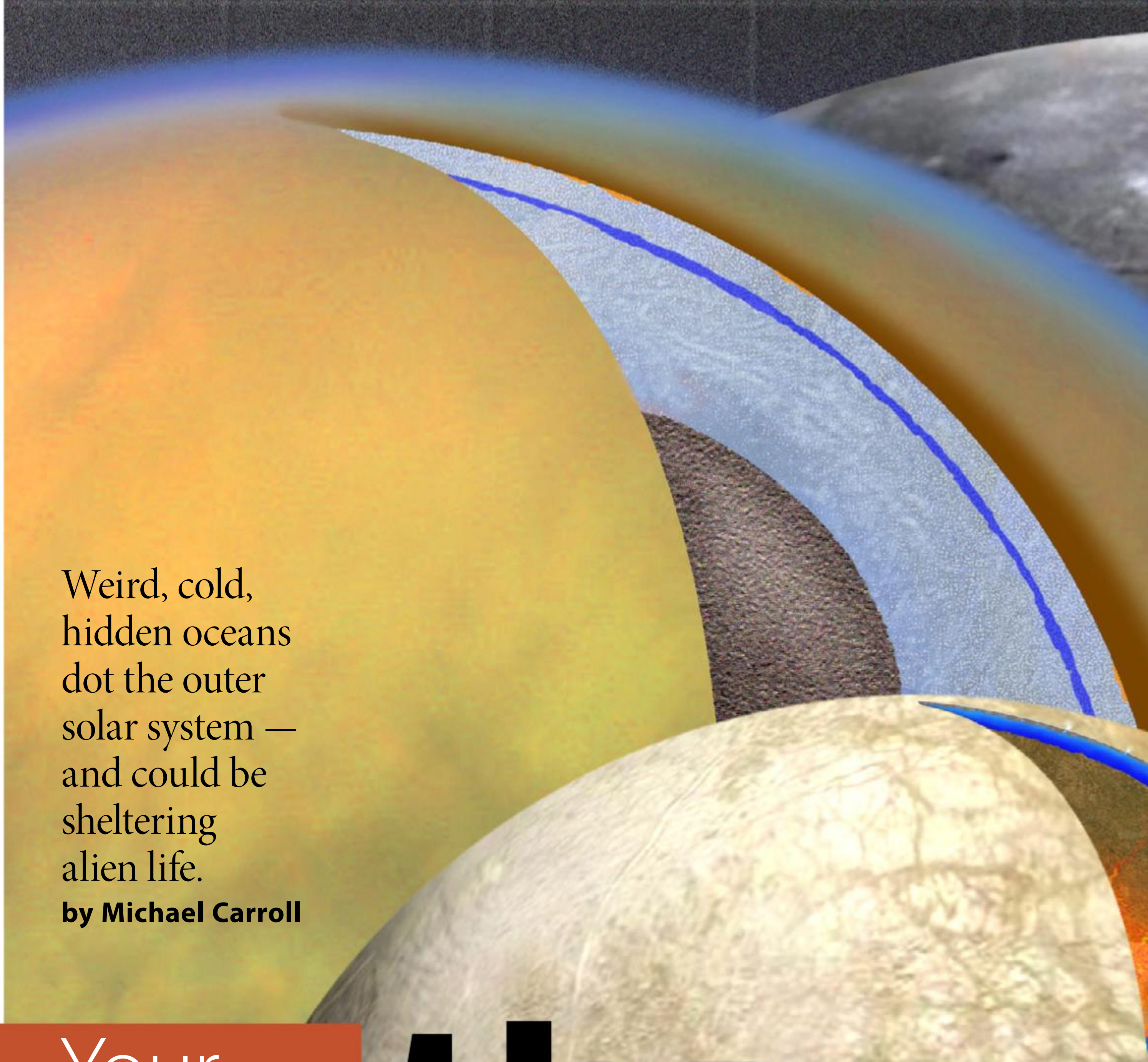
Of all astrophysical objects expected to produce gravitational waves LIGO could detect, cosmic strings are the most speculative and exotic. Some theories of cosmic inflation predict that strings of ultradense matter thinner than atoms formed when the early universe went through a phase transition. Some of these strings could stretch across millions of light-years of intergalactic space.

There is not a shred of observational evidence that cosmic strings even exist. But if they do, they could interact with each other occasionally, causing them to pinch off into loops that should radiate powerful bursts of gravitational waves. LIGO and Virgo might be able to hear these signals, or other phenomena relating to strings. Any such discovery could revolutionize cosmology.

But of all the potential sources that astrophysicists can dream up, the most tantalizing possibility is a completely unexpected type of signal. Any reputable physicist will admit that it's impossible to imagine that humans, with our itty-bitty brains, have conceived of every possible source that could produce detectable gravitational waves.

Stuver sums up the greatest hope of all: "What I really want is to find a gravitational wave that we know is real but have no idea what made it. The process of discovering its source will be an amazing scientific journey that will revolutionize our understanding of the universe. After all, every time humans have looked at the universe in a new way, it has always revealed something unexpected and exciting!"

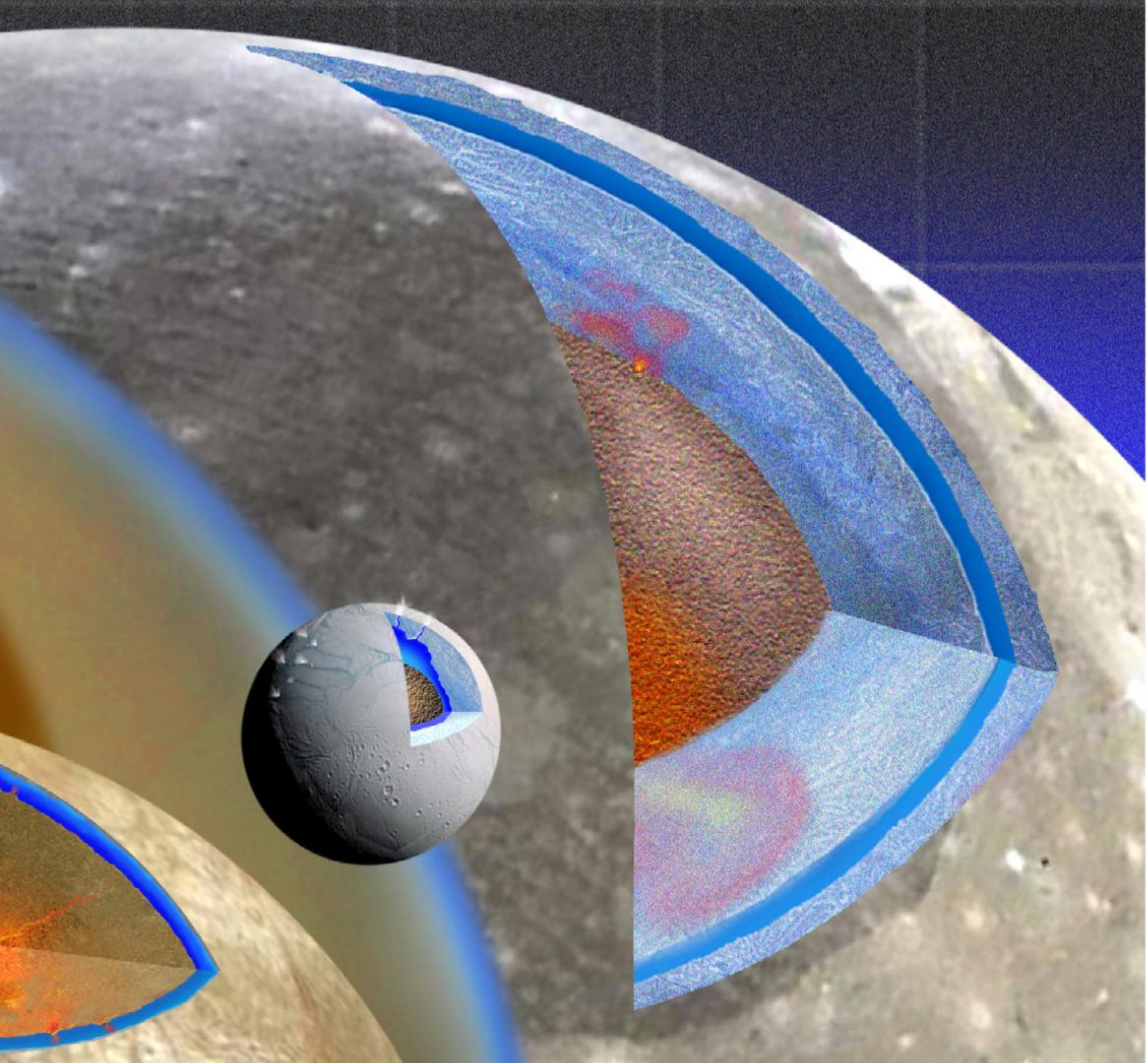
Robert Naeye *served on the editorial staff of* Astronomy *from 1995 to 2000. He was editor-in-chief of* Sky & Telescope *from 2008 to 2014.*



Weird, cold, hidden oceans dot the outer solar system — and could be sheltering alien life.

by Michael Carroll

Your guide to the oceans of our solar system



Astronomers have confirmed oceans beneath the icy crusts of four outer solar system moons. Cross sections of Titan, Ganymede, Enceladus, and Europa (clockwise from left, and shown approximately to scale) reveal the wide range of internal characteristics these worlds possess. MICHAEL CARROLL

The early days of our solar system were wet and wild. Amid a hail of asteroids and comets, the forming planets had plenty of water to go around. Today, Mars shows multiple signs of a vast ancient ocean that encircled its northern hemisphere. Chemical analyses hint at extensive seas on primordial Venus, our other next-door neighbor. But in addition to these past glories, there are still oceans beyond Earth, lurking within the outer solar system.

Genesis of a worldwide ocean

How did all that liquid get here in the first place? When it comes to water, our solar system is a tale of two cities. The planets formed within a disk-shaped cloud of dust and gas surrounding the nascent Sun. This planetary nursery contained water, minerals, dust, and metals, but it was drier close to the Sun and wetter out at a distance. The inner worlds lost their initial water, boiled away by our energetic young star. But infalling debris, mostly from asteroids, recharged the water inventories of the terrestrial planets. Tiny Mercury lost much of its brew, but Venus, Earth, and Mars all developed oceans to varying degrees. Only Earth's is still intact.

The outer solar system tells a different marine tale. All of those gas and ice giants cocooned themselves within their own disk-shaped clouds. As Jupiter, Saturn, Uranus, and Neptune chilled, they shrank, each leaving behind its own cooling cloud of gas, ice, and dust. Within these miniature accretion disks, moons coalesced. Jupiter's four major satellites,

The intricate pattern of fractures on Jupiter's moon Europa looks like the highway system of some advanced civilization. The icy crust's varied terrain results from its thick ice sheets shifting atop a vast ocean at least 60 miles (100km) deep. NASA/JPL-CALTECH/SETI INSTITUTE

the Galileans, provide the perfect example of the result. Close in to Jupiter, Io and Europa collapsed into spheres with dense, rocky cores and, in the case of Europa, a relatively thin water-ice crust. These are Jupiter's version of the terrestrial planets. In Jupiter's outer cloud, where more water was available, Ganymede and Callisto formed as larger, less-dense worlds with smaller rocky centers and deeper ice crusts. But how much of that water survives as hidden oceans?

As it turns out, quite a bit. Planetary scientist Alan Stern of the Southwest Research Institute (SwRI) in Boulder, Colorado, the principal investigator for NASA's New Horizons mission, which flew past Pluto in 2015, says, "One of the greatest paradigm shifts in planetary exploration has been that the solar system is teeming with oceans. Before the Space Age, no one predicted it."

Icy satellites expert William McKinnon adds, "Even though people suspected there might be oceans under Europa or even Enceladus, the data dragged us, kicking and screaming, to the conclusion that oceans are common in the icy moons."

Europa's frozen shell

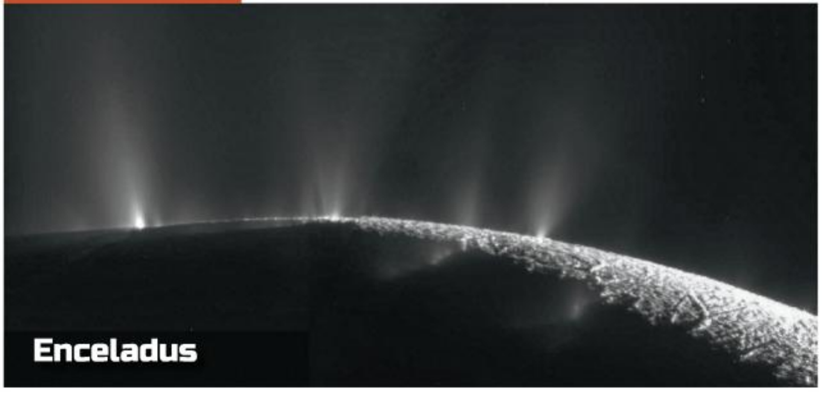
The poster child for extraterrestrial oceans, Jupiter's icy moon Europa, has become a favorite among astrobiologists in their search for life beyond Earth. Jupiter's fourth-largest moon sparkles with a glistening surface of water ice. An elegant calligraphy etches the surface in linear and curved stripes, telltale signs of powerful tectonic forces. Researchers offer several models to describe conditions beneath Europa's bizarre, grooved facade, ranging from soft ice over liquid water to an ocean about 60 miles (100 kilometers) deep. Whatever its true internal form, Europa is far more a "water world" than Earth ever was.

Clues to Europa's ocean come at the hands of ruler-straight lines streaking across the frozen landscape, bracketed by long ridges rising hundreds of feet into the black sky. Still other areas, called chaos regions, seem to have collapsed into a sea-like slurry, freezing into place after splintering into puzzle pieces that rotate and tip before freezing solid again.

Aside from these visual clues, Europa possesses a magnetic field consistent with one generated by an electrically conducting liquid, likely salt water, within Europa's upper ice region. Europa's field is *induced* — it is created in response to Jupiter's prodigious magnetic field. As Jupiter rotates, its mighty field swings around with it, constantly overtaking and sweeping across Europa. Under these conditions, any material that can conduct electricity will create its own magnetic field. The observed induced field leads researchers to conclude that the culprit is a near-surface conducting layer, such as an ocean with dissolved salts.

Europa travels halfway around Jupiter each time that Io completes an orbit, and twice for each of Ganymede's circuits. This resonance keeps the satellites' orbits slightly out of round and allows Jupiter's gravity to raise tides that warm the moons' interiors. Although the tidal heating on Europa is much less than on volcanically active Io, conventional volcanism may exist on Europa's seafloor, where the silicate mantle meets the ocean above. On Earth, such submarine volcanoes host rich biomes. Although submerged in eternal darkness, this Stygian environment has one advantage for any europan biology: It is sheltered from Jupiter's deadly rain of radiation by the moon's thick ice crust.

Europa's global ocean runs from pole to pole under the ice. Tracking surface features demonstrates that Europa's crust is "decoupled" from its



Plumes of water vapor and ice erupt from a huge geyser basin at the south pole of Saturn's moon Enceladus. Some of these geysers shoot as high as 300 miles (500km). The source of the material appears to be a global ocean beneath an icy crust that may be only a few miles thick in spots. NASA/JPL/SSI rocky heart, floating freely on a liquid layer. Data from the closest flybys of the Galileo spacecraft, which circled through the Jupiter system from 1995 through 2003, fit a model of a rocky interior capped by an outer layer of water some 60 to 125 miles (100 to 200 km) deep.

How thick is Europa's ice crust? One model posits a thin crust covering a 75-mile-deep (120km) ocean. In this model, plumes of heated water from seafloor volcanoes impinge on the surface ice, breaking through to create the domes, bands, and chaos regions. Another model suggests a thick ice crust. Masses of warm ice migrate up through the crust like the globules in a lava lamp, resulting in the surface features we see today. Rather than melting completely through the ice, the upwelling material would gradually deform the surface. Impurities in the ice would lower the melting point and might help the process. Small amounts of salt or sulfuric acid — both of which Galileo tentatively identified — could provide enough "antifreeze" to generate the domes and chaos, even through tens of miles of ice. In this scenario, chaos regions might also occur over subsurface lakes.

With all that action, does water ever escape as geysers? Evidence of possible eruptions includes halos of dark material surrounding possible vents, draping salts across the surface that follow fracture lines, and the necklaces of bright patches that align with nearby rifts. Conjectures about escaping water vapor came to the fore in late 2012, when a series of Hubble Space Telescope observations revealed the spectroscopic signature of water vapor above the moon's southern hemisphere. Scientists concluded that the water vapor likely was the fingerprint of geysers erupting at an estimated 1,500 mph (2,500 km/h) — three times the speed of a passenger airliner — and creating a giant plume that reached some 125 miles (200km) high.

But when researchers reviewed data from the Galileo encounters, they found no evidence of eruptions. And the Cassini spacecraft, which flew past Jupiter on December 30, 2000, on its way to Saturn, detected no plume activity. Even earlier Hubble observations in October 1999 and November 2012 did not detect any geysers on Europa. But in 2016, a Hubble observing campaign apparently detected Europa's plumes against Jupiter's disk. In fact, the space telescope spotted three events over the course of 15 months. If Hubble caught "cryovolcanoes" in action, it means that Europa could sport two kinds of volcanism: conventional silicate volcanoes belching lava at the seafloor, and cryovolcanoes spouting geysers of water "lava" through the ice crust above.

Energetic Enceladus

Saturn's small moon Enceladus is an extraordinary world. Its powdery ice surface is, in places, a tortured jumble of twisted ridges and cracked plains nearly devoid of craters. The entire moon is dusted with fresh icy material.

In 2005, the Cassini spacecraft discovered cryovolcanic activity on Enceladus. Most dramatically, this includes 101 active geysers that tower up to 300 miles (500km) above the south pole, likely driven by tidal forces similar to those that sculpt Europa and Io. The geysers erupt from fissures at the moon's south pole where temperatures can reach as high as –135° F (–93° C), some 195° F (108° C) higher than their surroundings.

In a series of encounters with the plumes, Cassini detected 90 percent water vapor with traces of carbon dioxide, methane, acetylene, propane, carbon monoxide, molecular nitrogen, and whiffs of quite intricate carbon-rich molecules. Something complicated is going on in the chemistry beneath Enceladus' ice. In addition to all that chemical excitement, the ice particles in the plumes contain

FOUR MORE POSSIBLE SEAS

Compelling evidence exists for oceans inside Europa, Ganymede, Enceladus, and Titan, and the odds favor an underground Pluto sea. A few other water worlds may lurk in the outer solar system. Here's a rogues' gallery of these potential oceans.

CERES: Scientists are convinced that this dwarf planet once had a large ocean — the question is whether a small residual of liquid water may still exist deep down. Observations showing water vapor above the world and bright salt deposits on its surface suggest that some water-based activity occurred fairly recently. **CALLISTO:** Jupiter's second-largest moon possesses a weak magnetic field. One possible reason is a 6-mile-deep (10km) ocean much farther down than the known oceans in Europa and Ganymede. Ammonia may help keep the ocean liquid — if there is an ocean. **MIMAS:** There's little doubt that Saturn's moons Enceladus and Titan have large internal oceans, but there appears to be some evidence for smaller oceans on other saturnian satellites. Dione, Mimas, and Rhea make the best cases. With Mimas, abnormalities in its orbit suggest that it either has a weirdly shaped core or an ocean. **TRITON:** Only Voyager 2 has visited Neptune's large moon, Triton. The probe revealed a world with active geysers near its south pole and other areas that lack impact craters. Both discoveries hint that Triton may still have an ocean of liquid water beneath its surface. CERES: NASA/JPL-CALTECH/UCLA/MPS/DLR/IDA; CALLISTO: NASA/JPL; MIMAS: NASA/JPL-CALTECH/SSI; TRITON: NASA/JPL/USGS

Clues to Europa's ocean come from the ruler-straight lines streaking across the frozen landscape.

Rugged coastlines resembling the fjords of Scandinavia scar the edges of Titan's seas.

sodium chloride and other salts. The plumes appear to be bringing up salty ice grains from the satellite's interior. The frozen spray could come from remnants of a long-dead ocean, but it is more likely that salt water exists not far below the surface right now, occasionally rocketing into the airless sky of the glittering white moon.

Cassini imaging team leader Carolyn Porco says she would choose Enceladus, with its benign radiation environment, over Europa for a crewed landing. "You don't have to bunker your spacecraft with 2 feet of lead to protect yourself. Just take a properly equipped spacecraft and test for organic molecules and for chirality. Chirality is a test for life." Most complex molecules are chiral, meaning they come in two forms that are mirror images of each other. All life on Earth uses "left-handed" amino acids; scientists assume life elsewhere would likewise show a strong preference for one variety.

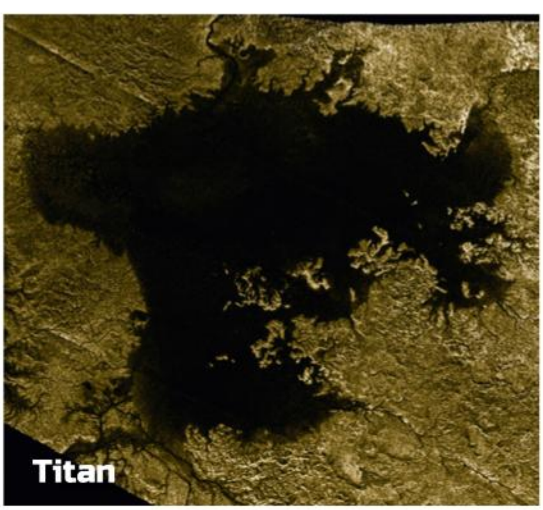
Porco also submits that the drilling required on Europa is not an issue on Enceladus. "Whatever it has in its subsurface ocean is there for the asking. It's accessible. All you really have to do is land on the surface, look up, and stick your tongue out."

SwRI researcher John Spencer says that discoveries at Enceladus were a game-changer. "The idea that the moons of the outer planets were active in recent geologic time was a huge revelation," he says. "With Cassini discovering the activity on Enceladus, it really changed so much of what we knew there, but we were already open to that possibility because of what Voyager had shown us of the activity on Io … it was amazing and fabulous and made sense of so many things that were quite puzzling up to that point, but it wasn't completely out of left field. We knew that such things were possible."

Spacecraft have revealed a pattern to the variety of small icy worlds, Spencer adds. "Here you have a world that combined these very old regions where not a lot had happened for a billion years with these very new regions where things were happening last week."

Jupiter's satellite Ganymede is the largest in the solar system, and even bigger than Mercury. Scientists think a global ocean that holds more water than all of Earth's seas combined lurks beneath its tortured surface. NASA/JPL

Saturn's largest moon, Titan, is the only known satellite with a thick atmosphere. This blanket of air allows lakes and seas of liquid hydrocarbons to remain stable on the surface. (This radar image shows the second-largest sea, Ligeia Mare.) Titan also may possess a global water ocean under a bedrock of solid water ice, giving Titan two wildly different liquid environments. NASA/JPL-CALTECH/ASI/CORNELL



Ganymede and Titan: Buried seas?

The big kahuna of the Galilean moons is Ganymede. Measuring 3,270 miles (5,262km) across, its diameter bests that of the planet Mercury by 238 miles (383km). The Galileo probe discovered that Ganymede has an intrinsic magnetic field, the only moon known to generate its own field, hinting at a core of molten iron. Galileo also found evidence of an induced magnetic field like Europa's, suggesting a deep internal ocean of briny water. In Europa's case, the ocean rests upon a floor of rock, where minerals and perhaps volcanoes add life-supporting materials to the mix. Not so at Ganymede. The moon's induced magnetic field suggests that an interior ocean some 10 times deeper than Earth's seas lies beneath the frozen crust, but it is probably sandwiched between ice layers above and below.

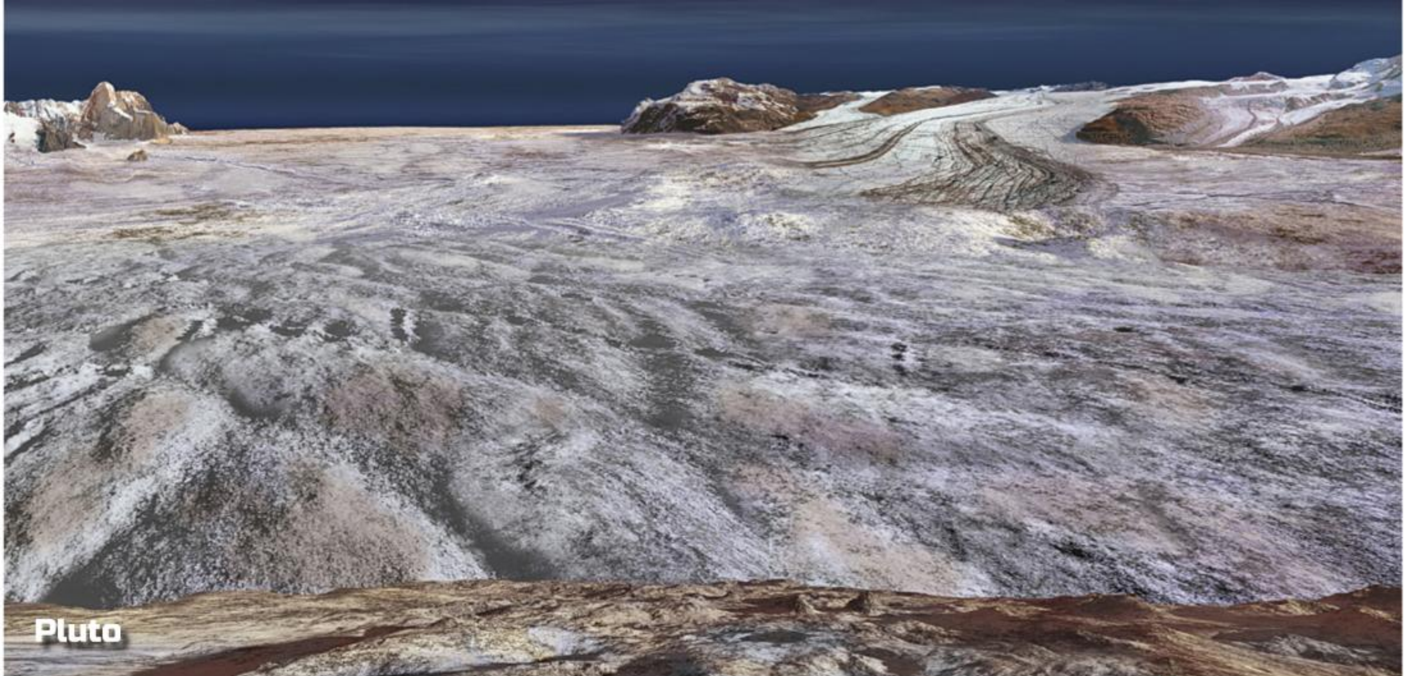
Cut off from the mineral-rich rocky core, what chance does this ocean have of sustaining life? Models indicate that salty water at the ice-rock interface may percolate upward, migrating toward the ice-locked ocean above. The water may congregate in internal "ponds" along the way. The pressures and temperatures found in Ganymede's ice are difficult to simulate in the lab, but it may be that the ice barrier between ocean and rock is not such a barrier after all. So while they have found no shopping malls, astrobiologists are beginning to reconsider Ganymede as a possible site for life.

A similar trapped ocean may slosh beneath the eerie landscape of Saturn's largest moon, Titan. If Titan's crust were solid ice, the planet's gravity should raise tides of about 3 feet (1 meter) each Titan day. But the crust actually bends upward by about 10 times that amount, showing a flexibility that can be explained by a hidden ocean. Titan's density indicates the moon is composed of equal amounts of water and rock. Water ice makes up the surface crust, but an ocean up to 185 miles (300km) deep could persist below. Its dark waters may be seeded with ammonia and complex organics.

Ganymede and Titan may not be alone in the buried-seas department. A new study from astronomers at the Royal Observatory of Belgium asserts that Saturn's moon Dione harbors an ocean dozens of miles deep starting about 60 miles (100km) beneath the surface.

Titan: The strangest seas of all

In addition to a possible buried ocean, Titan holds another kind of sea on its surface, and this may be the oddest of all. Beneath its opaque sheath of nitrogen-methane smog, Titan hosts an active cycle of rainfall fed by evaporation from surface lakes and rivers — the only known world besides our own with such a cycle. Titan's river valleys drain into liquid-filled basins that range from lakes at the limit of the Cassini spacecraft's resolution up to vast seas. The



Pluto's Sputnik Planitia appears to be the scar left behind by a Kuiper Belt object's impact. This vast frozen plain has more mass than its surroundings, which many planetary scientists interpret as a sign that a global ocean of liquid water welled up beneath the impact site. MICHAEL CARROLL

largest of these, Kraken Mare, has a surface area of roughly 155,000 square miles (400,000 square km). For comparison, Lake Superior is 31,700 square miles (82,100 square km) in extent, and the Black Sea is 168,500 square miles (436,400 square km).

But the seas aren't made of liquid water. Instead, they're ethane, methane, and possibly other hydrocarbons in an unknown mixture. Although scientists think methane rainfall is about 100 times greater than that of ethane, it is far more volatile and would evaporate from the surface more quickly. Over time, a standing body of liquid would become enriched with the more stable ethane, so ethane probably dominates the larger seas.

Rugged coastlines resembling the fjords of Scandinavia scar the edges of Titan's seas. But some smaller lakes show a different character. They seem to have circular, oblong, or curving shorelines, often with steep margins. Many are similar to the rounded lakes on Earth caused by melting ice blocks left behind by retreating glaciers. On our planet, such regions are often fractured and porous, with groundwater flowing beneath their surfaces. On Titan, these lake regions may drain into a web of underground methane aquifers that make their way to the coasts, eventually feeding the seas. If so, this underground river network may contribute significantly to Titan's atmospheric methane.

Scientists have proposed a number of future missions to explore the seas of this exotic moon. One such mission, called the Titan Mare Explorer, would float for weeks or months on the surface of Ligeia Mare, Titan's second-largest hydrocarbon sea. Studies show that natural lake currents would carry the probe completely around the sea to sample the environment at many sites.

Another proposal envisions a Titan submarine. The vehicle would deploy from a version of the U.S. Air Force's already-operational X-37B, an unmanned mini-space shuttle. After splashdown, the autonomous craft would investigate both on the surface and underneath this alien sea.

Pluto's farther sea

Another hidden ocean may lurk beneath the surface of our favorite dwarf planet, Pluto. Pluto's trademark "heart," Sputnik Planitia, provides researchers with clues to a watery underworld. The planet and its large moon, Charon, face each other in a tidally locked cotillion. Sputnik Planitia lies smack in the center of Pluto's anti-Charon-facing hemisphere. Its location tells planetary modelers that the vast plain is a positive mass anomaly, a region heavier than its surroundings. This is baffling because the feature likely formed when a massive Kuiper Belt object crashed into the surface. If Pluto has a concealed ocean, however, the Sputnik Planitia impact would have thinned the icy crust, and the sea would have welled up beneath. And, because water is denser than ice, this region would become more massive.

Some models suggest that this ocean may be global, up to 60 miles (100km) deep, and saltier than the Dead Sea. Other models propose that Pluto's underworld is a sea of icy slush. "It's not yet constrained," says Stern. "There's good evidence for a mass concentration below Sputnik Planitia, and the best explanation is liquid water."

He adds, "What's been crazy is the propensity for all these ocean worlds. They've got so many astrobiological applications." The buried oceans of Europa, Enceladus, Ganymede, Titan, and Pluto compel us to dig deeper in our search for life beyond our own world. These hidden oceans, along with the strange surface seas on Saturn's behemoth moon, hold the promise of exotic chemistries and new biomes in which extraterrestrial life may thrive.

Frequent contributor **Michael Carroll** *is a science writer and astronomical artist. His latest book is* Earths of Distant Suns *(Springer, 2017).*

Hubble Space Telescope imaging of "El Gordo," the most massive galaxy cluster known when the universe was half its present age, shows a vast splay of gas emitting X-rays (in pink) and a massive halo of dark matter (in blue). The dark matter is inferred by its warping of the light from beyond, like the distortion of a fun house mirror. NASA, ESA, J. JEE, J. HUGHES, F. MENANTEAU, C. SIFON, R. MANDELBAUM, L. BARRIENTOS, AND K. NG.

Why we need dark matter

Dark matter remains both a necessary part of the universe and a puzzling, unseen component.

by Francis Reddy

All of the matter we see around us — in our own bodies, in everyday objects, in planets, stars, nebulae, and galaxies — amounts to just 4.9 percent of the mass-energy content of the universe. Astronomers know this from recent studies of the cosmic microwave background, a remnant of the very first light in the cosmos, from the European Space Agency's Planck spacecraft.

By contrast, a substance of unknown nature — dark matter — makes up 26.8 percent of today's universe, outnumbering normal matter by better than 5 to 1. The remainder of the universe's mass-energy comes in the form of dark energy, a negative pressure that has been accelerating the expansion of space over the past 5 billion years and will determine the ultimate fate of the cosmos (see "How the universe will end," September 2014). Our story here will focus only on material matters.

Don't look — it would, after all, be pointless — but there's dark matter near you right now. It accounts for more than 80 percent of the matter in the universe, but it neither emits nor absorbs light and primarily interacts with the rest of the universe through gravity, the weakest force in nature. Astronomers see its effects throughout the cosmos — in the rotation of galaxies, in the distortion of light passing through galaxy clusters, in the weblike structure of the large-scale universe, and in the cosmic microwave background. They even see it in the abundances of light elements, like hydrogen and helium, produced during the first minutes of the expanding universe. None of these observations add up without some type of matter we can't currently detect that was also moving comparatively slowly — that is, it's cold — when structures began to form in the early universe.

This series of six frames shows a simulation of the substructure changing over time in a Milky Way-sized dark matter halo.

In 2015, astronomers discovered a large, dim, nearly featureless galaxy named Dragonfly 44 in the Coma Cluster of galaxies, about 330 million light-years away. Dragonfly 44 is one of a growing number of large, low-surface-brightness, featureless objects called ultra-diffuse galaxies now being discovered by the robotic Dragonfly Telephoto Array, a project led by Pieter van Dokkum at Yale University and Roberto Abraham at the University of Toronto.

What is unusual about this galaxy is that it contains so few stars that it should simply shear apart in the hurly-burly environment of a galaxy cluster. Using the Keck II and Gemini North telescopes on Mauna Kea, Hawaii, Dokkum and his colleagues studied the galaxy's stellar motions to determine its mass (see "Dark ages of dark matter," p. 35). The galaxy has a mass comparable to the Milky Way's, but 99.99 percent of it is in the form of dark matter. The team suggests Dragonfly 44 may be a failed version of the Milky Way, perhaps one stripped of the gas needed to build stars in its youth through processes we don't yet understand.

The most detailed computer simulations of the evolution of cosmic structure require dark matter in order to form galaxies at all. Small dark matter halos condense first, and their gravitational pull draws in normal matter, creating small galaxies that collide and merge to form larger ones. This "bottom up" assembly process implies astronomers should be seeing far more leftover debris — such as dwarf galaxies and streams of stars stripped from them — than we see around large galaxies like the Milky Way today. Ultra-diffuse galaxies like Dragonfly 44 offer a new possibility for reconciling theory and observation.

Crashing clusters

Galaxies can congregate into groups as small as a few dozen members up to rich objects like the Coma Cluster, containing some 10,000 galaxies. With typical sizes spanning tens of millions of light-years and masses reaching 100 trillion Suns or more, galaxy clusters are the largest objects held together by gravity in the universe. Gas with temperatures exceeding 20 million degrees Fahrenheit — hot enough to glow in X-rays — fills these objects and typically accounts for more than twice the mass of the galaxies. Even with this, these cosmic behemoths couldn't stay together without a heaping helping of dark matter, typically about 85 percent of the cluster's mass. Indeed, galaxy motions in the Coma and Virgo clusters provided the first hints that dark matter must be present within them.

Colliding clusters offer an opportunity for astronomers to explore how these various components interact. The Bullet Cluster, about 3.8 billion light-years away toward the constellation Carina, is a small cluster that has passed through a larger cluster in the past 200 million years, moving at about 10 million mph. In 2000, X-ray observations by NASA's Chandra X-ray Observatory revealed a conical cloud of X-ray gas — a bow shock — lagging behind the interloper. While the galaxies of both clusters simply passed by each other without interacting, their vast inventory of hot gas experienced a drag force akin to air resistance (called ram-pressure stripping) and was wrenched away from the galaxies and, presumably, their dark matter halos.

The dark matter in clusters is so massive that it distorts space-time in a noticeable way, warping the light from more distant objects. Using a technique called weak lensing, astronomers measured the distorted shapes of background galaxies to map out the distribution of dark matter in both clusters. Another technique, called strong lensing, looks for repeated warped images of background galaxies to accomplish the same goal. Astronomers have employed both methods on the Bullet Cluster with the same results: The dark matter halos line up with the galaxies of each cluster and show no indication of interaction. Similar studies of other interacting clusters demonstrate the presence and dominance of dark matter in these objects.

The standard model can't explain why matter is so much more common than antimatter.

Beyond the standard model

Particle physicists had their own reasons for positing the existence of new particles, many of which seem ready-made to play the role of dark matter. The so-called standard model of particle physics, developed in the early 1970s, describes a wide range of phenomena by the interactions of fundamental particles (for example,

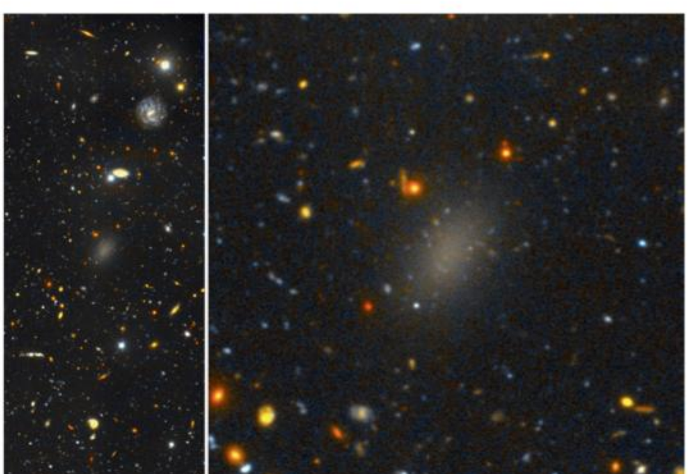
VOLKER SPRINGEL AND THE MAX PLANCK INSTITUTE FOR ASTROPHYSICS

electrons and quarks) through three of the four known fundamental forces (electromagnetism, and the strong and weak forces operating in atomic nuclei). The standard model's most recent success is the 2012 discovery of the Higgs particle in proton-smashing runs at the Large Hadron Collider (LHC) in Europe, the most powerful particle accelerator on the planet.

But the standard model doesn't include gravity, the weakest force, and there remain other aspects of the universe it cannot explain, such as why matter is so much more common than antimatter. So physicists have devised a number of extensions to try to address these issues. The most popular solution, called supersymmetry, predicts a massive partner for each particle in the standard model. The lightest supersymmetric particle predicted is the neutralino, which appealed to astronomers because its properties matched their favorite dark matter model, the weakly interacting massive particle (WIMP). WIMPs interact with normal matter rarely and only through the weak nuclear force. In some versions, WIMPs serve as their own antiparticle, annihilating when they collide and giving off gamma rays that can be detected by space-based observatories, such as NASA's Fermi Gamma-ray Space Telescope.

Physicists expected supersymmetric particles to start appearing in high-energy collisions at the LHC, but to the frustration of many, nothing new has turned up. "From the point-of-view of supersymmetric dark matter, I think the situation is becoming increasingly tight," says Troy Porter, an astrophysicist at Stanford University. "There is no evidence from the LHC and, so far, no detection of gamma-ray emission from places where there could be a chance for a relatively 'clean' astrophysical signal," such as dwarf galaxies orbiting the Milky Way, which have been monitored by Fermi. Detectors like the Large Underground Xenon experiment, located nearly a mile below Lead, South Dakota, similarly have nothing to show.

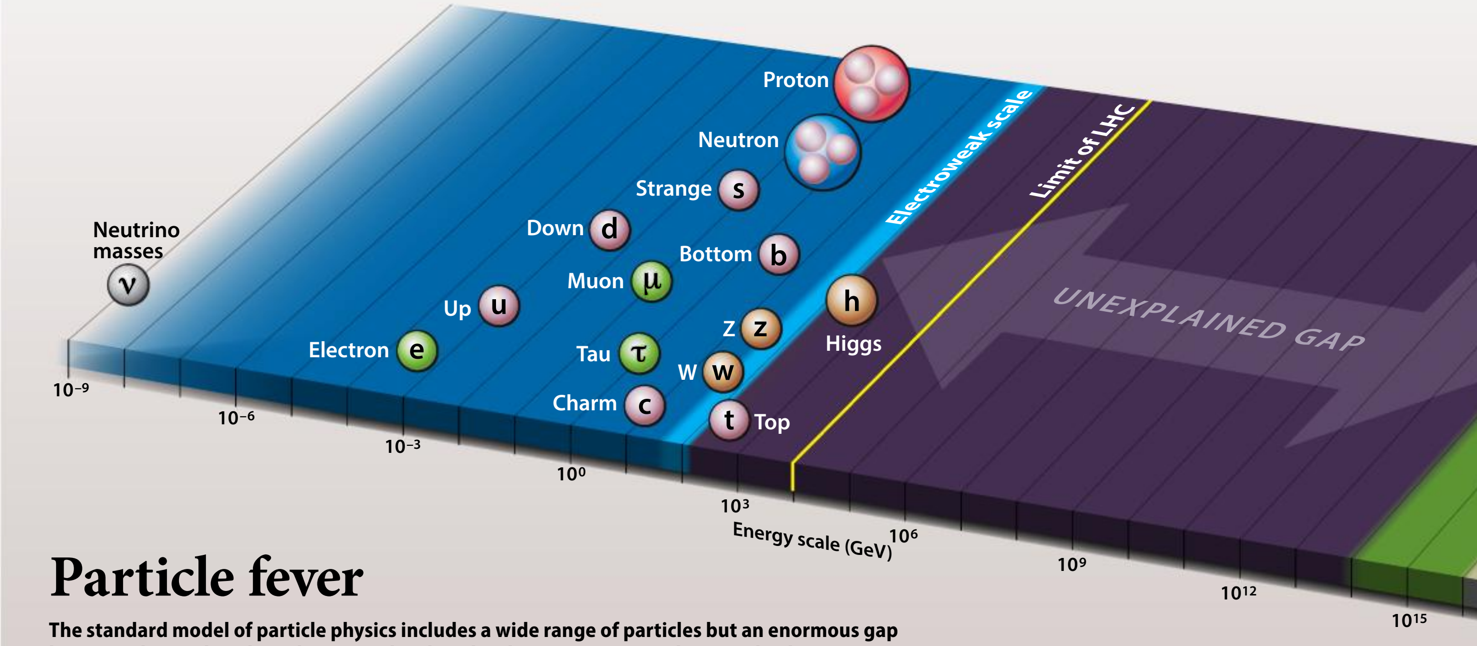
"There are two very different ways to read the current situation," says Dan Hooper, an astrophysicist at Fermilab in Batavia, Illinois. "On the one hand, no underground detectors or the LHC have seen anything that looks like a WIMP, constraining the range of models that are consistent with the data." This has had the effect of moving the dark matter



The ultra-diffuse galaxy Dragonfly 44 consists almost entirely of dark matter. A wide view of the galaxy (left) was taken with the Gemini North Telescope using the Gemini Multi-Object Spectrograph. A close-up from the same image (right) reveals the faint, elongated galaxy and its retinue of globular clusters. PIETER VAN DOKKUM, ROBERTO ABRAHAM, GEMINI, AND SLOAN DIGITAL SKY SURVEY

Extraordinary evidence for dark matter exists in the so-called Bullet Cluster, which formed after the collision of two giant clusters of galaxies. The bullet-shaped pinkish clump on the right is hot gas from one cluster that passed through the other cluster in the collision. The blue areas show most of the cluster's mass, which exists as dark matter and is separate from the normal matter.

X-RAY: NASA/CXC/CfA/M. MARKEVITCH ET AL.; OPTICAL: NASA/STScI; MAGELLAN/U. ARIZONA/D. CLOWE ET AL.; LENSING MAP: NASA/STScI; ESO WFI; MAGELLAN/U. ARIZONA/D. CLOWE ET AL.



Particle fever

The standard model of particle physics includes a wide range of particles but an enormous gap between the weak scale and gravity/Planck scale. This is one reason why particle physicists are attempting to look beyond the standard model for candidates to explain dark matter. *ASTRONOMY*: ROEN KELLY

community toward "hidden sector" models, where dark matter particles interact differently from normal matter with standard model forces, and other scenarios that are more difficult to detect. "If these experiments continue to come up empty-handed, the move away from conventional WIMPs will become only more and more evident," he says.

On the other hand, Fermi sees residual gamma-ray emission at energies greater than 2 billion electron volts (GeV) from the center of our galaxy, which is both a nearby source and expected to hold a large store of dark matter. "This represents the most promising possible signal of dark matter particles that we have had to date," says Hooper. "If future observations strengthen the case for this interpretation, then the community will refocus back to WIMPs, and in particular toward those WIMP models that can generate a signal like that seen from the galactic center."

Gamma-ray eyes

While the great amount of dark matter expected at the galactic center should produce a strong signal, it has to compete with many other gamma-ray sources, such as pulsars and cosmic ray interactions with interstellar gas. That's why the gamma-ray "excess" Fermi sees at the galactic center remains far from a slam dunk.

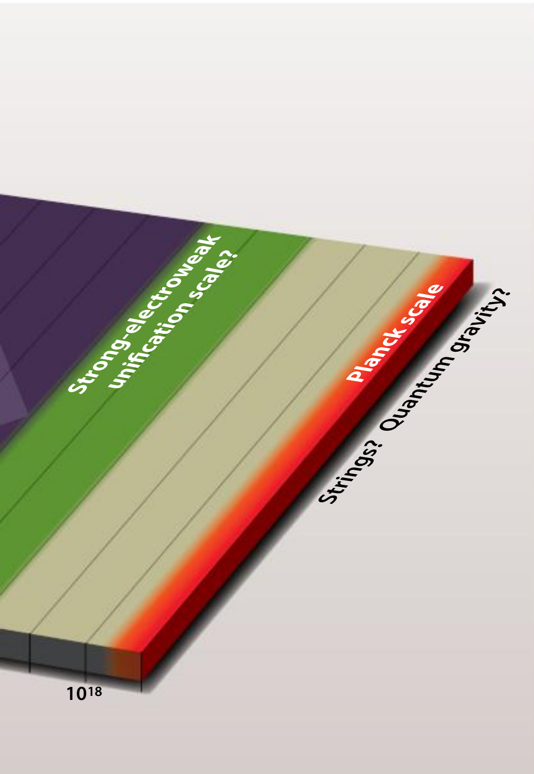
Astronomers recently used Fermi data to investigate the possibility that dark matter might consist of hypothetical particles called axions or other particles with similar properties. These particles don't require supersymmetry and rank highly among dark matter candidates. An intriguing aspect of axion-like particles is their ability to convert into gamma rays and back again when they interact with strong magnetic fields. These conversions would leave behind characteristic traces, like gaps or steps, in the spectrum of a bright gamma-ray source.

In the next few years, WIMPs could be more or less ruled out as a source of dark matter.

In 2015, Manuel Meyer at Stockholm University led a search for these effects in gamma rays from NGC 1275 (Perseus A), the central galaxy of the Perseus galaxy cluster, located about 240 million light-years away. Magnetic fields threading the cluster could enable gamma rays emitted by the galaxy to switch into axion-like particles as they make their way to us. Meyer's team searched for predicted distortions in the Fermi data and was ultimately able to exclude a small range of axion-like particles that could have made up about 4 percent of dark matter.

Regina Caputo at the University of California, Santa Cruz, sought these signals from the Small Magellanic Cloud (SMC), which is about 200,000 light-years away and is the second largest of the small satellite galaxies near the Milky Way. Part of the SMC's appeal for a dark matter search is that it lies comparatively close to us, and its gamma-ray emission from conventional sources, like star formation and pulsars, is well understood. Most importantly, astronomers have high-precision measurements of the SMC's rotation curve, which shows how its rotational speed changes with distance from its center and indicates how much dark matter is present. Caputo and her colleagues showed that the SMC possessed enough dark matter to produce detectable signals for two WIMP types. While Fermi definitely sees gamma rays from the galaxy, Caputo's team can explain them all by conventional sources.

In another study, researchers led by Marco Ajello at Clemson University in South Carolina and Mattia Di Mauro at SLAC National Accelerator Laboratory in California took the search in a different direction. Instead of looking at specific



DARK AGES OF DARK MATTER

In 1932, Dutch astronomer Jan Oort analyzed the vertical motions of stars near the plane of our galaxy and concluded the density of known stars was too low, suggesting unseen matter near the galactic plane was needed to explain them.

The following year, Swiss astronomer Fritz Zwicky showed that the motions of galaxies in the Coma Cluster implied the presence of much more mass than could be accounted for by its glowing galaxies alone. Zwicky suggested this extra mass was in the form of *"dunkle (kalte) materie"* — dark cold matter. In 1936, American astronomer Sinclair Smith found a similar discrepancy in the Virgo Cluster.

Just a few years later came the first evidence of a "missing mass" problem in individual galaxies. Measurements published by the American astronomer Horace Babcock in 1939 showed that the outer parts of the Andromeda Galaxy (M31) were rotating at a constant angular velocity. Astronomers assumed most of the mass of a spiral galaxy was concentrated at its center, which contained the highest concentration of stars.

In such a case, the rotational motion of stars in the galaxy's outer reaches should decrease steadily when measured at greater distances from the center. Instead they were constant, which implied the mass enclosed at those distances was still increasing. Although Babcock did not attribute the issue to missing mass, his study stands as one of the earliest indications of dark matter and foreshadows later work.

In 1970, Vera Rubin and Kent Ford Jr. at the Carnegie Institution of Washington tracked M31's rotation out to 78,000 light-years from its center using optical and radio data, revealing near-constant rotation in the outer regions, a finding confirmed in 1978. Over the next decade, Rubin, Ford, and other astronomers studied the rotation of hundreds of galaxies. Nearly all show similar flat rotational structure requiring that they reside within massive halos of dark matter. — *F. R.*

astronomical targets, the team used more than 6.5 years of data to analyze the background glow of gamma rays seen all over the sky.

The nature of this light, called the extragalactic gamma-ray background (EGB), has been debated since NASA's Small Astronomy Satellite 2 first measured it in the early 1970s. Fermi has shown that much of this light arises from unresolved gamma-ray sources, particularly galaxies called blazars, which are powered by material falling toward gigantic black holes in their centers. Blazars constitute more than half of the total gamma-ray sources seen by Fermi. EGB gamma rays could arise from distant interactions of dark matter particles, such as the annihilation or decay of WIMPs, but Ajello and his colleagues found that blazars and other discrete sources can account for nearly all of the emission.

"Fermi has done great in cutting into the parameter space" — that is, shrinking the theoretical box — "of dark matter models," Ajello says. That's because its Large Area Telescope surveys the whole sky every three hours, deepening its exposure with every orbit. WIMPs can produce gamma rays through a variety of mechanisms, such as converting into pairs of quarks, gluons, muons, and other particles, which then decay to emit gamma rays and stable particles. This provides scientists with many avenues to explore in the hunt for dark matter using Fermi. "Direct detections and collider searches test different aspects of dark matter and are complementary to indirect searches like Fermi's," he says. "These three approaches probe different regions of dark matter spaces, cutting even more into realistic models."

Dark matter candidates may fall out of fashion, but everything we know about the universe seems to require the substance itself.

"I'd say that in the next few years WIMPs could be more or less ruled out, but it's quite plausible that dark matter is made up of whole families of particles," says Caputo. "Think how diverse the standard model is — and it's only 5 percent of the matter budget of the universe."

R. CAPUTO ET AL., AND AXEL MELLINGER, CENTRAL MICHIGAN UNIVERSITY

The Small Magellanic Cloud is an irregular satellite galaxy of the Milky Way, lying some 200,000 light-years away. The left half of the galaxy is shown in its natural state; the right half shows the extent of its dark matter halo. Some 95 percent of the dark matter lies within the circle. The Fermi space telescope has not found gamma-ray emission from this galaxy's dark matter.

Francis Reddy *is the senior science writer for the Astrophysics Science Division at NASA's Goddard Space Flight Center in Greenbelt, Maryland.*

MARTIN RATCLIFFE and **ALISTER LING** describe the solar system's changing landscape as it appears in Earth's sky.

Visible to the naked eye
Visible with binoculars
Visible with a telescope

November 2017: Venus meets Jupiter

On December 1, 2008, a crescent Moon stood to the left of Jupiter while brilliant Venus hung below the other two. The three solar system objects meet again in the predawn sky November 16. ALAN DYER

The focus of backyard skygazers this month shifts from the evening to the morning sky. The predawn scene features a spectacular conjunction between Venus and Jupiter, the night sky's two brightest points of light. And though Mars pales in comparison, the Red Planet climbs higher before dawn as it embarks on its best show in more than a decade.

The evening sky boasts appearances from the other four planets. Mercury and Saturn shine brightly in the southwestern sky after sunset, while Uranus and Neptune reach their peak altitudes before midnight. All four make tempting targets through binoculars and telescopes.

Let's begin our night sky tour in the southwest during evening twilight. **Mercury** comes into view starting in mid-November for observers at mid-northern latitudes. On the 15th, it stands 5° above the horizon a half-hour after sunset. At magnitude –0.3, the planet is bright enough to pierce the twilight glow. If you can't spot it right away, binoculars gather enough extra light to show it easily.

The view of Mercury improves a bit during the next 10 days. The innermost planet reaches greatest elongation November 23, when it lies 22° east of the Sun and appears 7° high 30 minutes after sundown. Mercury also shines 0.1 magnitude brighter than it did on the 15th. Although the inner world fades to magnitude –0.2 by the end of the month, it manages to maintain its altitude.

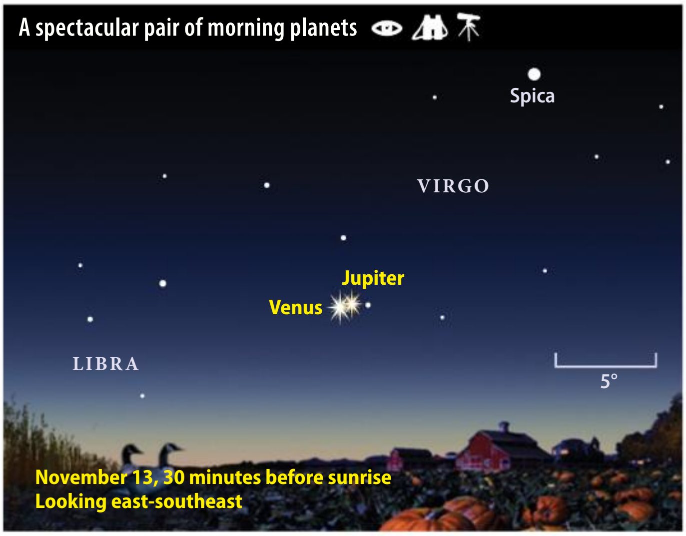
If you target Mercury through a telescope, you'll see its appearance change rapidly during November's second half. On the 15th, the rocky world's disk measures 5.7" across and is 80 percent lit. But the inner planet races around the Sun faster than any other, and this motion brings it closer to Earth in the following weeks. By the 30th, Mercury spans 7.6" and the Sun illuminates 44 percent of its Earth-facing hemisphere.

A scan for Mercury through binoculars in November's final days also will reveal the fainter glow of **Saturn**. This is the tail end of the ringed planet's evening appearance, however, and it will be far easier to spot early in the month. On the 1st, Saturn hangs 15° above the southwestern horizon an hour after sunset, and it is still 10° high at twilight's close.

Shining at magnitude 0.5, the planet appears four times brighter than any of the background stars in its home constellation, Ophiuchus. With binoculars under a haze-free sky, you also should be able to see the faint glows of the Lagoon (M8) and Trifid (M20) nebulae some 6° (a binocular field) east of Saturn. Although the planet's eastward motion during November carries it closer to these deep-sky objects, their decreasing altitude makes them harder to see. Saturn crosses into Sagittarius on the 19th.

Of course, the best way to enjoy the ringed planet is through a telescope. The finest views come early in the month when it lies highest. On the 1st, Saturn's disk appears 15" across while the rings span 35" and tilt 27° to our line of sight.

You'll also want to catch the waxing crescent Moon when it climbs past Mercury and Saturn. It might be hard



Don't miss the stunning conjunction between Venus and Jupiter as twilight paints the November 13 predawn sky. ALL ILLUSTRATIONS: *ASTRONOMY*: ROEN KELLY

RISING**MOON**

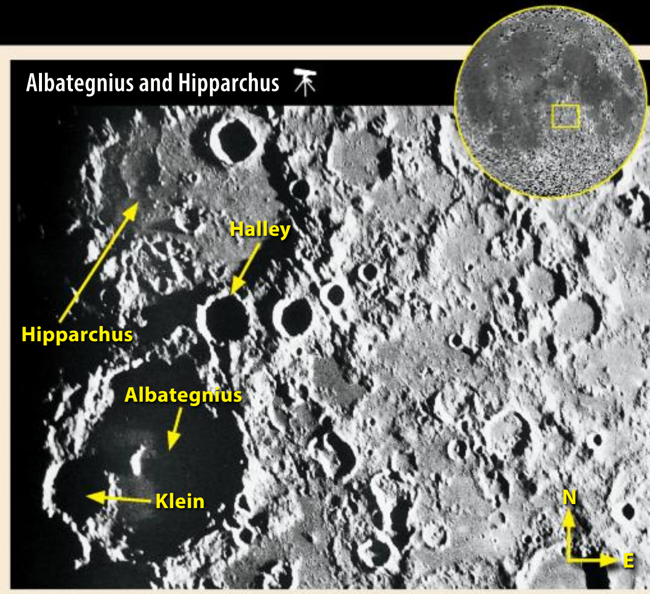
Compare old and ancient craters

The main reason lunar observers keep coming back for more is that the Moon's appearance constantly changes. The play of sunlight and shadow near the terminator — the dividing line between day and night on the lunar surface — transforms our perspective from day to day and often from hour to hour. A prominent crater boasting fantastic shadows one evening can nearly disappear the next under a higher Sun angle.

Two large impact craters stand out along the terminator on the waxing crescent Moon the evening of November 25. The southern and more rugged of the two is Albategnius, named after the ninth-century Arabian astronomer and prince al-Battani. A smaller impactor created the earring-like crater Klein on its western rim. The long shadows cast by Albategnius' tall rim and central peak retreat fast enough that you can notice a change in as little as 30 minutes. Also note the fairly smooth lava plain on the crater's floor.

The highly battered rim of Hipparchus lies just to the north, a mute testament to its greater age. Even the lava-flooded floor is clearly older, boasting many more features than its neighbor. Hipparchus nearly disappears a couple of nights later because its lower and rounder slopes don't cast shadows under the higher Sun angle.

Scientists named this crater for Hipparchus, a Greek astronomer whose second-century B.C. star catalog marked a significant milestone in science history. It enabled British scientist Edmond Halley to demonstrate, more than 1,800 years later, that stars move relative to one another. And just as Halley built upon Hipparchus' work, the lunar crater Halley stands on the broad shoulders of his predecessor's crater.



A pair of battered craters calls attention to the waxing crescent Moon the evening of November 25. *CONSOLIDATED LUNAR ATLAS*/UA/LPL; INSET: NASA/GSFC/ASU

to glimpse the one-day-old Moon on November 19, when it lies 8° to Mercury's right. You'll have an easier time the following evening, when a significantly fatter crescent stands 3° to Saturn's upper right and 8° above Mercury. The planets themselves have a close conjunction the evening of the 27th, when Mercury passes 3° due south of Saturn.

While Mercury and Saturn appear low and bright on November evenings, Uranus and Neptune are high and dim. **Neptune** climbs highest in the south around 7 P.M. local time at midmonth, when it stands nearly halfway to the zenith. The ice giant world glows at magnitude 7.9 and shows up nicely through binoculars against the backdrop of Aquarius the Water-bearer.

Neptune's westward trek relative to the stars comes to a halt November 22, but its motion is slow and it appears

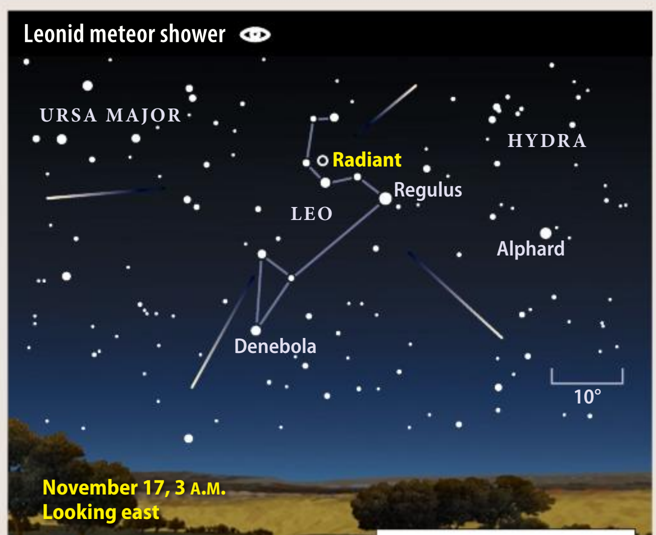
— Continued on page 42

METEORWATCH

On the prowl for the Lion's meteors

New Moon arrives November 18, just one day after the peak of the annual Leonid meteor shower. With no Moon to interfere, observers under dark skies can expect to see up to 10 meteors per hour. The "shooting stars" appear to radiate from a point in the Sickle asterism of the constellation Leo the Lion. This region rises in late evening and climbs high in the southeast before dawn. Prime viewing occurs between 3 A.M. local time and the start of twilight some two hours later.

The meteors blaze into Earth's atmosphere at a sizzling 44 miles per second, the fastest of any shower meteors. The high speeds mean they produce a greater percentage of fireballs than most showers.



The Moon doesn't interfere with the peak of this year's shower, leaving ideal conditions for viewing this shower's bright meteors.

Leonid meteors

Active dates: Nov. 6–30
Peak: November 17
Moon at peak: New Moon
Maximum rate at peak: 10 meteors/hour

OBSERVING HIGHLIGHT Magnitude –3.9 Venus passes just 0.3° north of magnitude –1.7 Jupiter on the morning of November 13.

STAR DOME

How to use this map: This map portrays the sky as seen near 35° north latitude. Located inside the border are the cardinal directions and their intermediate points. To find stars, hold the map overhead and orient it so one of the labels matches the direction you're facing. The stars above the map's horizon now match what's in the sky.

The all-sky map shows how the sky looks at:

10 P.M. November 1
8 P.M. November 15
7 P.M. November 30

Planets are shown at midmonth

STAR MAGNITUDES

- Sirius
- 0.0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0

STAR COLORS

A star's color depends on its surface temperature.

- The hottest stars shine blue
- Slightly cooler stars appear white
- Intermediate stars (like the Sun) glow yellow
- Lower-temperature stars appear orange
- The coolest stars glow red
- Fainter stars can't excite our eyes' color receptors, so they appear white unless you use optical aid to gather more light

MAP SYMBOLS

- Open cluster
- Globular cluster
- Diffuse nebula
- Planetary nebula
- Galaxy

NOVEMBER 2017

Note: Moon phases in the calendar vary in size due to the distance from Earth and are shown at 0h Universal Time.

SUN.	MON.	TUES.	WED.	THURS.	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		

ILLUSTRATIONS BY *ASTRONOMY*: ROEN KELLY

Calendar of events

1 Venus passes 4° north of Spica, 11 A.M. EDT

2 The Moon passes 4° south of Uranus, 9 P.M. EDT

3 Asteroid Nysa is at opposition, 2 A.M. EDT

4 Full Moon occurs at 1:23 A.M. EDT

5 The Moon is at perigee (224,587 miles from Earth), 7:10 P.M. EST

The Moon passes 0.8° north of Aldebaran, 10 P.M. EST

10 Last Quarter Moon occurs at 3:36 P.M. EST

11 The Moon passes 0.4° north of Regulus, noon EST

12 Mercury passes 2° north of Antares, 10 A.M. EST

13 Venus passes 0.3° north of Jupiter, 1 A.M. EST

14 The Moon passes 3° north of Mars, 8 P.M. EST

16 The Moon passes 0.4° south of asteroid Vesta, 4 A.M. EST

The Moon passes 4° north of Jupiter, 4 P.M. EST

17 The Moon passes 4° north of Venus, 1 A.M. EST

SPECIAL OBSERVING DATE

17 The annual Leonid meteor shower peaks under a Moon-free sky before dawn.

18 New Moon occurs at 6:42 A.M. EST

20 The Moon passes 7° north of Mercury, 4 A.M. EST

The Moon passes 3° north of Saturn, 7 P.M. EST

21 The Moon is at apogee (252,358 miles from Earth), 1:53 P.M. EST

22 Neptune is stationary, 4 P.M. EST

23 Mercury is at greatest eastern elongation (22°), 7 P.M. EST

26 First Quarter Moon occurs at 12:03 P.M. EST

The Moon passes 1.2° south of Neptune, midnight EST

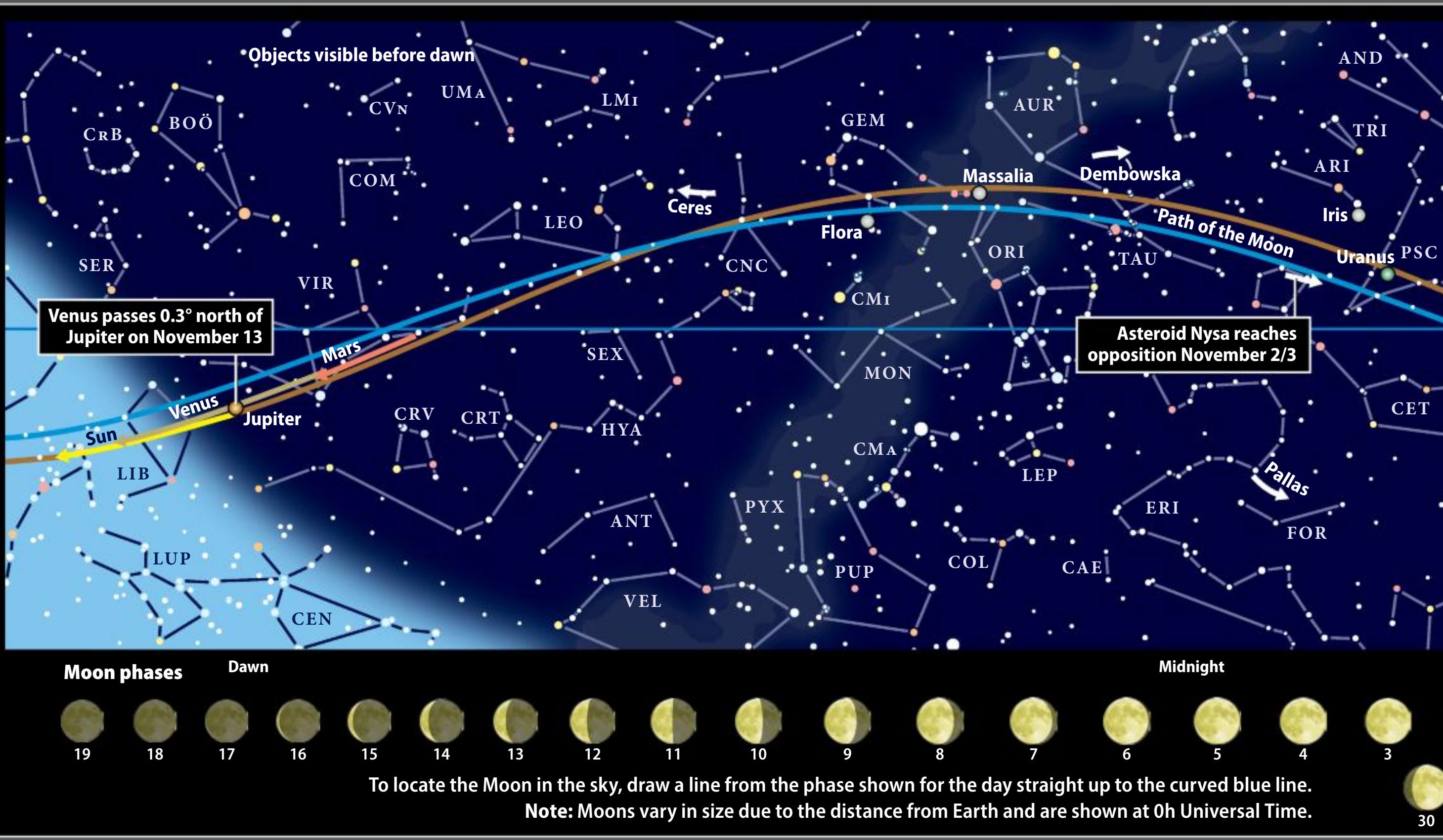
27 Mars passes 3° north of Spica, 7 P.M. EST

28 Mercury passes 3° south of Saturn, 4 A.M. EST

30 The Moon passes 4° south of Uranus, 5 A.M. EST

BEGINNERS: WATCH A VIDEO ABOUT HOW TO READ A STAR CHART AT **www.Astronomy.com/starchart.**

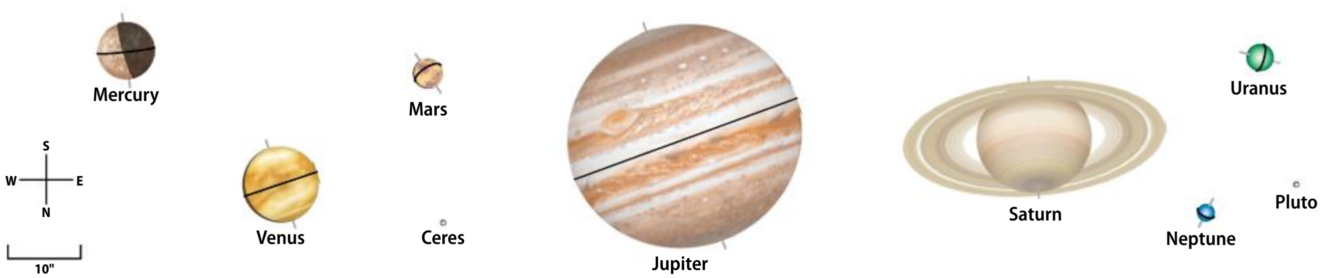
The planets in November 2017



To locate the Moon in the sky, draw a line from the phase shown for the day straight up to the curved blue line.
Note: Moons vary in size due to the distance from Earth and are shown at 0h Universal Time.

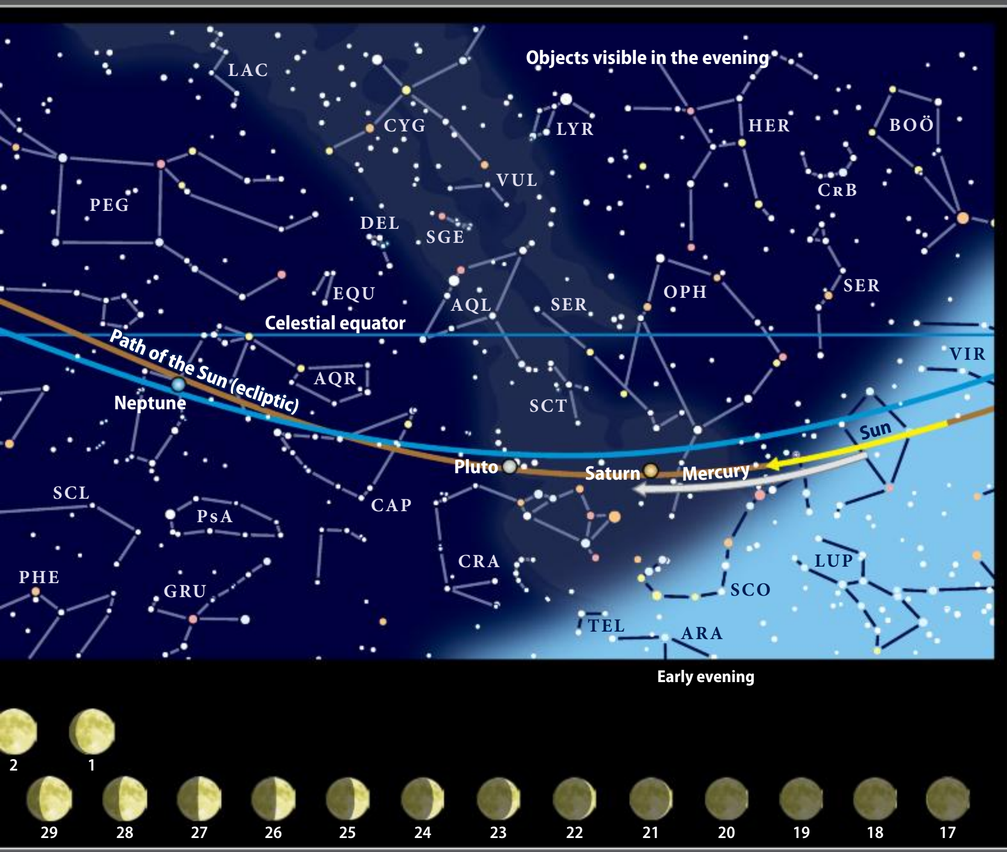
The planets in the sky

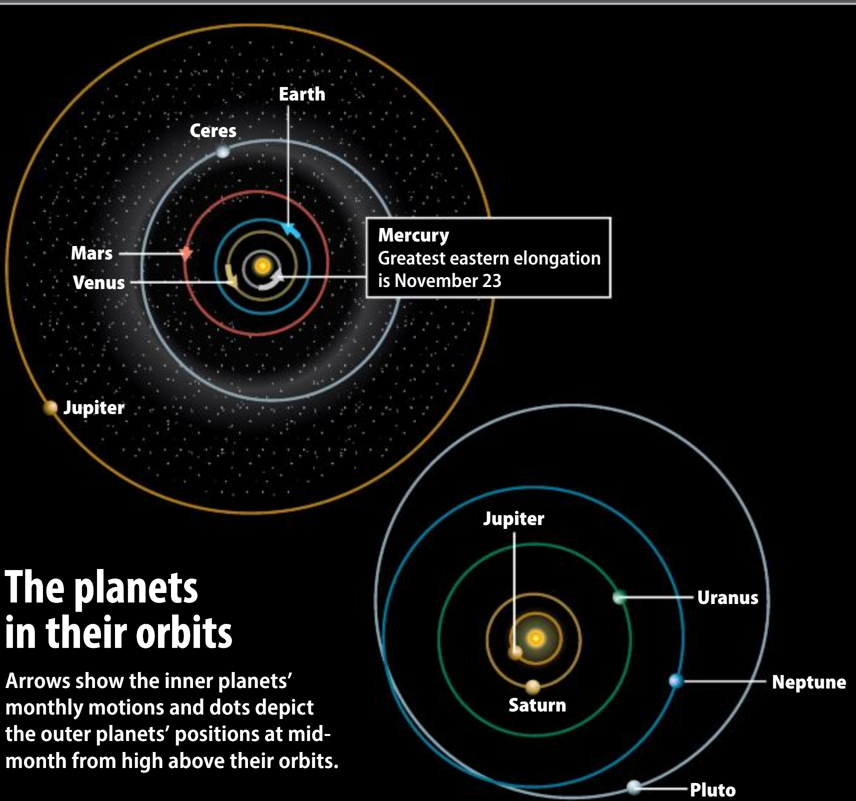
These illustrations show the size, phase, and orientation of each planet and the two brightest dwarf planets at 0h UT for the dates in the data table at bottom. South is at the top to match the view through a telescope.



Planets	MERCURY	VENUS	MARS	CERES	JUPITER	SATURN	URANUS	NEPTUNE	PLUTO
Date	Nov. 30	Nov. 15	Nov. 15	Nov. 15	Nov. 15	Nov. 15	Nov. 15	Nov. 15	Nov. 15
Magnitude	–0.2	–3.9	1.8	8.3	–1.7	0.5	5.7	7.9	14.3
Angular size	7.6"	10.1"	4.0"	0.6"	30.9"	15.3"	3.7"	2.3"	0.1"
Illumination	44%	97%	96%	96%	100%	100%	100%	100%	100%
Distance (AU) from Earth	0.882	1.646	2.320	2.275	6.388	10.877	19.024	29.614	34.009
Distance (AU) from Sun	0.349	0.722	1.659	2.602	5.439	10.064	19.908	29.946	33.445
Right ascension (2000.0)	17h52.1m	14h28.8m	12h54.8m	9h16.6m	14h21.8m	17h41.7m	1h34.5m	22h52.2m	19h14.1m
Declination (2000.0)	–25°19'	–13°23'	–4°40'	22°39'	–13°03'	–22°24'	9°13'	–8°13'	–21°49'

This map unfolds the entire night sky from sunset (at right) until sunrise (at left).
Arrows and colored dots show motions and locations of solar system objects during the month.



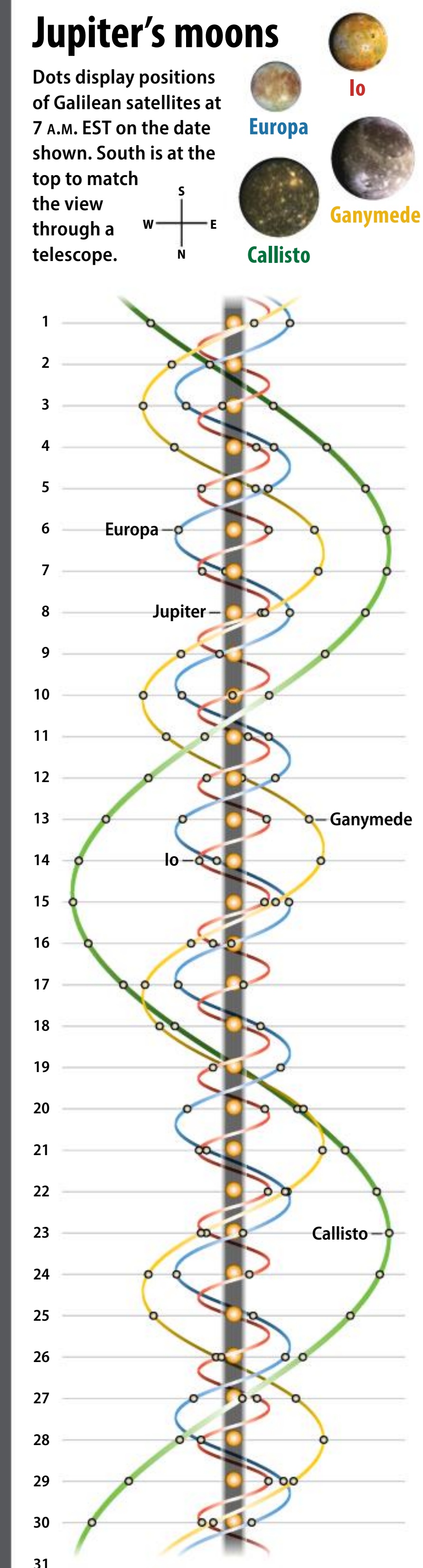


The planets in their orbits

Arrows show the inner planets' monthly motions and dots depict the outer planets' positions at mid-month from high above their orbits.

Jupiter's moons

Dots display positions of Galilean satellites at 7 A.M. EST on the date shown. South is at the top to match the view through a telescope.



ILLUSTRATIONS BY ASTRONOMY: ROEN KELLY

— *Continued from page 37*

WHEN TO VIEW THE PLANETS

EVENING SKY	MIDNIGHT	MORNING SKY
Mercury (southwest)	Uranus (southwest)	Venus (east)
Saturn (southwest)	Neptune (west)	Mars (southeast)
Uranus (east)		Jupiter (east)
Neptune (southeast)		

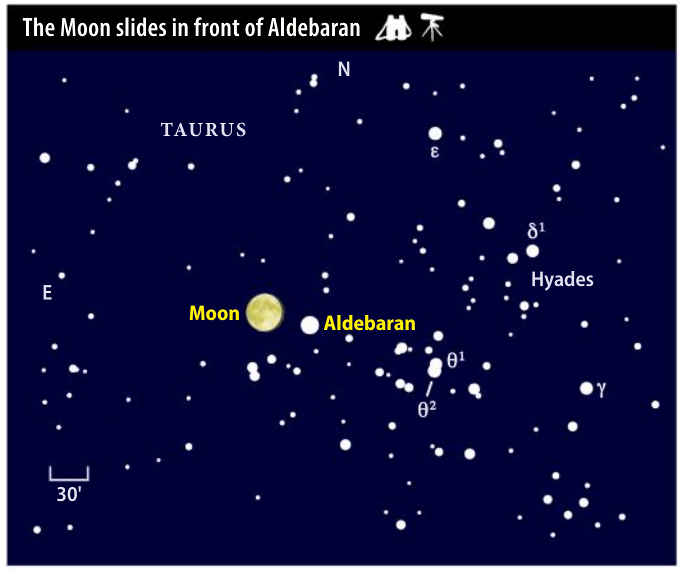
nearly stationary all month. To find it, locate 4th-magnitude Lambda (λ) Aquarii. Neptune spends November just 0.6° south of this star.

No background star of similar brightness lies in this vicinity, so you shouldn't have much trouble identifying it through binoculars. If you're unsure, target the possible planet through a telescope. Only Neptune shows a disk, which appears 2.3" across and boasts a subtle blue-gray color.

Uranus resides one constellation east of Neptune, in the similarly indistinct Pisces the Fish. But Uranus glows at magnitude 5.7, some eight times brighter than its ice giant sibling, and is far easier to spot through binoculars. In fact, sharp-eyed observers can glimpse it with the naked eye under a dark sky.

The world appears in the east as darkness falls and reaches its peak around 10 P.M. local time in mid-November. It then lies two-thirds of the way to the zenith and in prime viewing position.

But this doesn't mean finding it will be simple. Most of the stars in Pisces disappear under light-polluted skies, so getting to the right spot can be a challenge. Here's the fastest way. First, locate magnitude 2.8 Algenib (Gamma [γ] Pegasi), the star at the southeastern corner of the Great Square of Pegasus. Then, look



Watch Taurus' luminary emerge from behind the Moon the evening of November 5. This view shows the scene shortly after the star reappears.

43° east-southeast for magnitude 2.5 Menkar (Alpha [α] Ceti), the brightest star in the head of Cetus the Whale.

Uranus lies midway between these conspicuous stars. Scan the area through binoculars until you find magnitude 4.3 Omicron (ο) Piscium, the brightest star in this part of Pisces. Uranus stands 2.3° west of Omicron on November 1. The planet's motion relative to the background carries it to a position 3.2° west of the star by month's end.

Although Uranus is the brightest object in this area, several slightly fainter stars share the same binocular field. To confirm a sighting, aim a scope toward your

COMETSEARCH

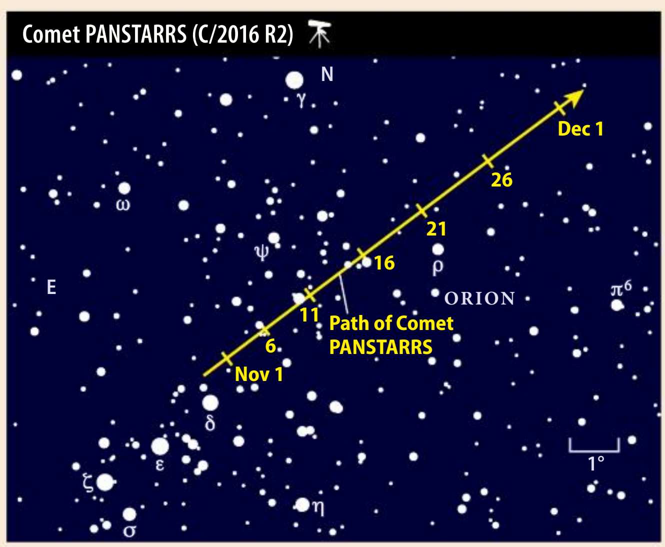
An Oort Cloud visitor keeps its distance

Comet PANSTARRS (C/2016 R2) likely began its journey from the distant Oort Cloud tens of thousands of years ago. Its long trek now nearly complete, PANSTARRS should glow around 10th or 11th magnitude in November, bringing it within range of a 4-inch telescope under a dark sky.

C/2016 R2 will be a delicate sight silhouetted against the picturesque backdrop of the constellation Orion the Hunter. The rich star fields here will help you zero in on the comet's position, and the lack of background galaxies will make it fairly easy to identity the interloper.

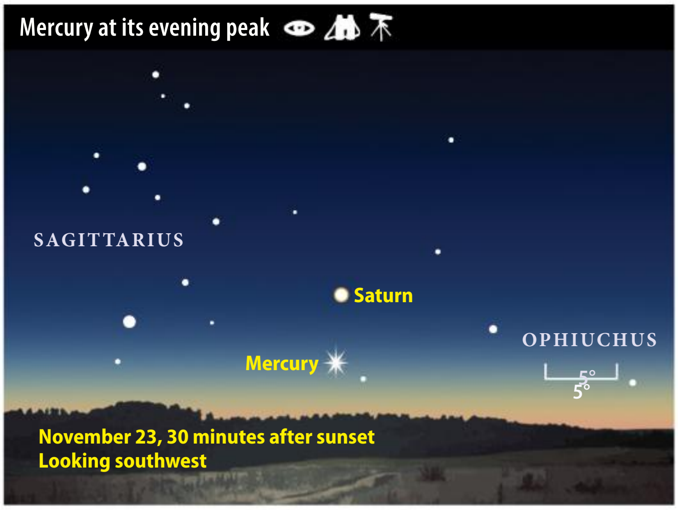
PANSTARRS begins the month just 1° north-northwest of magnitude 2.2 Mintaka (Delta [δ] Orionis), the westernmost star in Orion's Belt. It heads northwest from there toward the Hunter's Shield, passing 1° north of magnitude 4.5 Rho (ρ) Ori at the start of November's fourth week. This region climbs highest after midnight, so the best views will come in mid- and late November when the Moon is absent from the morning sky.

Astronomers expect the comet to span only a couple of arcminutes, making it visually similar to one of the smaller galaxies in the Virgo Cluster. You might not see it at low power, so bump up the magnification to 100x or more and take your time locating the cotton ball, letting your eyes adjust to the darker field.



This visitor to the inner solar system glows around 10th magnitude as it travels from near the belt of Orion toward his shield.

Comet PANSTARRS will take a long time to cross Earth's northern sky because it is still three times farther from the Sun than Earth is. Even at its closest point to our star in May 2018, it will reside well beyond Mars' orbital distance.



The innermost planet puts on a nice display in evening twilight as it pulls away from the Sun during the second half of November.

suspect. Uranus displays a 3.7"-diameter disk with a distinct blue-green hue.

As Uranus dips low in the west, **Mars** pokes above the eastern horizon. The Red Planet rises nearly three hours before the Sun on November 1 and almost four hours before sunrise on the 30th. Though Mars appears bright at magnitude 1.8, it stands out more for its distinctive ruddy color.

The planet tracks eastward across Virgo the Maiden this month. It starts November 1.0° southeast of magnitude 3.9 Eta (η) Virginis, passes 1.8° south of magnitude 2.8 Gamma Vir on the 9th, and 3.3° north of magnitude 1.0 Spica (Alpha Vir) on the 28th. Notice the stark color contrast between the orange-red planet and Virgo's blue-white luminary.

The view of Mars through a telescope remains disappointing, however. With a diameter of only 4", it shows no detail. But the planet's fortune will improve dramatically in 2018. By spring, Mars will shine at magnitude –1 and span 10". And its July opposition will be the best in 15 years.

Shortly after twilight begins in early November, **Venus** appears low in the east. On the 1st, the planet rises about 90 minutes before the Sun and stands 4° north of Spica. Shining at magnitude –3.9, Venus appears 100 times brighter than the star.

Although Venus slips deeper into twilight as the month progresses, that's when it has its finest moments. **Jupiter** passed on the far side of the Sun in late October and is now climbing rapidly into the predawn sky. The planets meet each other November 13 in the finest planetary conjunction of 2017. The two rise in the east-southeast some 70 minutes before sunrise and climb 5° high a half-hour later. Venus, still glowing at magnitude –3.9, appears just 0.3° to the left of magnitude –1.7 Jupiter. A telescope shows both in a single field. Venus spans 10" and appears nearly full, while Jupiter appears three times bigger and at the center of an entourage of four bright moons.

Three mornings later, on the 16th, a stunning sight awaits early risers. Jupiter now stands 3° above Venus while a slender crescent Moon appears 6° above the giant planet.

By the end of November, Venus disappears into the Sun's glare. But Jupiter improves markedly, rising in a dark sky more than two hours before the Sun and climbing nearly 15° high an hour before sunup. It appears among the background stars of Libra the Scales.

Observers in eastern and central North America are in for a surprise the evening of November 5. Although the waning gibbous Moon lies among the background stars of Taurus the Bull, constellation's brightest star will be absent — Luna is blocking 1st-magnitude Aldebaran from view. Observers should target the Moon's dark limb through their telescopes and try to view the star as it suddenly reappears. To find the precise time when Aldebaran returns to view for your location, visit www.lunar-occultations.com/iota/bstar/bstar.

Martin Ratcliffe *provides planetarium development for Sky-Skan, Inc., from his home in Wichita, Kansas. Meteorologist* **Alister Ling** *works for Environment Canada in Edmonton, Alberta.*

LOCATING**ASTEROIDS**

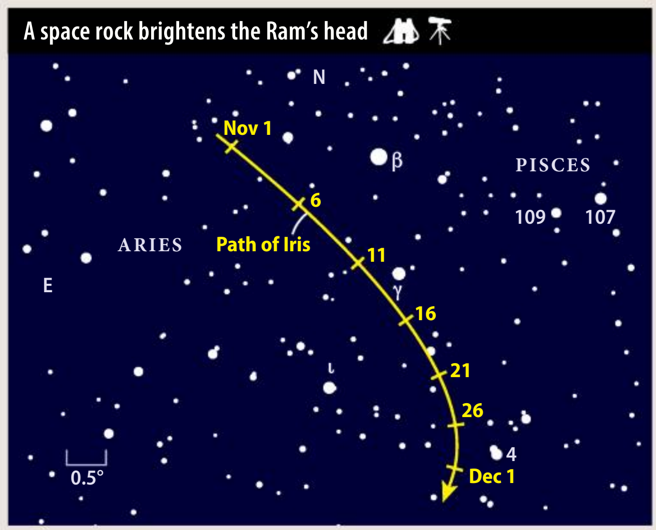
Iris flowers on chilly November nights

Asteroid 7 Iris reached opposition in late October, and it begins this month at its peak brightness of magnitude 6.9. Although it fades to magnitude 7.7 by November's close, Iris remains bright enough to pick up through binoculars from the suburbs. It should be a snap to find as it climbs high in the late-evening sky.

The asteroid resides in Aries the Ram. This constellation appears halfway to the zenith in the eastern sky once darkness settles in and climbs highest in the south around 10 P.M. local time. Iris executes a gentle arc south of Aries' brightest stars, limiting itself to a single binocular field for the entire month.

You can track the asteroid's nightly position with the chart below, which shows stars to magnitude 9.5. The space rock begins the month 2° east of magnitude 2.7 Beta (β) Arietis before heading southwest toward magnitude 3.9 Gamma (γ) Ari. Iris slides within 0.4° of Gamma — a fine double star — from November 12–15. During the month's final few days, the asteroid passes 0.5° east of the magnitude 5.9 star 4 Ari.

Iris glows about as bright as it can this month. It won't reach 7th magnitude again until 2028.



The second-brightest asteroid of 2017 glows at 7th magnitude and should be easy to find as it skirts near the conspicuous stars of Aries.

METEORITE ORIGINS

NWA 869 is an ordinary chondrite, the most common type of stony meteorite found on Earth. Planetary geologists believe these objects originate from asteroids. JAMES ST. JOHN

Q: HAS A METEORITE EVER BEEN FOUND THAT IS SUSPECTED TO HAVE COME FROM A SOLAR SYSTEM OTHER THAN OUR OWN? HOW WOULD WE RECOGNIZE SUCH A METEORITE?

***Michael Rodriguez,** Corvallis, Oregon*

A: Most (99 percent) of the meteorite inventory on Earth comes from the main asteroid belt, between the orbits of Mars and Jupiter. A small fraction of meteorites come from Mars (about 180) and the Moon (about 275). Some meteorites have been suspected to come from comets. Famous astronomer Carl Sagan once said, "It is unlikely that a single meteorite of extrasolar origin has ever reached the surface of the Earth." Numerical calculations suggest that the possibility of exchange of meteoritic fragments between stellar systems is highly unlikely. Indeed, extrasolar meteorites have not been identified in our meteorite collections.

Although we don't have extrasolar meteorites, "presolar" materials have been found in some primitive meteorites. These materials are called presolar because they were created in stars before our solar system formed and were transported to our protosolar nebula. We can identify these tiny grains, which range in size from a nanometer to a few micrometers, based on their anomalous isotopic compositions. There is also evidence for the delivery of material from nearby supernovae at least twice within about the last 10 million years. This material was deposited on Earth and is identified based on the isotopic anomalies found in ocean sediments. However, we don't have actual rock fragments from outside our solar system.

If extrasolar meteorites do exist, their chemical, mineralogical, and isotopic composition would be important signatures of their origin. But how different or similar these signatures would be, compared to our own solar system material, is left to speculation for now.

Prajkta Mane
Postdoctoral Research Associate, Department of Planetary Sciences and Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona

The Large (upper right) and Small (lower left) Magellanic Clouds orbit the Milky Way at a distance of 160,000 light-years and 200,000 light-years, respectively. Even at these distances, the two satellite galaxies are close enough for astronomers to resolve and study individual stars. ESO/S. BRUNIER

Q: ARE THERE 3-D RENDERINGS OF THE SMALL AND LARGE MAGELLANIC CLOUDS AVAILABLE TO VIEW?

Patrick Clough
Wichita, Kansas

A: The Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC), satellite galaxies of the Milky Way, are close enough that astronomers can resolve these dwarf galaxies into their individual stars. Several projects exist to study — and subsequently map — the clouds' stellar populations and their distances. However, no such renderings using current data are available for public use as of yet.

To map the Magellanic Clouds, many studies have used variable stars, namely Cepheid and RR Lyrae variables, to determine the distances to these stars within the LMC and SMC quite accurately. These variable stars are such accurate distance indicators because they display a clear correlation between their pulsation periods and their intrinsic brightnesses. By measuring a star's light curve and determining the period of time over which it varies, astronomers can calculate the star's intrinsic brightness and compare it to observations. Any dimming of the star with respect to the brightness we expect to see is thus related to the star's distance.

Over time, increasing the catalogs of these variables and others within the Magellanic Clouds has begun to reveal their 3-D structure. From these measurements, astronomers have already determined that the SMC is highly elongated along our line of sight, stretching away from us with a length between 32,600 and 65,200 light-years. Overall, the SMC's shape can be described as an "extended ellipsoid," while the LMC appears to have a central bar structure and at least one spiral arm.

Alison Klesman
Associate Editor

ESO/A. ROQUETTE

Gamma-ray bursts (GRBs) are the most luminous explosions in the universe. Although their exact origin remains unknown, astronomers envision that GRBs are the result of either a massive star's life-ending supernova, or the merging of two compact objects, such as neutron stars or black holes.

Q: GAMMA RADIATION FROM SPACE HAS VERY HIGH ENERGY LEVELS. WHAT IS THE THEORETICAL LIMIT ON THE ENERGIES OF GAMMA-RAY PHOTONS? IS THERE A CURRENT TECHNOLOGY TO DETECT AND MEASURE THE HIGHEST ENERGY LEVEL?

John Zinke
Cambria, California

A: There is no strict theoretical limit on the highest energy of astrophysical gamma rays, so far as I know, but there are some practical limitations.

The first is the energy of the particle that produces the gamma ray. Gamma rays result from the interactions of electrons and protons that have been accelerated to almost the speed of light. Higher-energy particles produce higher-energy gamma rays, so one limitation to the maximum gamma-ray energy is the maximum energy to which particles can be accelerated. To accelerate a particle, it must be confined to the region of space where the acceleration takes place using magnetic fields — in the same way as particles are confined to the radius of the Large Hadron Collider here on Earth. The maximum particle energy therefore depends upon the magnetic field strength and the size of the acceleration region. Pulsars, for example, are relatively small but have intense magnetic fields. Galaxy clusters, on the other hand, are enormous but have weak magnetic fields. When a particle reaches a velocity high enough that it can escape the acceleration region, the acceleration stops, and the particle gains no further energy.

The other limitation is the ability of the gamma ray to survive its journey to Earth. Gamma rays are destroyed when they interact with lower-energy photons. Since the universe is full of low-energy photons from starlight and the cosmic microwave background, gamma rays are limited in the distance they can travel. This limit changes with the energy of the gamma ray — low-energy gamma rays can travel across most of the universe; higher-energy gamma rays can only survive if they are produced inside of our galaxy, or in a near neighbor.

Detecting a high-energy gamma ray is relatively simple, but high-energy gamma rays are extremely rare. A typical astronomical source produces just a few gamma rays per square meter of Earth's surface every year — so we need a very large detector. When a gamma ray strikes the top of the atmosphere, it initiates a cascade of particles, which in turn produces a flash of blue light.

Gamma-ray observatories, such as the Very Energetic Radiation Imaging Telescope Array System (VERITAS) and the High-Altitude Water Cherenkov Gamma-Ray Observatory (HAWC), can observe over effective areas as large as a football field by detecting the products of these particle cascades at ground level. The highest-energy gamma rays that have been detected by these observatories have energies of around 50 teraelectron volts, or 50 billion times the energy of an X-ray. Higher-energy gamma rays certainly exist in the universe, since particles with much higher energies have been observed. Large area cosmic ray observatories, like the Pierre Auger Observatory, are searching for them.

Jamie Holder
Associate Professor of Physics & Astronomy, University of Delaware, Newark, Delaware

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Q: YOUR OCTOBER 2016 ARTICLE ON BLACK HOLES DESCRIBES A SINGULARITY WITH INFINITE DENSITY. IT HAS BEEN MY UNDERSTANDING THAT ANYTHING WITH INFINITE DENSITY ALSO HAS INFINITE MASS AND INFINITE GRAVITATIONAL ATTRACTION. WOULDN'T ANYTHING WITH INFINITE ATTRACTION COLLAPSE THE UNIVERSE?

Dan Johnston,
Hermitage, Pennsylvania

A: A simple description is that the infinite density of the singularity corresponds to the finite mass of a star collapsed to a point. The density is infinite but the volume infinitesimal, so the mass is still finite. The true description is a bit more complex due to the distortion of space-time that the concentration of mass produces.

However, we believe that the general theory of relativity of Einstein stops being valid before the star shrinks to a point and has to be replaced by a more general theory that takes quantum effects into account. There is no general agreement yet on what such a theory looks like. There are some preliminary indications that such theories would replace the singularity with a region of large density and large quantum fluctuations.

Jorge Pullin
Professor and Hearne Chair of Theoretical Physics, Louisiana State University, Baton Rouge, Louisiana

Send us your questions

Send your astronomy questions via email to **askastro@astronomy.com**, or write to Ask Astro, P. O. Box 1612, Waukesha, WI 53187. Be sure to tell us your full name and where you live. Unfortunately, we cannot answer all questions submitted.

FALL INTO AUTUMN GALAXIES

Beg, borrow, or steal the biggest scope you can find, and settle in for a great night of deep-sky observing. **by Stephen James O'Meara**

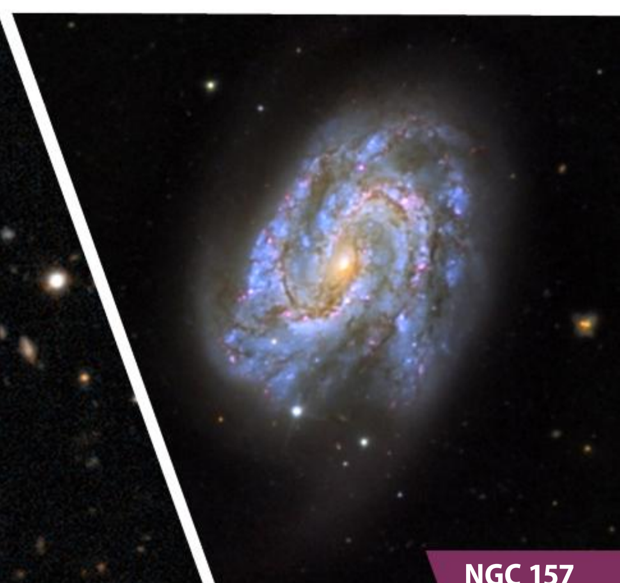
AUTUMN NIGHTS PROVIDE us with a transparent view of the deep universe. The sky above much of the southern horizon is largely devoid of dense Milky Way star clouds, so galaxies stand out more boldly in telescopic fields of view.

In addition to autumn's bright perennial favorites — the Andromeda Galaxy (M31) with its two clingy companions (M32 and NGC 205); the Pinwheel Galaxy (M33) in Triangulum; and the Phantom Galaxy (M74) in Pisces — a slightly fainter selection of exotic galaxy types awaits your gaze.

While some will display rich details in small scopes, others will challenge skilled observers using larger instruments. These include a variety of prototypical galaxies that just might satiate a curious observer's visual palate, if not the imagination.

Getting down in Aquarius

We start our journey about 30' southeast of 5th-magnitude 41 Aquarii, diving 350 million light-years into deep celestial waters to find the magnitude 11.7 barred spiral galaxy **IC 1438**. Its light scrunches into a 2' disk, making it appear simply as a fuzzy star. Owners of larger telescopes should use high magnifications to search for the galaxy's tiny

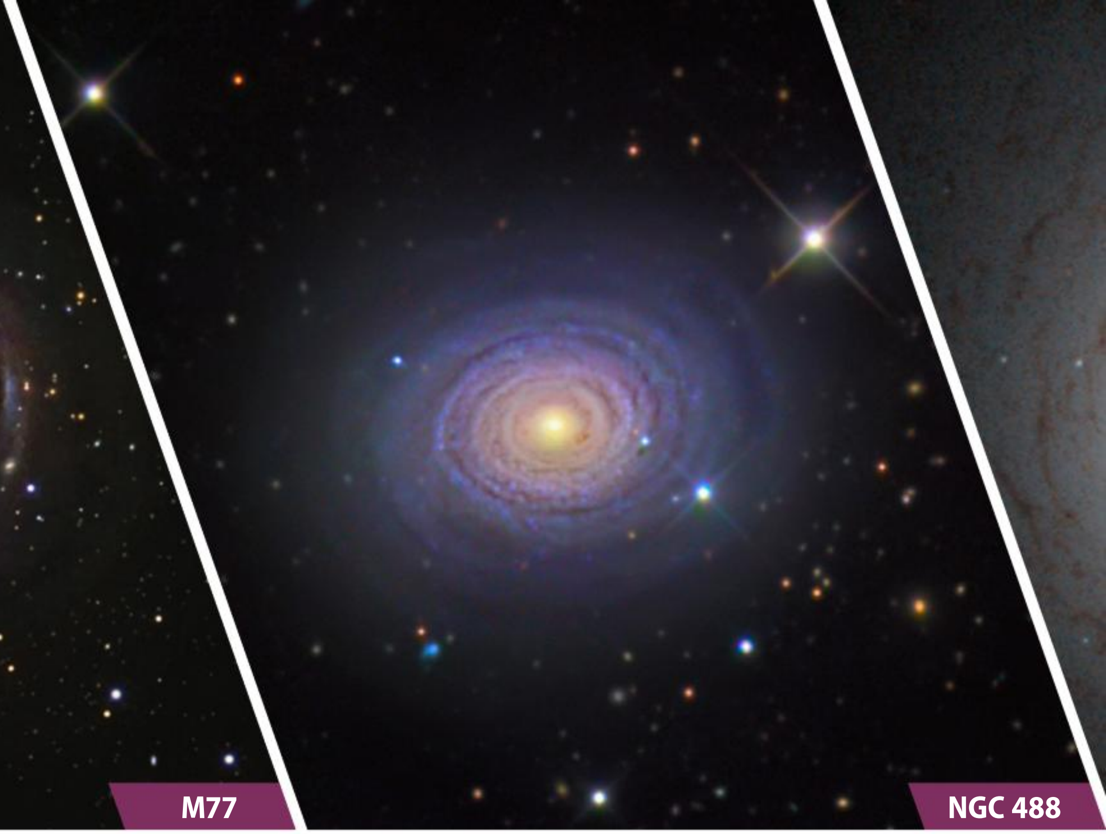


NGC 157

ADAM BLOCK/MOUNT LEMMON SKYCENTER/UNIVERSITY OF ARIZONA

M77

R. JAY GABANY



NGC 488

ADAM BLOCK/NOAO/AURA/NSF

bar and phantom arms, which spiral out to form a tight ring of light.

Next, drop about 3° south to 6th-magnitude 49 Aquarii, then 30' west to one of Aquarius' most unusual sights: **NGC 7252**, sometimes called the Atoms for Peace Galaxy. In images, this prototypical remnant of two galaxies colliding some 220 million light-years distant looks like a time-lapse exposure of a catfight — a swirling ball of tails, claws, and fur.

The Hubble Space Telescope has revealed a striking pinwheel structure at the galaxy's core, surrounded by bright star clusters, reinforcing the idea that elliptical galaxies form by the merging of spirals. NGC 7252 glows at magnitude 12.1. Most of that brightness is in the core, which spans only 2', making it appear like a swollen star through modest-sized instruments. Users of large scopes have dissected some of its brighter filaments, but it takes an extremely large telescope to see its two long and dim tidal tails.

Return to 49 Aquarii, then move 1° east to **NGC 7285**, a 12th-magnitude galaxy interacting with **NGC 7284** some 180 million light-years distant. I call them the Kiss and Tell Galaxies because, in images, their cores seem to be lip-locked with their arms wrapped around each other. Through a 10-inch telescope at high power, they appear like a 2'-wide misty double star with a dim northern brow. Higher powers and greater aperture may reveal NGC 7285's southern arm, but, again, has anyone seen its extremely faint tidal tail to the south?

Whale spotters

Cetus is a rich proving ground for galaxy hunters. We'll start off with **NGC 157**, a magnitude 10.4 spiral galaxy you'll find nearly 4° east of 4th-magnitude Iota (ι) Ceti. This 4'-wide cometary glow hides between two 9th-magnitude stars and appears as a mottled oval disk, oriented northeast to southwest, with a bright inner and fainter outer S-shaped spiral structure visible at 100x. If your observing site has good seeing (atmospheric steadiness), larger apertures at high power can resolve its arms into lumpy HII (star-forming) regions.

> **MAGNITUDE 10.3 NGC 488 IS A PROTOTYPICAL MULTIPLE-ARMED SPIRAL DISPLAYING RINGS OF STAR FORMATION.**

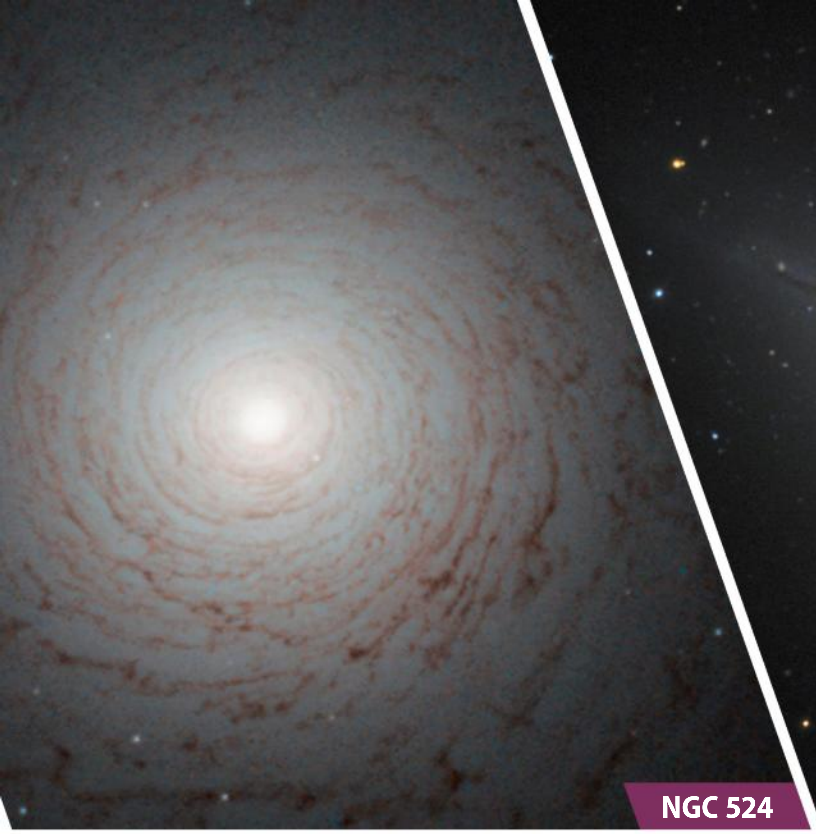
Next up is what I call the Cetus Chain — a roughly 2°-long string of six galaxies (approximately 80 million light-years away), about 2¼° north of magnitude 3.6 Theta (θ) Ceti. All are visible through 4-inch and larger telescopes, especially at magnifications of 100x or more, although some with difficulty.

The brightest member, the magnitude 10.5 **NGC 584**, sometimes called the Little Spindle Galaxy, is 4' of misty light with a starlike core. When you observe it, look for its non-interacting magnitude 13.2 elliptical companion **NGC 586** some 4' to the southeast.

Moving eastward, the other galaxies are as follows: the magnitude 10.9 elliptical **NGC 596** with its magnitude 12.4 barred spiral buddy **NGC 600**; the magnitude 11.6 nearly edge-on spiral galaxy **NGC 615**; and the magnitude 11.5 elliptical **NGC 636** at the chain's far eastern end.

We now head northeast to the somewhat brighter **NGC 936**, which glows at magnitude 10.2. This object is a prototypical barred spiral galaxy that lies 55 million light-years away. You'll find it almost midway between 4th-magnitude Delta (δ) Ceti and Mira (Omicron [ο] Ceti). Through a 5-inch scope, the galaxy's intense core lies in a soft nest of circular light, which itself is surrounded by a dim 3' collar of emission. Large telescopes can resolve the galaxy's strong bar with arcuate edges, which fade into a dim ring containing mere whispers of spiral structure.

Return your gaze to Delta Ceti and look 1° southeast for **M77** — the galaxy prince of Cetus. This prototypical Seyfert-type galaxy sports an active core dominated by massive gas clouds blasting forth from a supermassive black hole with enough energy to power several million supernova explosions. It is the closest we will ever get



NGC 524

ESA/HUBBLE AND NASA/JUDY SCHMIDT

NGC 7814

ADAM BLOCK/MOUNT LEMMON SKYCENTER/UNIVERSITY OF ARIZONA

to witnessing a quasar in action. The smallest telescopes will show M77's 10th-magnitude core, dense inner disk with traces of tight dusty spirals, and prolific HII regions. But how small of a telescope will show the galaxy's dim S-shaped outer spiral arms that nearly form a ring around the inner disk?

Swimming with the Fish

Working our way toward the surface of the liquid constellations, we head 2° west-southwest of Mu (μ) Piscium. There we find the magnitude 10.3 nearly perfect spiral **NGC 488**. In images, this prototypical multiple-armed spiral displays rings upon rings of star formation occurring within a uniform arrangement of thin and stringy spiral fragments.

You can't follow any of the galaxy's arms for more than about half a revolution. Visually through most apertures, this subtle object displays only a conspicuous starlike nucleus in a soft bed of light, surrounded by an even softer outer halo extending to 5'.

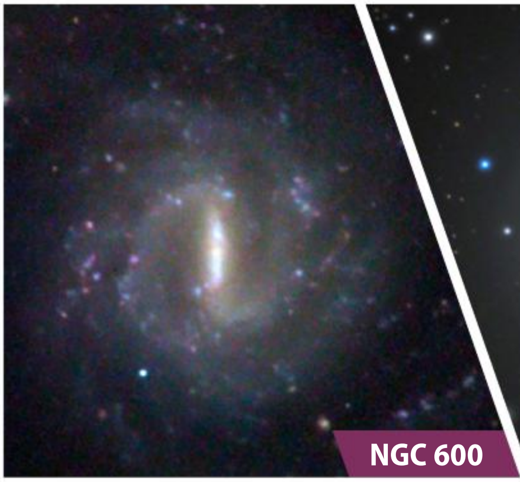
About 4° due north and slightly east of NGC 488, we find magnitude 10.3 **NGC 524**. It's an aged, face-on lenticular 90 million light-years distant. Lenticular systems represent a class of spiral that has depleted or lost its gas, leaving behind only ghostly footprints of its once (and now much weakened) spiral structure. Like NGC 488, it reveals scant visual detail, looking like a little orb of light surrounded by a faint outer halo.

Horsing around

Skirting the surface of the celestial waters 2½° northwest of magnitude 4.3 Theta Piscium across the border into Pegasus, we encounter a neglected pair of 11th-magnitude elliptical galaxies: **NGC 7619** and **NGC 7626**. Together with the interacting magnitude 12.3 Seyfert spiral **NGC 7469** about 4° to the west, these delicate ovals of light 200 million light-years away dominate the core of the Pegasus I galaxy cluster. Large telescope users should sweep this region to seek another dozen or so faint members in this cluster.

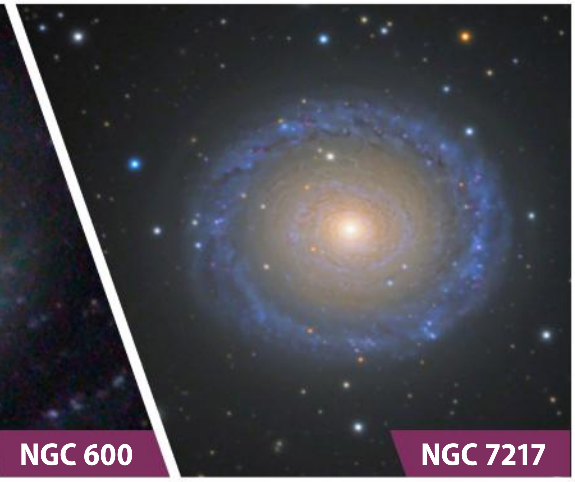
Look now about 2½° west-northwest of Gamma (γ) Pegasi, the southeast corner star of the Great Square of Pegasus, to **NGC 7814**, sometimes called the Little Sombrero Galaxy, which glows at magnitude 10.6. This nearly edge-on lenticular system lies 50 million light-years distant in the Pegasus Spur, which includes NGC 7331 (more on that later). A prominent dust lane heavily obscures the nucleus as it slices through the galaxy's paper-thin disk. Through most apertures, NGC 7814 resembles its larger namesake, M104, showing a sharp starlike core lurking inside a distinctive oval glow. Seeing the 5'-wide galaxy's ultrathin dust lane, however, is a challenge through modest apertures.

Sailing higher north, slip 2¾° due south of magnitude 4.3 Pi (π) Pegasi in the



NGC 600

BOB FERGUSON AND RICHARD DESRUISSEAU/ADAM BLOCK/NOAO/AURA/NSF



NGC 7217

ADAM BLOCK/MOUNT LEMMON SKYCENTER/UNIVERSITY OF ARIZONA

NGC 7331

BOB FERA

Stephan's Quintet

BRIAN PETERSON

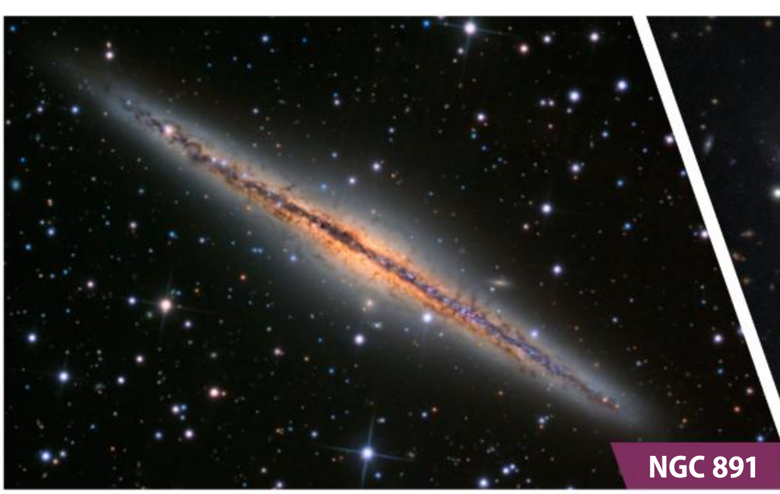
Horse's feet to find the neglected (but stunningly beautiful) magnitude 10.1 open-faced spiral **NGC 7217**. This little wonder has an active nucleus where matter swirls around a supermassive black hole. Like NGC 488, NGC 7217's 3.5'-wide disk is made up of concentric star-forming rings centered on a smooth inner lens. And though you can't see it, the inner disk also has stars rotating in the opposite direction around the galaxy's center, as well as curious dust features, suggesting that a past merger occurred with several smaller galaxies.

NGC 7331, the main member of the Deer Lick Group, is the spiral king of Pegasus. This magnitude 9.5 spectacle lies about 4½° north-northwest of Eta (η) Pegasi and can be glimpsed as a dim slash of light through a 3-inch telescope. Telescopically, NGC 7331 appears as a blazing star within a bright oval core surrounded by a mottled outer ellipse of light. The disk's grainy texture transforms into spiral structure with moderate to high magnifications and patience. Larger apertures reveal the galaxy in its true splendor — as an extragalactic hurricane of spiral madness with warped extremities.

About 0.5° south-southwest of NGC 7331 is one of the night sky's "cutest" extragalactic gatherings: **Stephan's Quintet**, a collection of five galaxies in a 3.5'-wide huddle: NGC 7317, NGC 7318A, NGC 7318B, NGC 7319, and NGC 7320. The brightest member shines at a mere magnitude 12.6, and most are tough captures through small telescopes. These objects make better targets for 8-inch and larger scopes.

Living on the edge

Sliding eastward to the beautiful 2nd-magnitude golden star Mirach (Beta [β] Andromedae) and looking just 6' northwest of it, you'll find the 10th-magnitude gem known as Mirach's Ghost, **NGC 404** — the nearest lenticular galaxy to our Milky Way. At a distance of 8 million light-years, it lies at the edge of the Local Group within the Coma-Sculptor Cloud of galaxies. Telescopically it looks like a faint comet with a bright nucleus passing through the glare of that bright star. Use enough magnification to separate the two and to enjoy



NGC 891

ADAM BLOCK/MOUNT LEMMON SKYCENTER/UNIVERSITY OF ARIZONA

NGC 772

ADAM BLOCK/MOUNT LEMMON SKYCENTER/UNIVERSITY OF ARIZONA

NGC 404

ANTHONY AYIOMAMITIS

IC 342

TONY HALLAS

its soft oval sheen that spans 6'.

NGC 7331 APPEARS AS A BLAZING STAR WITHIN A BRIGHT OVAL CORE SURROUNDED BY A MOTTLED OUTER ELLIPSE.

Jumping far to the north, locate 5th-magnitude Gamma Camelopardalis, then sweep 3¼° south to the mixed spiral **IC 342**. The 8th-magnitude galaxy may have once been a part of the Local Group but was ejected after a violent encounter with M31. Astronomers have found its loose and flamboyant arms undergoing prodigious bursts of star formation, suggesting this spiral is transitioning to a barred spiral. Through modest apertures, IC 342 has a 12th-magnitude nucleus in a tight ellipse of light from which at least three loose and wild spiral arms flee freely across 16' of sky. Larger telescopes will reveal the arms' broad and feathery filaments.

The last stretch

Dropping back down into Andromeda, we set sail for **NGC 891**, a stunning magnitude 9.9 edge-on spiral only 30 million light-years distant. Next to the Needle Galaxy (NGC 4565) in Coma Berenices, NGC 891 is the most sought after edge-on galaxy in the northern heavens.

You'll find it about 3½° east of the double star Gamma Andromedae. In wide-field images, NGC 891 looks like a flying saucer pitching sharply (northeast to southwest) through a rich patch of Milky Way. The galaxy wears a substantial sash of dust that slices across its 12' length, making it a challenge to see through small telescopes under light-polluted skies. It's been spied through 2½-inch scopes without difficulty under a dark sky. Large aperture scopes can resolve its feathery dust rising like mist off hot pavement all along the dust lane.

We now slip over to Mesarthim (Gamma Arietis), then make a clean 1.5° sweep east-southeast to **NGC 772**, sometimes called the Fiddlehead Galaxy. Lying some 100 million light-years distant, this magnitude 10.3 peculiar galaxy sports only one prominent spiral arm, which is most likely the result of a tidal encounter with its compact magnitude 12 companion galaxy NGC 770 a few arcminutes to its south.

Moderate apertures at 100x will show the galaxy's bright core surrounded by an apostrophe of light. Concentration is needed to spy its "prominent" arm to the north, which appears as a slight lash of light. How large of a telescope is needed to see its more delicate spiral structures, including its warped and stringy spiral tendril to the south and east?

We end our tour by dipping into the Perseus Milky Way toward the galactic anti-center, about 2° east–northeast of Algol (Beta Persei). Here lies Perseus A (**NGC 1275**), a peculiar magnitude 11.9 galaxy, which is the brightest and most central member of the Perseus Cluster of galaxies, a dense nest of some 12,000 systems roughly 230 million light-years away.

In images, NGC 1275's wild face, which looks like someone tossed a bowl of spaghetti on it, is one of the most fascinating sights in the autumn sky. Here is a galaxy with a monstrous supermassive black hole voraciously consuming untold other galaxies while spitting out their dusty skeletal remains.

Telescopically, this site of extragalactic cannibalism is but a mere 3' fuzzy speck of celestial lint. You'll find equally bright **NGC 1272** a few arcminutes to its west; together they look like two sleepy eyes. Owners of large telescopes will find about 14 other dim galaxies in a 30'-wide field of view surrounding the two.

I hope you enjoyed this selection of weird and wonderful autumn galaxies. Savor them as you would something you desire that's far out of reach — using your eyes and your mind.

Stephen James O'Meara *is a contributing editor of* Astronomy. *He writes the Secret Sky column and has never met a celestial object he doesn't like. He's especially fond of galaxies, whether in the fall sky or not.*

The Statue of Liberty Nebula (NGC 3576) is a wonderful mixture of emission, reflection, and dark nebulosity in the constellation Carina. To capture the data, the author used a 20-inch PlaneWave CDK20 at f/6.8 with an SBIG STX-16803 CCD camera attached. He combined 13 hours of exposures through Hα, OIII, and SII filters with 2 hours of exposures through RGB filters.

MEET THE filter guy

How an average Joe turned a hobby into an astronomy-based business.

text and images by Don Goldman

When I attend astronomy conventions or star parties, I meet lots of people who know me as "the guy who sells filters." Fair enough. I've been producing high-quality filters for astroimaging through my company, Astrodon, for 14 years. Far fewer people realize that I also love to image. So, when *Astronomy* asked me to briefly describe that part of my life (in words and pictures), I agreed.

It seems like everyone has a unique story about how they became passionate about astroimaging — I do, too. I didn't get interested until about 2000, despite several events that should have tipped me off to where my interests are.

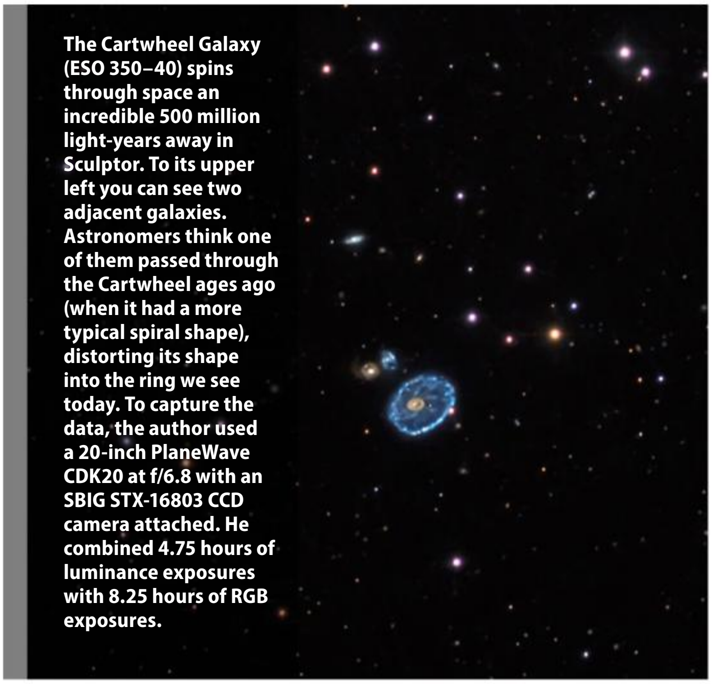
I earned a Ph.D. from Caltech in its Earth and Planetary Sciences Department, where I studied field geology under Gene Shoemaker, the co-discoverer of Comet Shoemaker-Levy 9, which impacted Jupiter. At Caltech, I heard Carl Sagan and others give inspirational lectures. I analyzed Moon rocks with an electron microprobe in the wee hours of the morning when others might be out with their telescopes. (Then again, graduate students couldn't afford telescopes and didn't have the time for observing anyway.) I even ate lunch with Harrison Schmitt, the astronaut who brought those rocks back from the Moon.

The emphasis for my dissertation was spectroscopy, using light to analyze materials. Such a background was essential when I started my Astrodon business years later.

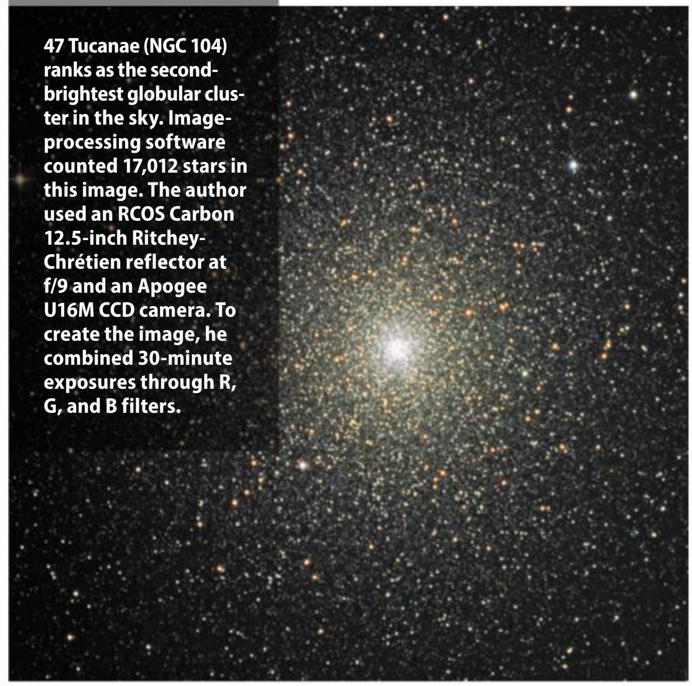
The beginning

In 2000, I bought a cheap telescope. That's when I learned three things: First, that you get what you pay for. Second, what 18.3 magnitudes per square arcsecond means in terms of light pollution in my backyard, which at the time was near Sacramento, California. And third, what an average person can expect to see through a telescope.

About that time, I also attended a talk at the local astronomy club about how cooled CCD cameras can cut



The Cartwheel Galaxy (ESO 350–40) spins through space an incredible 500 million light-years away in Sculptor. To its upper left you can see two adjacent galaxies. Astronomers think one of them passed through the Cartwheel ages ago (when it had a more typical spiral shape), distorting its shape into the ring we see today. To capture the data, the author used a 20-inch PlaneWave CDK20 at f/6.8 with an SBIG STX-16803 CCD camera attached. He combined 4.75 hours of luminance exposures with 8.25 hours of RGB exposures.



47 Tucanae (NGC 104) ranks as the second-brightest globular cluster in the sky. Image-processing software counted 17,012 stars in this image. The author used an RCOS Carbon 12.5-inch Ritchey-Chrétien reflector at f/9 and an Apogee U16M CCD camera. To create the image, he combined 30-minute exposures through R, G, and B filters.

through some of the light pollution by using specific filters and by combining images. So I jumped in and started to learn about how all the equipment goes together and how to process the resulting data.

The cameras of choice back then had cooled, monochrome CCDs because they provided the highest resolution and sensitivity. As such, they required that colored glass filters be placed between the camera and telescope, generally in a computer-controlled filter wheel.

Such setups produced filtered monochromatic data that astronomers combined to create color images. Even today, it's magical to see a color image on a computer monitor for the first time, realizing that no one has ever seen any of these objects, visually, in full color. Our eyes are simply not sensitive enough, even when we gaze through large telescopes.

This limitation raised a conundrum: If I couldn't see an object in full color, how would I know that computer enhancements produce the "correct" colors?

I sometimes think that if I had waited another decade to get into imaging, things would have been simpler. Today, DSLR cameras let you select a "white point," such as daylight, cloudy, etc. It gives the camera a reference to measure all colors against to allow its internal processor to correct them. For astroimages, different sensors have different sensitivities, and different brands of filters have different spectral responses. In general, it is the combination of the camera's sensitivity and filter's response that controls the resulting broadband color.

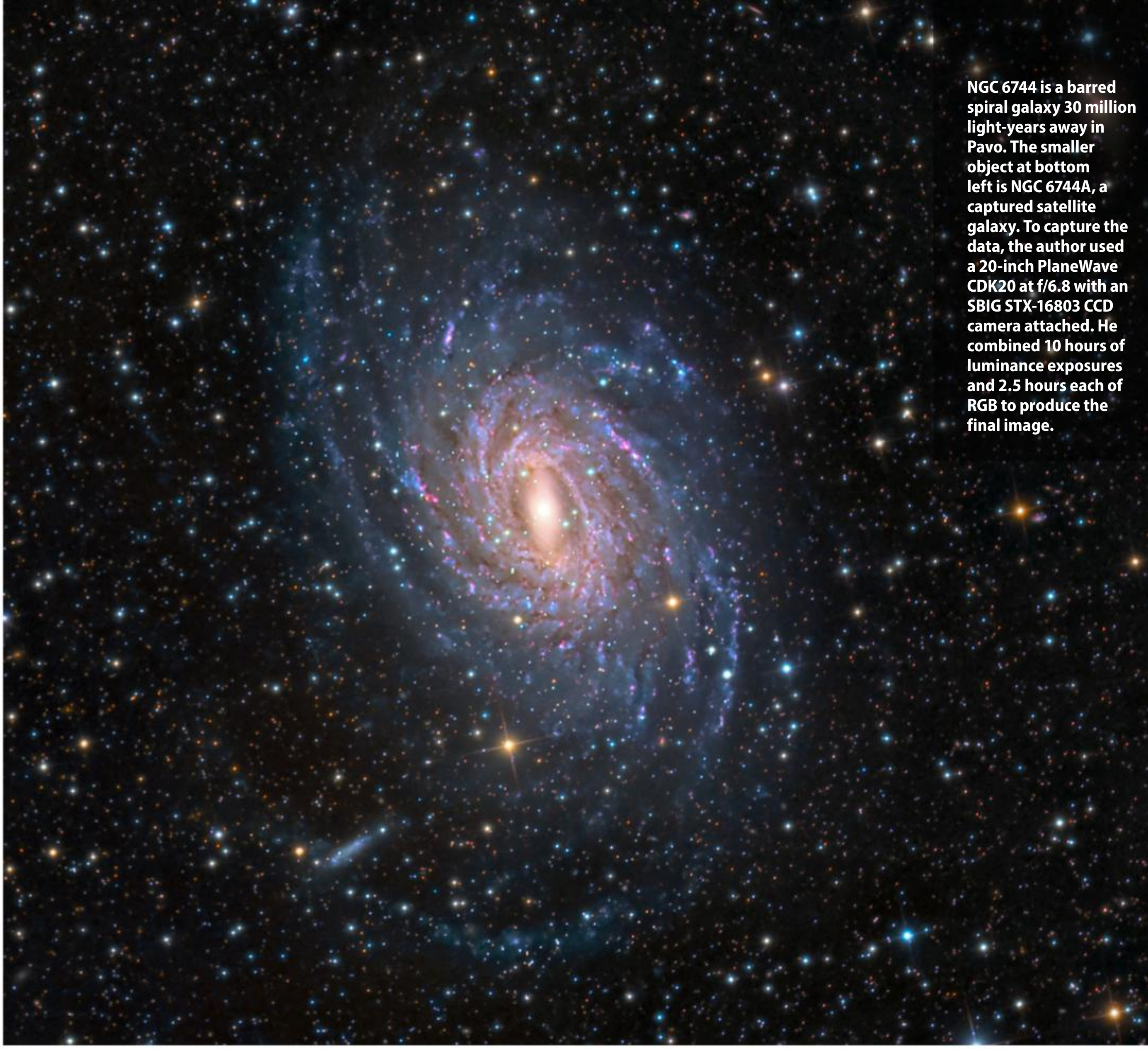
One long-standing method is to measure a Sun-like star through your red, green, and blue filters and determine the "weights," or sensitivity factors. That becomes our white point because we define sunlight as white. Done? Well, not quite. Here's where I got to use my background to better understand the problem.

Filtering the universe

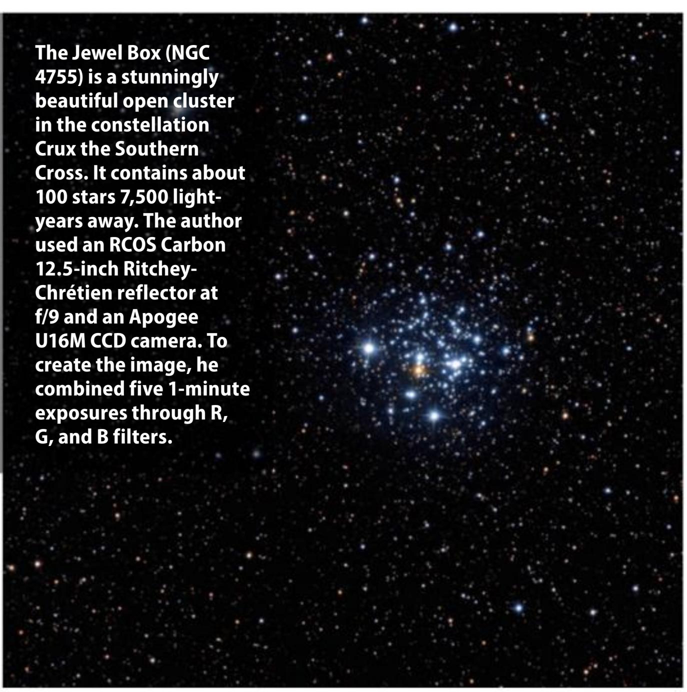
Unlike terrestrial subjects, emission nebulae, HII regions in galaxies, planetary nebulae, supernova remnants, and other sources also emit light in narrow wavelength ranges due to the excitation of elements such as hydrogen, oxygen, and sulfur. In particular, doubly ionized oxygen (OIII), which is present in many planetary nebulae and supernova remnants, emits light with wavelengths right between the green and blue filters.

Once I applied the broadband color weights described earlier to get "correct" broadband star colors, the distribution of OIII in the blue and green color channels became fixed by the design of the filters. The resulting OIII signals should be nearly equal, resulting in a blue-green or teal color. However, the filter brands of the day were all different; some produced greenish

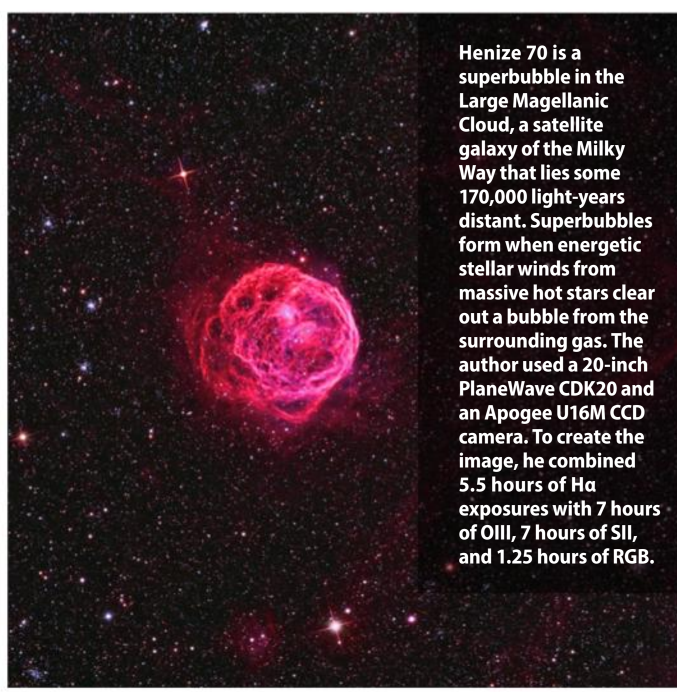
The Gourd Nebula (Sh 2–308) is a large, faint ring nebula surrounding the Wolf-Rayet star EZ Canis Majoris. Also known as WR 6, it's the bright blue star near the center of the image. The author used a 14.5-inch classical Cassegrain reflector at f/8.2 and an Apogee U16M CCD camera. He combined 2.67 hours of Hα, 3 hours of OIII, and 30 minutes of RGB exposures to produce the image.



NGC 6744 is a barred spiral galaxy 30 million light-years away in Pavo. The smaller object at bottom left is NGC 6744A, a captured satellite galaxy. To capture the data, the author used a 20-inch PlaneWave CDK20 at f/6.8 with an SBIG STX-16803 CCD camera attached. He combined 10 hours of luminance exposures and 2.5 hours each of RGB to produce the final image.

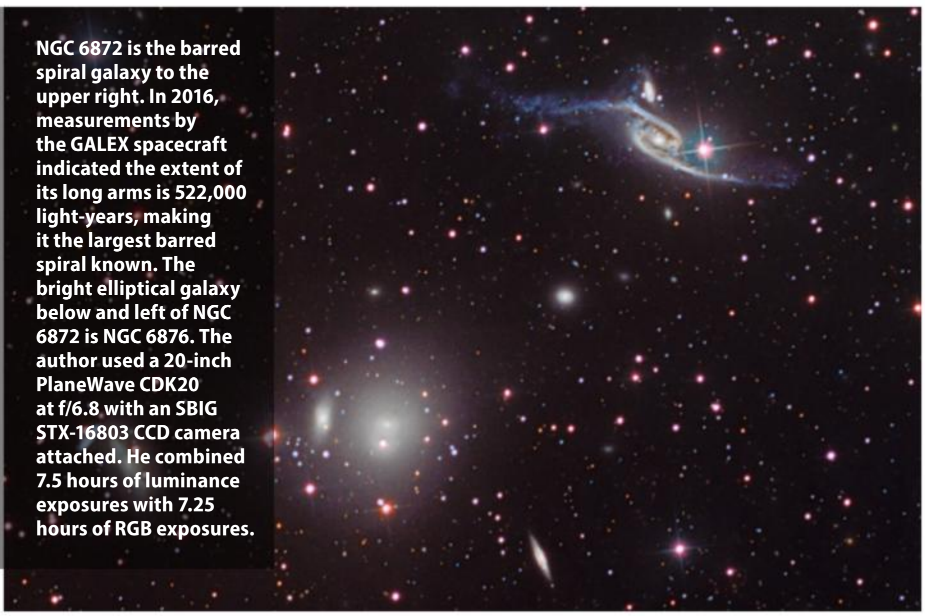


The Jewel Box (NGC 4755) is a stunningly beautiful open cluster in the constellation Crux the Southern Cross. It contains about 100 stars 7,500 light-years away. The author used an RCOS Carbon 12.5-inch Ritchey-Chrétien reflector at f/9 and an Apogee U16M CCD camera. To create the image, he combined five 1-minute exposures through R, G, and B filters.

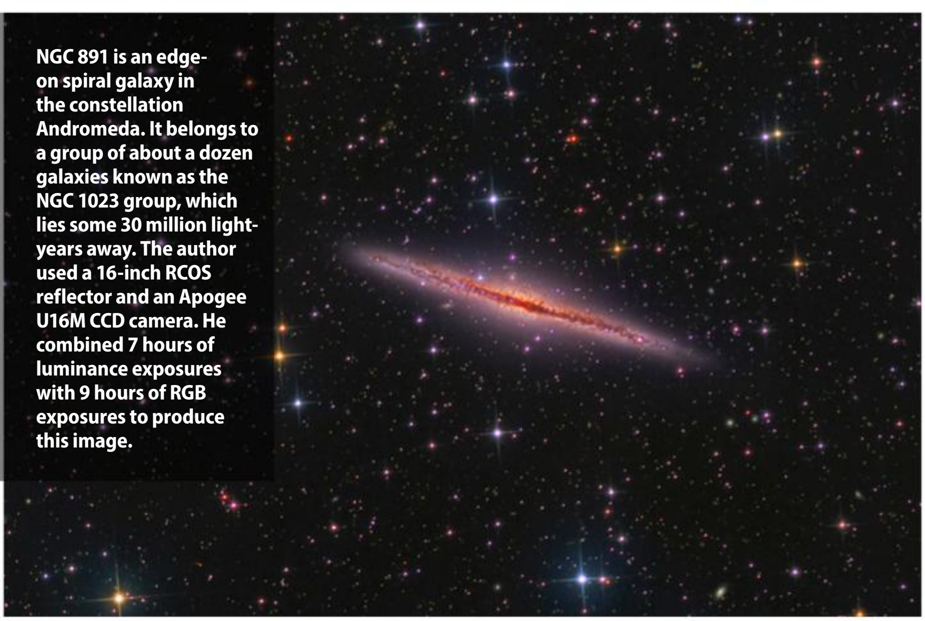


Henize 70 is a superbubble in the Large Magellanic Cloud, a satellite galaxy of the Milky Way that lies some 170,000 light-years distant. Superbubbles form when energetic stellar winds from massive hot stars clear out a bubble from the surrounding gas. The author used a 20-inch PlaneWave CDK20 and an Apogee U16M CCD camera. To create the image, he combined 5.5 hours of Hα exposures with 7 hours of OIII, 7 hours of SII, and 1.25 hours of RGB.

VBRC2 is a planetary nebula some 3,900 light-years away in Vela. This image is the first to clearly show the object's extended halo structure, which the Galactic Planetary Nebula Halo Survey team discovered in August 2014. The author used a 20-inch PlaneWave CDK20 at f/6.8 with an SBIG STX-16803 CCD camera attached. To create this image, the author combined 8.5 hours of Hα exposures with 4.5 hours of OIII and 2 hours of RGB.



NGC 6872 is the barred spiral galaxy to the upper right. In 2016, measurements by the GALEX spacecraft indicated the extent of its long arms is 522,000 light-years, making it the largest barred spiral known. The bright elliptical galaxy below and left of NGC 6872 is NGC 6876. The author used a 20-inch PlaneWave CDK20 at f/6.8 with an SBIG STX-16803 CCD camera attached. He combined 7.5 hours of luminance exposures with 7.25 hours of RGB exposures.



NGC 891 is an edge-on spiral galaxy in the constellation Andromeda. It belongs to a group of about a dozen galaxies known as the NGC 1023 group, which lies some 30 million light-years away. The author used a 16-inch RCOS reflector and an Apogee U16M CCD camera. He combined 7 hours of luminance exposures with 9 hours of RGB exposures to produce this image.

and others bluish cores in the Dumbbell Nebula (M27), for example. They both can't be right. So, I saw it as a design issue.

Also, back then the broadband filters (colorless, red, green, and blue) had different thicknesses compared with the narrowband filters, such as a hydrogen-alpha (Hα) filter. That required you to refocus your telescope in the middle of a run (in other words, in the middle of the night), and few electronically controlled focusers or automation programs existed.

All these factors led me to the initial design of Astrodon filters. I engineered them to be "balanced" for the majority of sensors in the market at the time. This meant that you could combine equal exposures of red, green, and blue with equal weights, use only one dark exposure time (which lets you subtract so-called "hot" pixels — those on your chip that are always on), and get the correct white point and OIII teal color. As I refined my techniques, I made the decision to manufacture all my filters to the same exacting thickness to minimize refocusing as you moved from one filter to the next.

My goal was to help simplify an already technically demanding hobby. I ran my own corporation during the day — building chemical analyzers — so the filter project was an evening adventure on top of an already busy life. At the time, the adage "don't quit your day job" applied.

By the way, I named the company Astrodon to combine "astronomy" and "Don," but did you know that the sauropod *Astrodon johnstoni* is the official dinosaur of the state of Maryland because of the star pattern found in its tooth? My first logo had a dinosaur in it for this reason.

Never in my wildest dreams did I think my part-time venture would grow into a real business that would allow me to sell my day company and retire from the corporate world in 2007. But that's what happened. Astrodon LRGB and narrowband filters are now sold worldwide and are highly sought after for their performance and durability. I actually use them myself!

To grow my business, I improved the filters and expanded the offerings through the years and also engineered photometric filters for professional research. Some of these are customized and need to be quite large (diameters greater than 100mm) for meter-class telescopes, such as the ones at McDonald and Palomar observatories. Now my business funds this amazing hobby that still excites and challenges me.

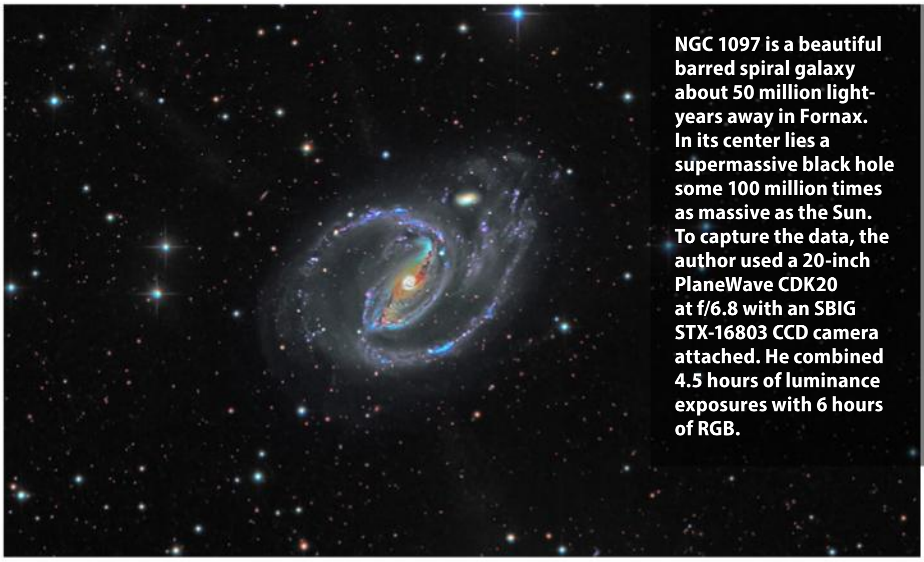
As noted in the story, the author has gotten interested in terrestrial photography. This image is of Castle Geyser, Yellowstone. This geyser is just a 15-minute walk from Old Faithful. He captured it with a Sony a7Rii full-frame mirrorless DSLR and a Sony 16-35mm lens set at f/4 and 18mm. He set the camera at ISO 3200 and took a 20-second exposure.

Passion for photons

That includes imaging from remote, dark sites, like Cerro Tololo, in Chile, the New Mexico Skies Observatories, and the Sierra Remote Observatories near Yosemite National Park. I currently have a 20-inch system at iTelescope.net's remote imaging site at Siding Spring Observatory, New South Wales, Australia. Imaging from the Southern Hemisphere is like finding a new candy store with treats you've never tried.

My interests have focused on narrowband imaging. I like to stay off the beaten track and capture faint halos around planetary nebulae or bring out unusual details in Wolf-Rayet nebulae or supernova remnants. I remember back when I started Astrodon, a color image of a galaxy might require a total of two to three hours of exposure time. Many of my recent narrowband images have taken between 15 and 40 hours depending on how faint the feature is. What amateurs lack in telescopic aperture, we can often make up in the amount of time we spend imaging the object.

Recently, I've expanded my interests into daylight photography, traveling the world with my wife, Nicolle. Processing astroimages is largely about bringing out faint signals while reducing noise. Doing that has helped considerably in my daylight photography processing. Different guidelines apply, such as the rule of thirds, depth of field, and leading lines. Shooting a landscape or wildlife isn't exactly the same as centering a spiral galaxy with everything in focus. But then, a galaxy doesn't fly away when you point the telescope toward it, as wildlife sometimes does.



NGC 1097 is a beautiful barred spiral galaxy about 50 million light-years away in Fornax. In its center lies a supermassive black hole some 100 million times as massive as the Sun. To capture the data, the author used a 20-inch PlaneWave CDK20 at f/6.8 with an SBIG STX-16803 CCD camera attached. He combined 4.5 hours of luminance exposures with 6 hours of RGB.

When I've submitted astrophotos of galaxies or nebulae to our local camera club competitions, the judges often do not quite know how to critique them, because they don't know what they're looking at. There is no common frame of reference for most people. However, take a picture of the Milky Way rising over a bristlecone pine or above an arch in Canyonlands National Park in Utah, and everyone gets it.

Sensing no cure for the photo bug that's bitten me, I hope to continue imaging bright daytime scenes, dimly lit nightscapes, and ultra-faint deep-sky objects for many more years — all to show what a truly spectacular universe we live in.

Don Goldman *runs Astrodon from his home in Roseville, California.*

Observe with both eyes open

Binoculars provide a great way to take in lots of sky. And the newest models have improved the classic design.

by Phil Harrington

Even in this age of advanced amateur telescopes, one of the most useful and versatile tools for viewing the universe remains binoculars. Not only are they portable and easy to use, but binoculars also let us enjoy the night sky as it was meant to be viewed — with both eyes.

I've long preached that when it comes to stargazing, two eyes are better than one. Using both eyes is more relaxing than squinting through a conventional telescope, and it also feels more natural.

Beyond the aesthetic appeal, binocular vision also increases an observer's perception of objects, borne out by ophthalmological studies. Experts refer to this effect as binocular summation. Depending on the type of object you're viewing, the brain processes up to 40 percent more information using both eyes instead of just one.

But which binoculars are right for you? Today, thousands of choices flood the market, but not all are geared toward stargazing. Some are better used for daytime viewing. Others fit into a purse or jacket pocket, to be taken to the theater or a sporting event. The hints offered here will help you decide whether a particular model is suitable for viewing the night sky.

The basics

Think of binoculars as two small refractors mounted parallel to one another. Like refractors, light enters each side through an objective lens and exits through an eyepiece. Internal sets of prisms reflect the light until the image exiting the eyepieces appears right side up.

Two types of prism assemblies are used in today's binoculars: Porro and roof prisms. Roof prism binoculars have sleek, straight barrels, thanks to how closely the assemblies fit together. The more common design uses Porro prisms, which you can recognize immediately by their familiar zigzag tubes, a result of the path light follows while traveling through the prisms.

Regardless of prism design, you can size up all binoculars by two numbers separated by an "x," such as 7x50 or 10x70. The first number is the magnification, and the second refers to the aperture, or the diameter of the front lenses, in millimeters.

Magnification is an important consideration when selecting binoculars. Low power binoculars (up to 10x) are great for wide views, but observers prefer higher power (11x and above) for the Moon, the Sun (using safe filters), and planets.

Selecting the proper aperture is just as important as choosing the right magnification. For best results, the objectives' diameters should be matched to your eyes as well as your observing site.

The pupil, the central opening of the iris, controls how much light enters each of our eyes. For most people, the pupil contracts to about 2.5mm in bright daylight and dilates (widens) up to 7mm in darkness. You'll get the best results when the diameter of the beam of light exiting the eyepieces, known as the exit pupil, is no larger than the diameter of your pupil.

You can calculate the approximate exit pupil of any binoculars by dividing the aperture by the magnification. So every 7x50 model has 7mm exit pupils.

If you're 30 years old or younger and do most of your observing under dark rural skies, your eyes' pupils should dilate to about 7mm. So, choose binoculars that produce a 7mm exit pupil, such as 7x50, 10x70, or 11x80. But if your location suffers from light pollution, or if you are older than 30, your pupils may never dilate beyond 5mm. You'll do best by selecting binoculars with a smaller exit pupil, such as 7x35 or 10x50.

OBERWERK MARINER 8X40

Another important consideration is eye relief, the distance from the eyepieces to where the observer sees the full field of view. Opticians express this value in millimeters, and for binoculars it typically ranges between 10mm and 20mm. If you must wear glasses for viewing (to fight astigmatism, for example), eye relief should be no less than 18mm.

For this survey, I've divided binoculars into two broad categories based on size and weight: hand-holdable and tripod-required. But first, a note: Some readers may be able to support heavy binoculars by hand. Remember, it's not just being able to pick up the binoculars for a casual glance. To survey the sky, you need to hold them steadily for minutes on end.

Hand-holdable

Binoculars light enough to support by hand typically range up to 56mm in aperture and weigh no more than 36 ounces (1 kilogram), although even that's a bit heavy for long-term use. The IS designation in Canon's **15x50 IS All Weather binoculars** ($960) stands for image-stabilized. Bring the binoculars to your eyes, find whatever it is you're looking for, and then press a button. The image appears to lock into place. The technology works great, and Canon optics make the image quality top-notch. This combination does not come cheaply, but for many it is money well spent.

At the other end of the price scale is Celestron's **Cometron 7x50**, which retails for only $35. Despite the low price, image quality is surprisingly good. Admittedly, the optics don't measure up to some of the others profiled here, but the price is better. If you are looking to give a budding young stargazer his or her first binoculars, you can't go wrong here.

If you have young eyes and are viewing from a dark location, Celestron's **SkyMaster DX 8x56** ($189), which sports a 7mm exit pupil, is a good choice. Thanks to multicoated optics, nitrogen-purged barrels to prevent fogging, and high-quality prisms, these deliver sharp, bright images. Be aware, however, that they weigh 38 ounces (1.1kg), which is on the heavy side. They would benefit from being braced.

The small size of Oberwerk's **Mariner 8x40** ($149.95) binoculars makes this unit ideal for viewing on the go. The field of view is wide, perfect for sweeping the Milky Way. Images have high contrast and are razor-sharp. The rubber-armored metal construction is rugged enough to handle bumps, but it does add a bit of weight that some may find fatiguing over time.

An excellent middle-of-the-road model is Orion's **Scenix 10x50** wide-angle binoculars ($102.99). This choice won't break the bank, but it has high-quality multicoated optics and a wide field of view. Focusing is smooth and precise, and images are sharp and clear.

Phil Harrington *writes the Binocular Universe column for* Astronomy. *He also serves as a contributing editor.*

ORION ULTRAVIEW 10X50

For a little more money, Orion's **UltraView 10x50** ($175.99) and **Resolux 10x50** ($288.99) are also outstanding choices. Both include fully multicoated optics for excellent image contrast and brightness. The Resolux is also waterproof. Each offers generous eye relief (22mm and 18mm, respectively) for eyeglass wearers.

Tripod-required

Giant binoculars add a dimension to backyard astronomy that telescopes simply can't compete with. But to enjoy this to the fullest, a tall, sturdy tripod is a must.

Celestron's **SkyMaster Pro 15x70** ($199.95) is competitively priced and produces images that are bright and contrasty. While you absolutely should use a support to get the most out of these binoculars, they are also light enough (3.5 pounds, 1.6kg) to hold by hand for quick views of favorite targets.

You won't be holding Celestron's hefty **SkyMaster 25x100** ($399.95) by hand for long, but the views are staggering once you properly secure it. This model tips the scales at 8.8 pounds (4kg). A reinforcing bar bridges between the objectives for added stability, and a permanently attached tripod adapter slides back and forth along a bar for easy mounting and balancing.

Many stargazers agree that binoculars don't come much better than Fujinon's **16x70 Polaris FMT-SX** ($920). Images snap into clarity as the observer focuses each eyepiece. And when you're in focus, everything is in focus all the way to the edge of the field. There is no hint of field curvature or other common optical faults that plague lower quality glasses.

As you would expect with anything carrying the Nikon name, the **Astroluxe 18x70IF WP WF** binoculars ($1,799.95) are remarkable. Images are tack sharp with great contrast. The individually focused eyepieces feature wide apparent fields for panoramic views. Nikon's optional tripod adapter is required because there is no built-in adapter like most others of this genre.

One of our Star Products for 2013, Oberwerk's **BT-70-45** Binocular Telescope ($849.95) is unique among all models featured here. True, it does include triplet objective lenses and fully multicoated optics, but what makes the BT-70-45 stand above the crowd is how both prism housings are tilted 45° for more comfortable sky viewing. And did I mention that the eyepieces are interchangeable? Oberwerk sells several matched pairs, but you can use any set of 1¼" eyepieces.

Finally, we have Zhumell's **25x100 Tachyon** binoculars. Binoculars this large can cost $1,000 or more. Not these. Although Zhumell lists them at $499, you can find them online for less than half that. These monsters are built around two fully multicoated 4-inch objective lenses. Their large aperture and high magnification translates to a greater depth of deep-sky penetration. Although the eyepieces are not removable, they are threaded to accept 1¼" filters. As a result, they represent one of the best buys in astro-binoculars today.

The bottom line

Any of these binoculars will sate your astronomical curiosity. If you can move up in price beyond the starter units, you'll reap the benefits of larger apertures, higher-quality optics and smoother operation. And you'll discover that, like I always say, two eyes are better than one.

CELESTRON SKYMASTER 25X100

A quick guide to scopes for kids

Gifting the right equipment doesn't need to be a daunting task.

by Tom Trusock

The first rule for choosing a telescope for a child is to start him or her off with decent gear. With the recent explosion in imported and inexpensive equipment, you should be able to accomplish this fairly economically.

For a teenager, a gift of binoculars might be a good option, but they aren't the easiest to share. And for young kids, you'll probably have a hard time getting the binoculars pointed in the right direction. Additionally, inexpensive models won't weather much abuse.

I'd also steer clear of go-to and other electronic add-ons. While the bleeps of the computerized world are tempting, inexpensive telescopes with such options tend to try to do too much for their price point. This results in a frustrating evening for adults and children. Typically, I don't even recommend a motorized drive on a first telescope. It's just one more thing to power, one more thing to fiddle with, and one more thing that can fail. Keep things as simple as possible.

Refractor or reflector?

A small refractor with a lens about 3 inches (75 millimeters) in diameter would be a decent choice. Just make sure it comes with a sturdy mount. A setup like this will be portable, require little to no maintenance (in the form of collimation, optical alignment), and be relatively child friendly.

One option to consider is a scope offered by Explore Scientific. Listed under the catchy name **FL-AR80640TN** ($149.99), this 3.15-inch refractor measures a bit more than 2 feet long, and comes with a 25mm eyepiece (which provides a usable magnification of 25x), a red-dot finder, and a decent altitude-azimuth mount (one that operates like a camera tripod). It provides great views of the Moon, planets, and brighter deep-sky objects.

I love refractors, but with telescopes, aperture (the diameter of the main lens or mirror) rules. If you're looking to stay in the same price range as my previous choice, you might consider something like Meade's **LightBridge Mini 114mm Dobsonian Telescope** ($149). This 4½-inch reflector is a counterpart to the refractor I mentioned earlier, although it's not quite as resistant to hard use.

The "Dobsonian" in the name refers to the mount for this scope. Invented by amateur astronomer John Dobson, it's the simplest type of mount for reflectors. Essentially, you aim the scope by moving it up and down and left and right.

Compared with an inexpensive refractor, a reflector will show better color (no purple fringes) on bright objects like the Moon and Venus. Because of the larger aperture, they provide a brighter image and thus support more pleasing high-power views.

However, because a reflector usually has such a short focal length, it will also require careful collimation for best performance. You'll

Explore Scientific's FL-AR80640TN

also need to supply a table to bring it to a usable height. That can be a drawback if you're trying to keep things simple.

I'd recommend a reflector on a Dobsonian mount, even though it requires a bit more space. The typical configuration is either an 8-inch f/6 or a 6-inch f/8. Both measure about 4 feet long and give the same magnifications whichever eyepieces you use. The 8-inch model will give you a brighter image, though, because its larger mirror captures 78 percent more light.

Both can bring enough celestial wonders into view to keep a budding amateur astronomer busy for a long time. Both also have multiple upgrade paths and are available in reasonably priced starter kits from various sellers. Older children will appreciate the light-gathering power of the 8-inch, while younger ones will like the smaller physical size of the 6-inch.

A few choices

For younger or smaller individuals, a 6-inch telescope still might be pushing it in terms of size. In these cases, I recommend Orion's **SkyQuest XT4.5 Classic Dobsonian Telescope** ($249.99).

A 4½-inch scope offers more than twice the light-gathering ability of a 3-inch while sporting a lightweight and portable

Meade's LightBridge Mini 114mm Dobsonian Telescope

package. This telescope weighs just over 17 pounds (8 kilograms), making it easy to pick up and maneuver. The included handle and tension springs will let adults and large children carry the telescope outdoors in one piece, and the navigation knob makes the tube easy to guide to the next target.

As a bonus, Orion includes an eyepiece rack and two decent Plössl eyepieces: 25mm (36x) and 10mm (91x). The focuser is firm yet responsive, and the mount is smooth enough that even tracking with the higher-power eyepiece isn't an issue. The scope provides a nice view of the Moon, the rings of Saturn, the belts of Jupiter, and many bright deep-sky objects. Open star clusters look pleasing through this telescope.

Orion does include a 6x26 finder scope, but I'd replace it with a BB gun or Reflex finder, found online for as little as $15. In my experience, it's much easier for beginners to "put the red dot on that part of the sky" when learning how to star-hop than to interpret the image they see through a finder scope.

Finally, Orion includes a download link to a special version of the company's Starry Night software to help observers plan their evenings. My daughter will attest that it's a fun way to spend a cloudy evening.

Children also will need a red flashlight and star charts. You'll find a great starter chart in the center of this magazine. Traditional finder charts and an inexpensive lunar map are something else you'll want to acquire. Several out there are geared toward beginners, but you might want to specifically look for star charts that combine the maps with additional information.

Over the years, I've found that everyone enjoys a good story. I recommend *A Walk through the Heavens: A Guide to Stars and Constellations and their Legends* by Milton D. Heifetz and Wil Tirion. It's a simple guide to discovering the constellations and finding your way around the night sky. Plus, it collects many fascinating ancient myths of the heavens.

Pass on what you know

Gear is fun, and a kid-friendly telescope is a great start toward getting children involved in the hobby. Keep in mind, however, that the most precious gift you can give a child is one that doesn't cost a dime: your time. Nothing will replace it, and nothing will stir interest faster. We spend a lot of effort trying to protect and promote our night skies. Isn't it time to start involving its inheritors?

Tom Trusock *is an astronomy equipment guru who actually uses the stuff from his home in Ubly, Michigan.*

Orion's SkyQuest XT4.5 Classic Dobsonian Telescope

Mallincam ships a complete package with its DS2.3 Plus, including cables, software, and a C-mount adapter.
J. THOMPSON

Get started in VIDEO ASTRONOMY

Mallincam's SkyRaider DS2.3 Plus is adept at both solar system and deep-sky video imaging. **by Jim Thompson**

I CAN RECALL PRECISELY THE DATE that I fell in love with using a video camera for astronomical viewing. It was August 26, 2010, the first night I looked at the Moon through an old security camera that I had jury-rigged to my telescope.

Back in 2010, there were few commercially available astro-video camera choices, but that situation has changed. More recent cameras generally have filled specific roles, like cameras with high frame rates for solar system imaging, or those with high sensitivity and low noise for deep-sky work. But few were good at both. That is, until now.

Last year I had an opportunity to try out the Mallincam SkyRaider DS2.3 Plus. During the six months that I had the camera, I tested it on a variety of celestial targets, on a range of telescopes, and under both light-polluted and dark skies.

What's in the box?

When I received it, the camera arrived in a sturdy cardboard box. The package included a rubber dust cap, a 1¼" nosepiece, a 15-foot-long (4.6 meters) USB cable, a 10-foot-long (3m) ST-4 guider cable, and an installation disk.

The DS2.3 Plus is a 2.3-megapixel one-shot color camera containing a Sony IMX302 Exmor CMOS sensor. The sensor measures 13.4mm diagonally and has pixel dimensions of 5.86 x 5.86 micrometers. Potential exposure times range from 25 microseconds to just over 16 minutes with a maximum frame rate of 30 per second.

The camera body measures 80mm wide and 85mm long, and has an integrated fan-cooled heat sink to regulate its temperature. The camera has a standard T-mount interface but also comes with a C-mount adapter. The camera body with its C-mount adapter weighs just under 1 pound (430 grams).

The machining and finishing of the all-metal casing is of high quality, and the little details — such as a sealed sensor chamber, a robust USB 3.0 B-type connector, and a whisper-quiet cooling fan — combine to make a top-notch product.

Getting started

To use the camera, I first installed the drivers and software on my computer. All files necessary were on the provided disk, but I also would have been able to download them from the Mallincam website. I then started the software and plugged the camera into my computer's USB port. I found the software easy to use, with all the camera functions organized in expandable tool boxes along the left-hand side of the screen.

The software comes with a large assortment of features. These include gain and exposure controls, color and gamma adjustments, a histogram with adjustable black and white points, and adjustments for regions of interest, crosshairs, live stacking with star alignments, and dark field correction. The last feature lets you record a number of frames with the telescope covered and then subtract them from the live image.

Installing the camera on my telescope was as easy as slipping an eyepiece into the focuser. The 1¼" nosepiece turns it into essentially a big, fancy eyepiece. For those unfamiliar with video astronomy, scope alignment and focusing is normally a breeze, with the same being true using the DS2.3 Plus. I set the camera exposure to one second and gain at maximum, which gave me a view with plenty of stars visible and a fast refresh rate. This made it easy to focus and to navigate around the sky to perform my mount's alignment routine.

Sun, Moon and planets

Mallincam doesn't market the DS2.3 Plus as a solar system imager, but I decided to try it in that role nonetheless. First up was the Moon. I had some concerns that the moderately sized sensor pixels of the DS2.3 Plus would hurt its ability to capture fine detail and that I'd need more magnification. Typically that means longer exposure times, which in turn allows more atmospheric distortion.

In the end, I found that the high sensitivity of the IMX302 sensor allowed for generally low exposure times. This sensitivity extends well into the infrared, allowing for the use of an IR pass filter to further improve the image quality.

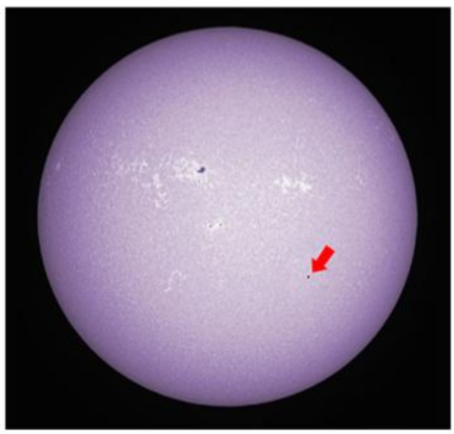
I then aimed it toward visible planets. On the first evening, I had a look at Jupiter with the IR pass filter. Imaging Jupiter in IR can reveal details in cloud features that you cannot discern visually. Later on, I imaged Jupiter again, but in the visual band, along with Mars and Saturn. Saturn was near the horizon, so I'm surprised I got a useful image. My image of Mars, however, is probably the best I have ever captured from my location in Ottawa, Canada.

Finally, I observed the Sun with the DS2.3 Plus. I used it with white-light, Calcium-K, and Hydrogen-alpha filters. I also had a rare opportunity to use the DS2.3 Plus to observe the May 9, 2016, Mercury transit from the lawn in front of the Canadian Parliament buildings. It was quite an experience sharing my live view of the event with the public and a number of dignitaries, including retired Canadian astronaut Marc Garneau. In all cases, I found the camera worked well for solar imaging, again due to its high sensitivity, which allows short exposure times.

Deep-sky video observing

For many, the main attraction to the DS2.3 Plus is its ability to provide a live view of sky objects. I tested the camera in my light-polluted backyard and from the relatively dark skies at the family cottage. Most of my previous experience had been with an analog video camera with an 8mm sensor that produced a standard

This close-up view of the camera's back panel shows the cooling fan and cable connections. MALLINCAM



The author imaged Mercury (arrow) transiting the Sun on May 9, 2016. He used a William Optics FLT98 refractor at f/6.3, an Omega Optical CaK filter, and took a 4-millisecond exposure. J. THOMPSON

definition signal. Stepping up to the DS2.3 Plus gave me 7.5 times the resolution plus a 68 percent increase in field of view for the same scope and focal ratio. The result was a big improvement in image quality.

From my backyard, the DS2.3 Plus performed well on bright objects such as those in Messier's catalog. Faint details were easier to see when I used the built-in live stacking function, and color was easy to adjust using the push-button white-balance tool. The histogram tool made it simple to fine-tune the image, and the gamma setting allowed me to brighten faint regions if I needed to.

I found it most convenient to record a library of dark frames at different exposures and gains beforehand that I was able to call up later during my observing session. I also tried for a few dimmer objects, but those were much better when I was under darker skies.

My only complaint with this camera is that there's a delay after you change

The author captured the Tycho-Clavius region of Moon on April 16, 2016, by connecting the DS2.3 Plus to his 10-inch Ritchey-Chrétien reflector at f/20, using a Baader Moon & Skyglow filter and taking a 20-millisecond exposure. J. THOMPSON

PRODUCT INFORMATION

Mallincam SkyRaider DS2.3 Plus
Sensor: CMOS (13.4mm diagonal size)
Pixels: 2.35 megapixels (1936x1216)
Connectivity: USB 3.0
Dimensions: 3.1 by 3.4 inches (79 by 86 millimeters)
Weight: 15.1 ounces (429 grams)
Price: $899.99
Contact: Procom Electronics
56–5450 Canotek Road
Ottawa, Ontario, Canada K1J-9G4
613.749.7592
www.mallincam.net

settings in the software before you see the effect. User setting changes are not implemented until the next frame refresh. So, if your exposure time is 60 seconds, you'll wait that long to see the impact of your change. This slows down imaging, especially when you use long exposure times.

Jack of all trades

All things considered, Mallincam's DS2.3 Plus is a highly capable camera. I didn't try the camera in a traditional astrophotography role, but there is no reason why you couldn't use it for that. There may be a better-performing camera for doing only solar system imaging or only deep-sky observing, but if you are looking for a camera that gives good results at everything, the DS2.3 Plus is the one for you.

Jim Thompson *is an aerospace engineer working for the defense industry in Ottawa, Canada. He enjoys beating back the light pollution of his backyard using video astronomy.*

ASTRO**SKETCHING**

BY ERIKA RIX

Kepler near the terminator

Practice your lunar sketching technique on this large, easy-to-spot crater.

A couple of days after First or Last Quarter Moon, train your telescope toward the eastern shores of Oceanus Procellarum. You'll be treated to an impressive view of Kepler Crater and its complex ray system that spreads across the dark basaltic plains. The nearby terminator (the line that divides night from day) will advance 0.5° each hour, so you'll need to work swiftly to render the scene before it changes significantly.

I start with black paper to represent the vast shadow area along the terminator, and I draw the sunlit features in white. You'll need a sheet of black sketching paper (one suitable for pastels) attached to a clipboard, a stick of white hard pastel, a white pastel pencil, and a black charcoal pencil.

You'll also want to add blending stumps of various sizes, cleaned and sharpened with sandpaper. Because the Moon is so bright, using a soft white light to see what you're sketching won't affect your dark adaption.

Kepler is a relatively young crater that formed during the Copernican period of lunar history (1.1 billion years ago to the present). The impact ejected bright material already at the site (ejecta from the formation of the Imbrium Basin 3.8 billion years ago) and created Kepler's pronounced ray system.

I began by drawing the terminator's gray backdrop (Figure 1). I put the pastel stick on its side and rubbed a broad 7-inch swath of chalk across the length of my paper. I continued inward by several inches to include the area for Kepler and its rays, and then blended it with my fingertips. Then, with the pastel pencil, I added the bright highlights that reach across the terminator. To maintain accurate proportions, I concentrated first on the distinguishing features toward the middle and either ends of the terminator before filling in the gaps.

Next, I refined the shading around the terminator with a charcoal pencil (Figure 2). I adjusted the pencil's pressure as needed for tonal variances. For smooth areas like maria that require the softest shading, I used a clean blending stump. I rubbed away layers of pastel to reveal hints of the paper below.

Then I drew Kepler's bright rim and shadows and added the surrounding craters (Figure 3). If you struggle with the three-dimensional relief, try visualizing a range of tones and shapes rather than the crater and its surrounding terrain. I alternated between the white pencil to draw the rays and a large blending stump to form the dark maria within them.

In my final step (Figure 4), I refined the ray network and retouched areas that became softened during the sketching session. Here's an extra tip: I preserve my pastel sketches by spraying them afterward with a workable fixative.

Questions or comments? Contact me at erikarix1@gmail.com.

Figure 1. The author used a white Conté pastel pencil to draw sunlit areas along the Moon's terminator. ALL SKETCHES: ERIKA RIX

Figure 2. She then added dark shadows near the terminator with a charcoal pencil. She formed soft shadows and maria by rubbing excess white pastel from the paper with a clean No. 4 blending stump.

Figure 3. Working inward from the terminator toward the sunlit portion of the Moon, the author included more detail, starting with highlights, then the shadows, and finally the bright ejecta that formed the rays. She used a No. 6 blending stump to draw the larger darkened portions of maria.

Figure 4. The author completed this sketch June 16, 2016, between 3h20m and 4h45m UT, while observing through a 6-inch Ritchey-Chrétien telescope on a German equatorial mount. She used an 8mm eyepiece for a magnification of 172x. The author also used a 13 percent neutral density filter to reduce the Moon's brightness for eye comfort and to enhance contrast. The sketch media consisted of a 9-by-12-inch sheet of black Strathmore Artagain paper, a white Conté pastel pencil and crayon, a black charcoal pencil, and No. 4 and No. 6 blending stumps. The sketches have south at the top and west to the left.

Erika Rix is co-author of Sketching the Moon: An Astronomical Artist's Guide *(Springer-Verlag, 2011).*

FOR**YOUR**CONSIDERATION

BY JEFF HESTER

Entropy redux

Why our universe isn't boring.

I had so much fun writing about entropy last month that I just couldn't stop! To catch you up on our sojourn through one of the most important but misunderstood ideas in science, here is a quick summary:

Disorder, schmisorder!

The Second Law of Thermodynamics is as much about building structure and complexity as it is about tearing them down. Last month I followed the entropy of an interstellar cloud as it collapsed to form stars and planetary systems. All of that complexity arose from a random, unguided progression toward more and more statistically likely configurations.

As it goes for stars and planets, so it goes for life, the universe, and everything. Not only can increasing entropy lead to structure and complexity, increasing entropy is the only thing that can produce complexity.

Let me explain. Shortly after the Big Bang, the universe was small, dense, and hot. The particles and radiation filling the universe were in thermodynamic equilibrium, which is just shorthand for saying that their entropy was as high as it could be. Had that been the end of the story, the universe would be a very boring place indeed. With no way for entropy to increase, nothing would have changed. There would be no galaxies, no stars, no planets, no nothing!

Fortunately for us, there was more to it than that. For reasons that remain unclear, but may have to do with the effects of cosmic inflation, the gravitational entropy of the early universe was much, much smaller than it might have been. The gap between what the entropy of the universe is and the maximum that it could be gives The Second Law elbowroom to do its thing.

The gap between actual and maximum possible entropy represents possibility.

Which brings us to what for many is the sticky wicket: entropy and life. Quoting Henry Morris of the Institute for Creation Research, "The law of increasing entropy is a universal law of decreasing complexity, whereas evolution is supposed to be a universal law of increasing complexity. … This, indeed, is a good question, and one for which evolutionists so far have no answer."

Mr. Morris needs to get out more. The dismissive tone of his pronouncement does not change the fact that he doesn't know statistical physics from cow dung.

Reiterating, quite often the most likely path to increasing entropy globally involves decreasing entropy locally. Granted, accomplishing a local decrease in entropy requires energy. In the case of the interstellar cloud, that energy was gravitational, but other sources of energy will do. If you have ever paid a summer electric bill in Phoenix, your bank account understands the concept.

An air conditioner sucks heat out of already cool air, then exhausts that heat into already hot air. That's about as uphill for entropy as it gets! I wonder if Mr. Morris marvels at the magical violation of the Second Law that keeps the temperature of his house pleasant. But there is no Second Law violation here. The energy dissipated (and entropy produced) powering the compressor and fan more than makes up for the entropy lost pumping heat from cold to hot.

Creationists sometimes claim that entropy stands in the way of evolution. But in doing so they fail to understand both entropy and evolution. Both were already underway in the earliest forms of life, as with these (modern) stromatolites in Shark Bay, Western Australia. PAUL HARRISON/CREATIVE COMMONS

So, what about life? Life isn't plugged into the electrical grid, but we do have a handy fusion reactor nearby, along with an efficient energy-delivery system. Earth absorbs visible sunlight. That incoming energy is balanced by infrared light radiated into space. There are roughly 20 times as many reradiated infrared photons as there are absorbed visible photons. With 20 times as many photons to play with, there are a lot more ways of arranging things; the entropy of the reradiated infrared is far greater than the entropy of the absorbed sunlight. A lot can ride on the back of that huge increase in entropy.

In 2009, physicist Emory Bunn of the University of Richmond did a fun calculation. He started by making a very generous estimate of just how much localized decrease in entropy was needed to account for the evolution of life on Earth. Then he compared that with the rate at which absorption and reradiation of sunlight produces entropy. What he found is that all 4 billion years of the evolution of life can be "paid for" with just a few months of Earth's entropy budget.

Putting that into terms that even Mr. Morris should be able to understand, claiming that entropy stands in the way of evolution is, quite literally, like saying that a billionaire can't afford a stick of gum.

The next time you see a thunderstorm building overhead, or watch the flapping of a hummingbird's wings, or hear a child's laughter, smile and think about the beauty of the structure and complexity that surround us. The Second Law of Thermodynamics may get a bad rap, but any way you slice it, entropy rocks!

Jeff Hester is a keynote speaker, coach, and astrophysicist. Follow his thoughts at **jeff-hester.com.**

BROWSE THE "FOR YOUR CONSIDERATION" ARCHIVE AT **www.Astronomy.com/Hester.**

BINOCULARUNIVERSE

BY PHIL HARRINGTON

Sparkling star clusters

Check out dazzling star groups under a dark sky.

Of the dozens of open star clusters scattered across the autumn sky, none is finer through binoculars than NGC 869 and NGC 884, the famous **Double Cluster** in Perseus. Even from suburban backyards, this striking pair shows up to the naked eye as a faint, elongated smudge of light about halfway between the "W" of Cassiopeia and the northern tip of Perseus.

If you have trouble spotting it, scan through your binoculars along a line extending from Gamma (γ) Cassiopeiae, the center star of the W, through Ruchbah (Delta [δ] Cassiopeiae) and continuing toward the southeast. Maintain a straight course, and you will see both clusters as two clumps of stars.

Few autumn clusters compare to either NGC 869 or NGC 884 alone. But when you add both together, the field literally overflows with stars. And unlike many star clusters, which need telescopes to be seen at their best, NGC 869 and 884 are just as wonderful through binoculars. In fact, in my opinion, while they are impressive through telescopes, the narrower views sacrifice the area's overall beauty.

Seven- to 10x binoculars resolve each cluster into a tight knot of white stars against a star-strewn backdrop. Higher-power giant binoculars only improve the view by increasing resolution as well as heightening the radiance of the many colorful suns scattered across the region.

Last fall, I had a chance to view the clusters through monstrous 25x100 binoculars as the pair rose just above some distant pine trees. The field overflowed with stardust, pouring over and around the distant pines. The view was magnificent, creating a magical moment that could never be captured in a photo, but whose image is forever filed away in my mind's astronomical album.

The Double Cluster in Perseus is simply one of the best open clusters in the sky — a beautiful sight in binoculars. THOMAS V. DAVIS

History doesn't record who discovered the Double Cluster, but we do know that their combined presence attracted the eyes of Hipparchus back in the second century B.C., when he mentioned them in his notes. Three centuries later, Ptolemy recorded them in the *Almagest* as a nebulous or misty spot at the tip of Perseus' right hand. Messier apparently knew of the Double Cluster, but never recorded them in his catalog. Why he ignored them but included the likes of M73 (a four-star asterism in Aquarius) is difficult to understand.

Are the two clusters actually physically linked to one another? They almost certainly have some gravitational effect each other, since NGC 869 (the westernmost cluster) is 7,100 light-years away, while NGC 884 is slightly farther at 7,400 light-years. Both are primarily composed of hot type A and type B supergiant, superluminous stars. Some 200 call NGC 869 home, while NGC 884 is made up of about 150. Several red supergiants are seen in NGC 884, but are conspicuously absent in NGC 869.

After you have enjoyed the Double Cluster, follow an arc of stars to the north, crossing into Cassiopeia. Look there, about 2° north of the Double Cluster, for a somewhat rectangular clumping of faint stars. That will be **Stock 2**, a little-known open star cluster that stands out remarkably well through binoculars despite its crowded surroundings.

Stock 2 is an often overlooked, scattered, and very attractive open cluster for binocular observers. DAN CROWSON

Stock 2's 50 member stars cover a full degree of sky, the same as two Full Moons stacked end to end. About 20 of these stars can be resolved through 10x binoculars, although they only shine between 7th and 9th magnitude.

Take a long, careful look at the stars in Stock 2 and let your imagination run wild for a moment. See any pattern among them? Careful scrutiny will show that the stars seem to fall into four distinct threads curving away from the center.

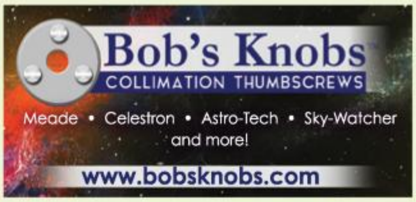
My longtime friend John Davis from Amherst, Massachusetts, has mentioned to me that the brighter stars look like a headless stick figure flexing his muscles. He christened it the "Muscleman Cluster." Can you spot him? His legs stretch out in two straight lines to the east, while his flexing arms curve to the west.

Imagine Stock 2 as a muscleman, figure skater, or ballerina as you wish. The next time you are enjoying the beauty of the Double Cluster, be sure to swing northward to enjoy this underappreciated beauty.

I'd love to hear about your binocular adventures and conquests. Contact me through my website, philharrington.net.

Until next month, remember that two eyes are better than one.

Phil Harrington is a longtime contributor to Astronomy *and the author of many books.*



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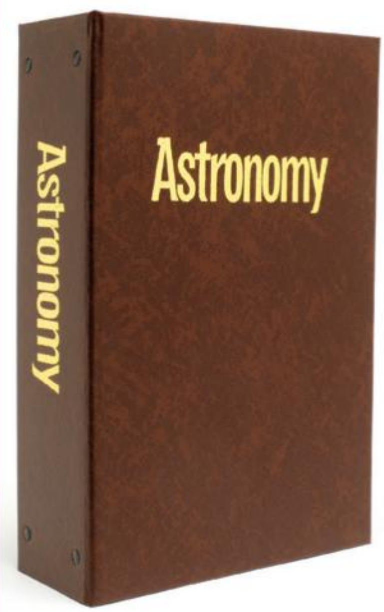


READER GALLERY

1. DARKNESS AND LIGHT
This three-part panorama shows the Milky Way beginning to set from central Brazil. The amazing aspect of this image is the amount of dark nebulosity blocking the light from millions more stars that ordinarily would be visible. • ***Carlos Eduardo Fairbairn***

2. GALAXIES, ASSEMBLE!
M49, the large elliptical galaxy on the right-hand edge of this image, belongs to the huge Virgo Cluster. Astronomers estimate that M49 contains nearly 6,000 globular clusters, compared with our galaxy's 157. M49 also interacts with UGC 7636, the small dwarf irregular galaxy just below and to the left of it. • ***Dan Crowson***

3. CRIMSON DYNAMO
Open cluster NGC 6823 is surrounded by a spectacular array of red emission nebulosity known as Sharpless 2–86. There's also a lot of dust in the region. The small fan-shaped nebula at upper left is NGC 6820. • ***Bruce Waddington***


1


2


3

4. STARRY, STARRY SIGHT
You'll find open clusters M46 (left) and brighter M47 (right) in the constellation Canis Major. Few photographers have captured them in the same frame. Note that M46 has a partner. And although it appears that planetary nebula NGC 2438 lies within the cluster, it's actually about 2,000 light-years closer to us. • ***Burley Packwood***

5. GALACTIC TANGO
Tidal forces rule the day as a large spiral galaxy, NGC 2207, collides and interacts with a smaller barred spiral, IC 2163. The pair lies some 60 million light-years away in the constellation Canis Major. • ***Warren Keller/Steve Mazlin/Mark Hanson/Rex Parker/Tommy Tse***

6. TWILIGHT PAIRING
The crescent Moon and Venus hang in the morning sky May 22, 2017, as seen from Dayton, Ohio. The photographer even got their reflections from the back of his car, despite it being covered with dew. • ***John Chumack***

7. BLUE ON BLACK
The Iris Nebula, often referred to as NGC 7023, is one of the most famous reflection nebulae in the sky. Its vivid blue color contrasts nicely with the clouds of dark nebulosity that surround it. But "NGC 7023" refers only to the star cluster within the gas. Officially, the larger blue nebula is LBN 487. • ***Terry Hancock***

Send your images to:
Astronomy Reader Gallery, P. O. Box 1612, Waukesha, WI 53187. Please include the date and location of the image and complete photo data: telescope, camera, filters, and exposures. Submit images by email to readergallery@astronomy.com.

BREAK THROUGH

The final frontier

The Hubble Space Telescope recently wrapped up a three-year imaging project to study some of the universe's earliest galaxies. The Frontier Fields program targeted six massive galaxy clusters, each of which acts as a gravitational lens to magnify and warp the feeble light from background objects. Hubble scientists completed the program with observations of Abell 370, a cluster of several hundred galaxies that lies roughly 4 billion light-years from Earth. Many of the streaks and arcs seen here are distorted images of galaxies that existed less than 1 billion years after the Big Bang. NASA/ESA/THE HST FRONTIER FIELDS TEAM (STScI)

MARTIN GEORGE describes the solar system's changing landscape as it appears in Earth's southern sky.

January 2018: Enjoy a total lunar eclipse

For the first time in more than a year, the evening sky contains no naked-eye planet. Observers who want to see Earth's siblings will have to be up before dawn. But those early risers are in for some treats because January's morning sky delivers two beautiful planet pairings.

Mars and **Jupiter** take center stage as the month begins. The two rise more than three hours before the Sun and climb nearly 25° above the eastern horizon at the start of twilight. On the 1st, ruddy Mars stands 3° to the upper left of brilliant Jupiter. The gap closes during January's first week, and the two pass within 0.2° of each other January 7. This fine conjunction occurs against the background stars of Libra the Scales. Although Mars glows brightly at magnitude 1.4, Jupiter appears 20 times brighter at magnitude –1.8.

The distance between Earth and Mars shrinks a bit during January, so the Red Planet brightens to magnitude 1.2 by month's end. Mars' disk also grows slightly during January, from 4.8" to 5.6" across, though that's still too small for a telescope to reveal surface detail.

With Jupiter now fairly high in the predawn sky, the view of it through a telescope should be splendid. During January, the gas giant's diameter swells from 33" to 36". That's big enough for small scopes to reveal structure in the massive atmosphere. Look for two dark belts sandwiching a bright zone that straddles the planet's equator. In moments of good seeing, larger instruments reveal even finer details. And don't forget to enjoy the dance of the four Galilean moons — Io, Europa, Ganymede, and Callisto — as they endlessly circle Jupiter.

On the mornings of January 11 and 12, a waning crescent Moon passes Mars and Jupiter. Luna appears about one-third illuminated and to the planet pair's left on the 11th; on the 12th, the Moon is one-quarter lit and directly below the duo.

The view becomes even more pleasing January 15, when the Moon slides to the left of our other planet couple — **Mercury** and **Saturn**. The Sun then illuminates just 5 percent of our satellite's Earth-facing hemisphere.

Mercury and Saturn were in conjunction with each other just two mornings earlier. On the 13th, the inner planet appears 0.6° above the ringed world. Astroimagers will want to be ready to capture the unfolding morning drama throughout the January 11–15 period.

At the time of its January 13 conjunction with Saturn, Mercury is on the backside of its morning apparition. The inner world reaches greatest elongation January 1, when it lies 23° west of the Sun and stands 9° high in the east-southeast 45 minutes before sunrise. It then shines at magnitude –0.3 and stands out nicely in the gathering dawn. A telescope reveals Mercury's 7"-diameter disk and slightly gibbous phase.

Saturn is nearly a magnitude fainter than Mercury, glowing at magnitude 0.5 throughout January. Still, the ringed planet becomes easier to see as the month progresses and it climbs higher. On the 31st, it rises more than 2.5 hours before the Sun and appears some 15° high as twilight begins. By February, Saturn once again will become a magnificent telescopic object.

Venus passes on the far side of the Sun from our perspective January 9 and is lost from view all month. It will reappear in the evening sky by March.

While the Moon figures prominently in this month's highlights as it passes four bright planets, it reaches a stunning climax January 31. That night's Full Moon dives deeply into Earth's shadow, creating the first **total lunar eclipse** since September 2015. Australia and New Zealand are the best spots in the Southern Hemisphere to view this event. The partial umbral phases of the eclipse run from 11h48m to 15h12m UT, while totality lasts from 12h51m to 14h08m UT.

The starry sky

Amateur astronomers often comment on the fact that the North Celestial Pole — the point in the northern sky at which Earth's axis points — has a bright star, Polaris, less than 1° away, while the South Celestial Pole has no such nearby luminary.

Sigma (σ) Octantis is the naked-eye star closest to the South Celestial Pole. At magnitude 5.4, however, it is barely visible without optical aid under a good sky and invisible under a light-polluted sky.

But the situation isn't always this bad. Earth's axis precesses, or wobbles, describing a 47°-wide circle in the sky that repeats every 25,800 years. This means the pole star changes slowly over time — in both hemispheres. Some 5,400 years ago, magnitude 0.5 Achernar was only 8° from the South Celestial Pole. Nowadays, it's 33° away.

Canopus, the night sky's second-brightest star, also can appear much closer to the pole than it does now. It was only 9° from the pole about 14,000 years ago, and it will return to a similar position in about 12,000 years. Long before that happens, in some 3,000 years, the Southern Cross will be only half as far from the pole as it is now.

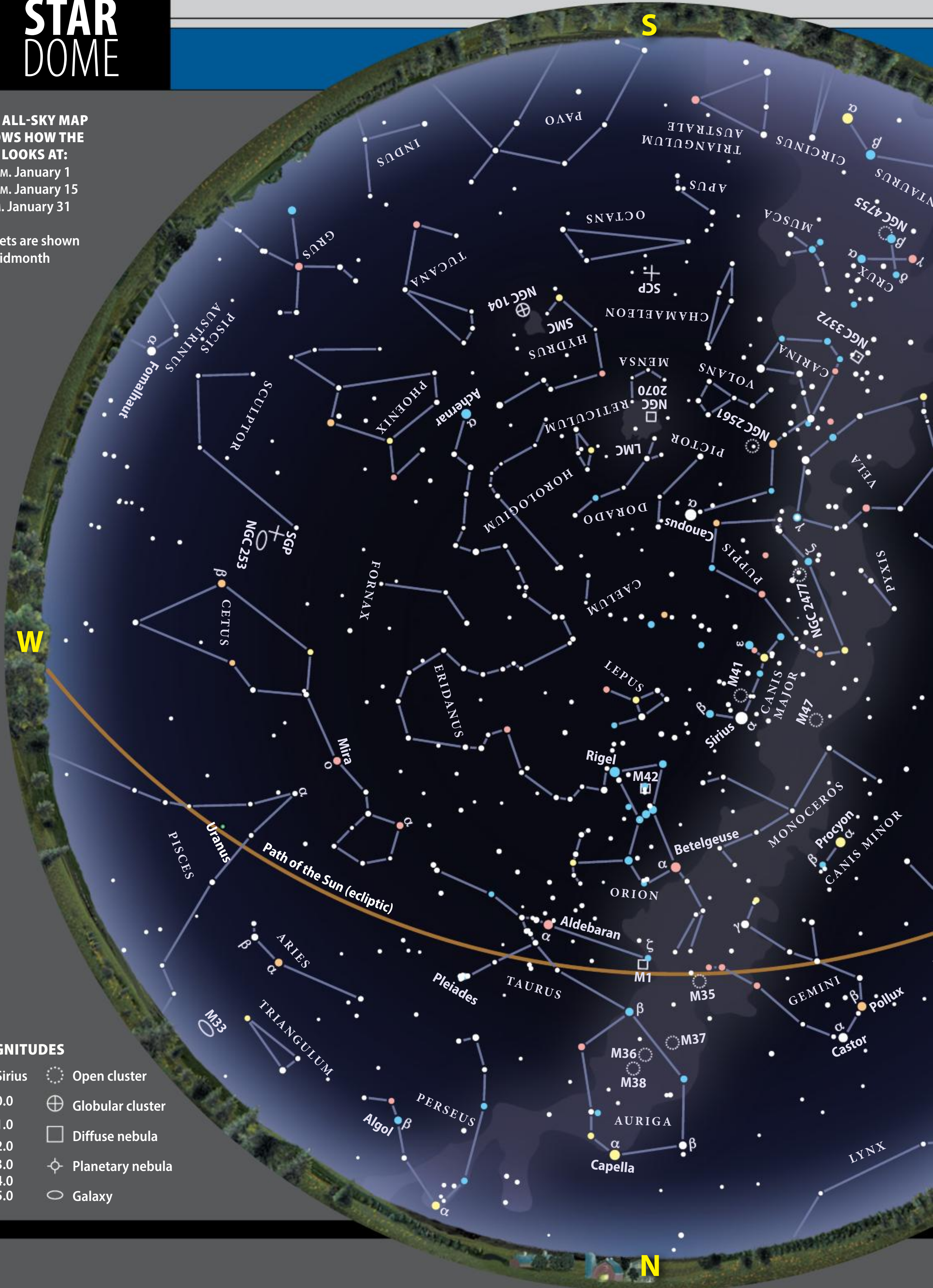
Is there ever a time when a bright star stands really close to the south pole? Yes! Intriguingly, the False Cross — so named because many people confuse it with the Southern Cross — can be a south polar group, and its magnitude 2.25 member Iota (ι) Carinae can be the "South Star." Iota currently lies 31° from the pole. But 20,000 years ago it was less than 1° away, and it will be that close again about 6,000 years from now.

Sadly, we won't be around to see this happen, but it's fun to contemplate a time when the False Cross will appear to be turning around our south pole with Iota Carinae as a pivot, just as the Little Dipper currently does with Polaris as the pole star for our friends in the Northern Hemisphere.

STAR DOME

THE ALL-SKY MAP SHOWS HOW THE SKY LOOKS AT:
11 P.M. January 1
10 P.M. January 15
9 P.M. January 31

Planets are shown at midmonth



MAGNITUDES

- Sirius
- 0.0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0

- Open cluster
- Globular cluster
- Diffuse nebula
- Planetary nebula
- Galaxy

HOW TO USE THIS MAP: This map portrays the sky as seen near 30° south latitude. Located inside the border are the four directions: north, south, east, and west. To find stars, hold the map overhead and orient it so a direction label matches the direction you're facing. The stars above the map's horizon now match what's in the sky.

STAR COLORS: Stars' true colors depend on surface temperature. Hot stars glow blue; slightly cooler ones, white; intermediate stars (like the Sun), yellow; followed by orange and, ultimately, red. Fainter stars can't excite our eyes' color receptors, and so appear white without optical aid.

Illustrations by *Astronomy*: Roen Kelly

JANUARY 2018

Calendar of events

1 Mercury is at greatest western elongation (23°), 20h UT

The Moon is at perigee (356,565 kilometers from Earth), 21h49m UT

2 Full Moon occurs at 2h24m UT

Asteroid Flora is at opposition, 18h UT

Uranus is stationary, 21h UT

3 Earth is at perihelion (147.1 million kilometers from the Sun), 6h UT

5 The Moon passes 0.9° north of Regulus, 8h UT

7 Mars passes 0.2° south of Jupiter, 4h UT

8 Last Quarter Moon occurs at 22h25m UT

9 Venus is in superior conjunction, 7h UT

Pluto is in conjunction with the Sun, 10h UT

11 The Moon passes 4° north of Jupiter, 6h UT

The Moon passes 5° north of Mars, 10h UT

12 The Moon passes 0.4° south of asteroid Vesta, 4h UT

13 Mercury passes 0.6° south of Saturn, 7h UT

15 The Moon passes 3° north of Saturn, 2h UT

The Moon is at apogee (406,464 kilometers from Earth), 2h10m UT

The Moon passes 3° north of Mercury, 7h UT

17 New Moon occurs at 2h17m UT

20 The Moon passes 1.6° south of Neptune, 20h UT

24 The Moon passes 5° south of Uranus, 1h UT

First Quarter Moon occurs at 22h20m UT

27 The Moon passes 0.7° north of Aldebaran, 11h UT

30 The Moon is at perigee (358,994 kilometers from Earth), 9h57m UT

31 Dwarf planet Ceres is at opposition, 13h UT

Full Moon occurs at 13h27m UT; total lunar eclipse