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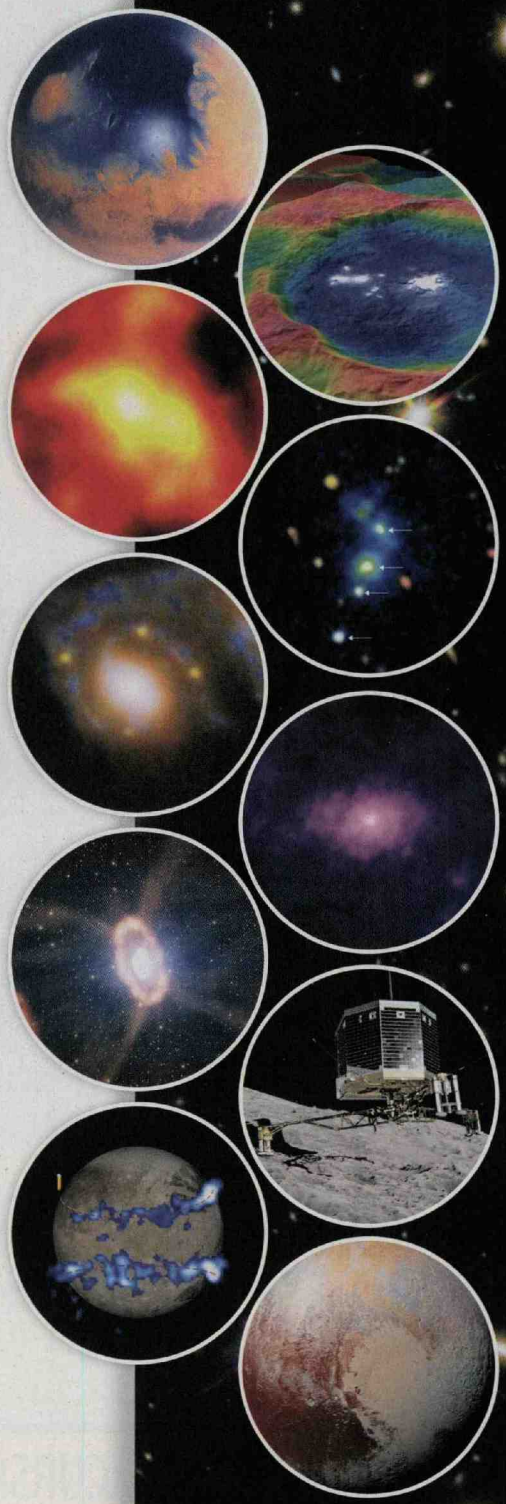
Editors' picks

TOP 10 SPACE STORIES of 2015

Astronomers find signs of dark matter close to home, unravel the mystery of a famous supernova, and take a trip to Pluto.

by Liz Kruesi

Astronomy *Contributing Editor* **Liz Kruesi** *writes about the wonders of the cosmos from Austin, Texas.*



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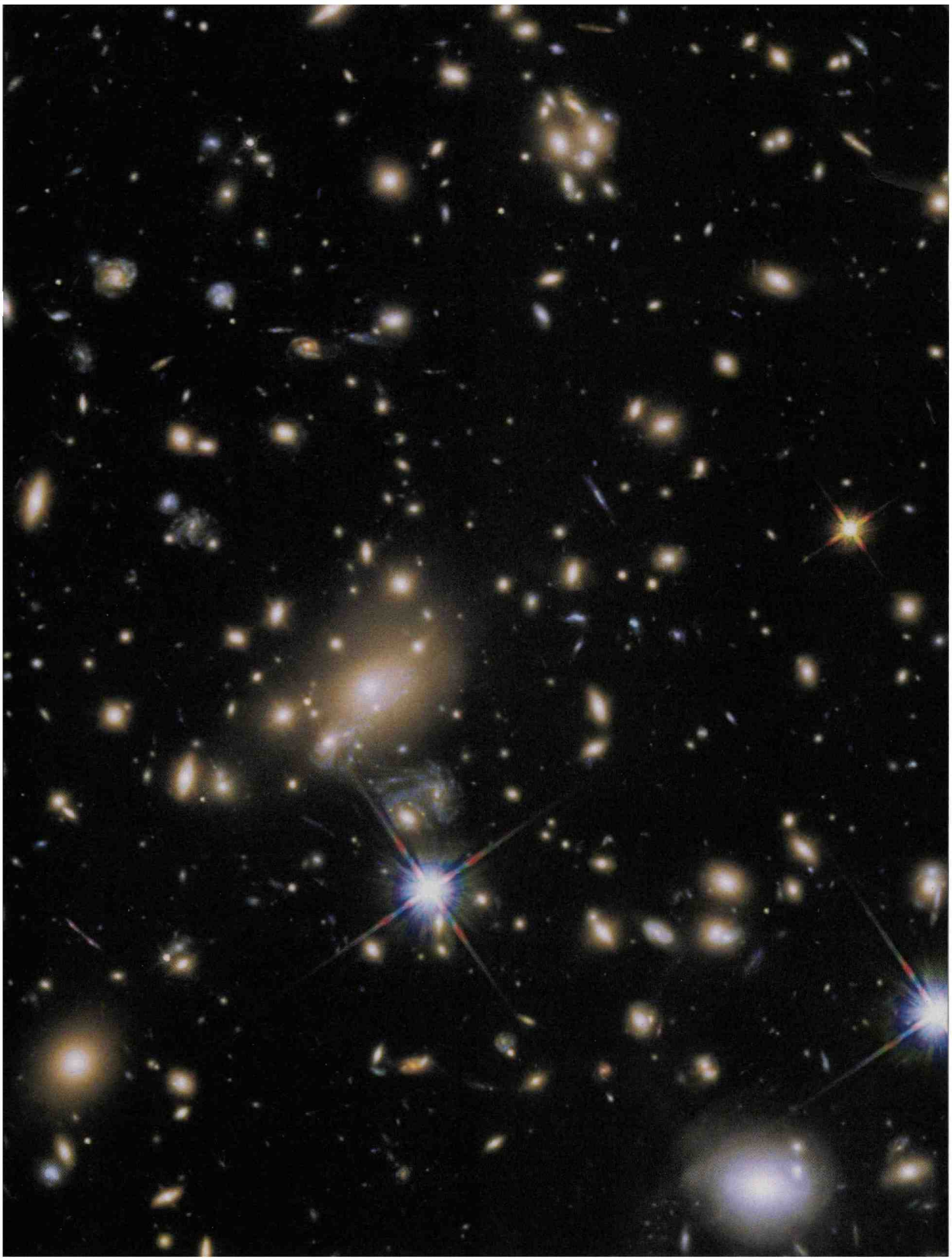

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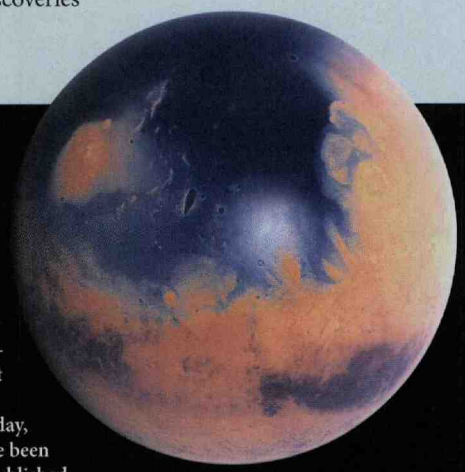
Planetary science drew the most attention in 2015, and for good reason. Mysterious bright spots on the largest asteroid in our solar system puzzled scientists. The spacecraft following a comet as it hurtled toward and then retreated from the Sun continued to make surprising discoveries. And, of course, the year saw the history-making and expectation-shattering observations of Pluto.

But discoveries about celestial objects beyond the solar system deserve attention, too. The center of the Milky Way Galaxy harbors a mysterious glow from dead stars or something even stranger, while astronomy's most studied stellar explosion is changing before our eyes.

Each year, *Astronomy* ranks the top 10 astronomical discoveries and space stories. Here's where 2015's biggest ones fall.



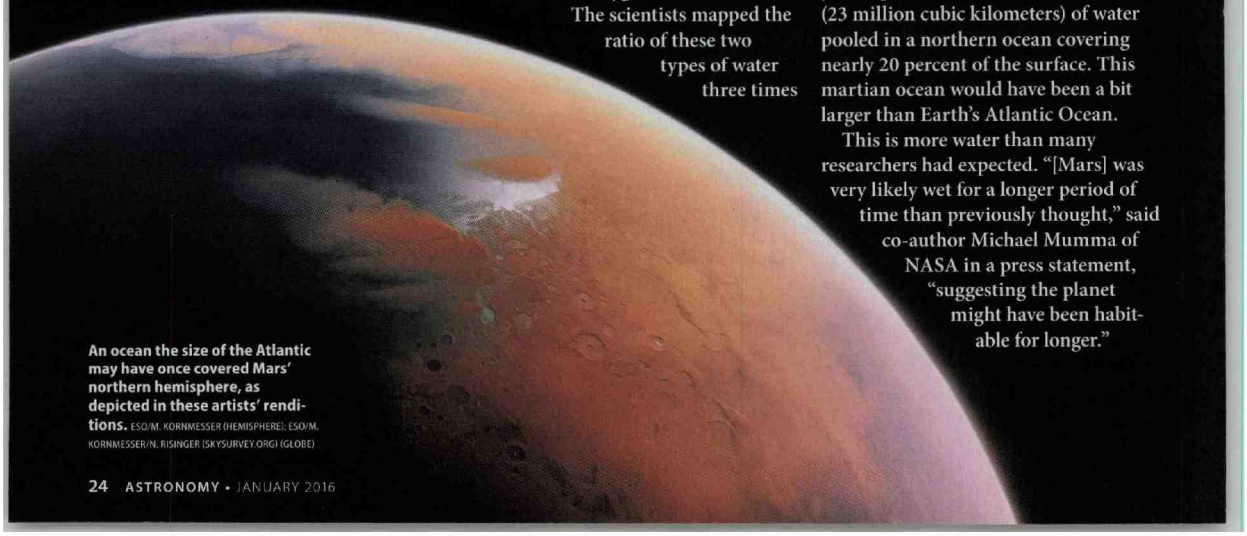
10 The Red Planet under water

The rovers and orbiters at Mars have uncovered plenty of evidence that the planet once had liquid water on its surface, from etched river gullies and dried-up shorelines to minerals that need water to form. But a new study, some five years in the making, confirms that the Red Planet hosts liquid water on its surface today. Since 2010, Lujendra Ojha, from Georgia State University, and colleagues have used Mars Reconnaissance Orbiter (MRO) data to study streaks running down martian crater walls. They suspected that the streaks, called "recurring slope lineae," which appear to lengthen from one image to the next, mark flowing salt water. But they didn't have proof. In the new study, published in the September 28 issue of *Nature Geoscience*, Ojha's team provides the spectral signature (from MRO) of salty water at four locations of recurring slope lineae on the Red Planet's surface — confirming that flowing water is present today on Mars.

While little water remains today, scientists know that it must have been bountiful in the past. A study published in the April 10 issue of *Science* analyzed how much water the planet once had. Researchers used several Earth-based telescopes to look at the martian atmosphere in infrared light. Geronimo Villanueva of NASA's Goddard Space Flight Center and colleagues were looking for specific colors: one that corresponds to normal water (H_2O) and one that comes from a heavier form of water that has an extra neutron (hydrogen-deuterium-oxygen, or HDO). The scientists mapped the ratio of these two types of water three times over six years (or three martian years) to compare the water in the atmosphere at different seasons.

H_2O is lighter than HDO and thus evaporates more easily. So by measuring the ratio of the two, the researchers could calculate how much water Mars has lost over time, and thus how much water it would have started with. Villanueva's team says that 4.5 billion years ago, some 6 million cubic miles (23 million cubic kilometers) of water pooled in a northern ocean covering nearly 20 percent of the surface. This martian ocean would have been a bit larger than Earth's Atlantic Ocean.

This is more water than many researchers had expected. "[Mars] was very likely wet for a longer period of time than previously thought," said co-author Michael Mumma of NASA in a press statement, "suggesting the planet might have been habitable for longer."



An ocean the size of the Atlantic may have once covered Mars' northern hemisphere, as depicted in these artists' renditions. ESO/M. KORNMESSER (HEMISPHERE); ESO/M. KORNMESSER/N. RISINGER (SKYSURVEY.ORG) (GLOBE)

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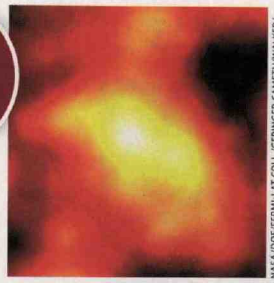
9 Dark matter hints next door



NASA/DOE/FERMI LAT COLL. (GERINGER-SAMETH/WALKER/CMU/KOUSHIAPPAS/BROWN UNIV.

Dark matter annihilation may be the cause of the gamma-ray glow emanating from nearby dwarf galaxy Reticulum II, shown here in red and yellow.

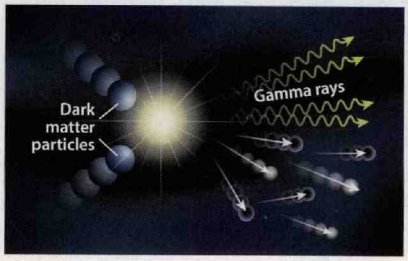
The invisible and perplexing material that makes up at least 80 percent of our universe's mass keeps leaving clues for astronomers, but not enough to solve its identity. While scientists do not know yet what makes up this dark matter, one search method has given tantalizing hints over this past year.

Scientists believe that when two dark matter particles collide they destroy themselves — a process called annihilation — and create other familiar particles. Among this shower of particles is gamma radiation. And nearby dwarf galaxies are an ideal place to look for dark-matter-produced gamma rays. "[Dwarf galaxies] are calm, quiet places; we don't know any reason why they should be emitting high-energy gamma rays on their own," says Carnegie Mellon University's Alex Geringer-Sameth, lead scientist of one of the searches. "Therefore, if you see some gamma rays coming from one of these dwarf galaxies, it is very exciting because it could be a sign that dark matter is annihilating within it."

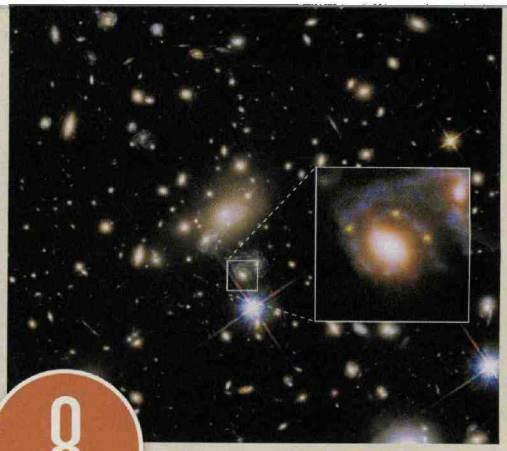
This past year, a sky survey uncovered nine dwarf galaxies within 1 million light-years of the Milky Way. And one of the galaxies from this Dark Energy Survey (DES) was a prime dark matter target: Reticulum II.

Geringer-Sameth's team and another — Dan Hooper and Tim Linden, both of the University of Chicago — used seven years of data from the Fermi Gamma-ray Space Telescope to find that this dwarf galaxy looks a bit brighter than it should in gamma rays. "We provide an indication that *something* is emitting gamma rays from the direction of Reticulum II, and that something seems to be consistent with dark matter annihilation," says Geringer-Sameth. "While the signal from Reticulum II is tantalizing, it would be premature to conclude it has a dark matter origin."

Hooper and Linden calculated a similar chance that the signal has dark matter origins. "You might call that evidence; you won't call that a discovery," Hooper says of the studies. "We really need more data to resolve the issue." Scientists expect DES to uncover some 20 more nearby dwarf galaxies, and future surveys will find even more. Scientists will then be able to compare archived Fermi gamma-ray data with these dwarf galaxies to see if they have a signal similar to Reticulum II's.



When dark matter particles collide, they may annihilate each other in a shower of other particles, including gamma rays. ASTRONOMY: ROEN KELLY



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Astronomers used the Hubble Space Telescope to catch a faraway galaxy focusing the light of an even more distant supernova four times over. NASA/ESA/STScI/UCLA

Supernova hunters see quadruple

In November 2014, Patrick Kelly was looking through his team's recently collected Hubble Space Telescope images of galaxy cluster MACS J1149.6+2223 when something stood out: four stars with exactly the same pattern of light surrounding one of the cluster's member galaxies. "I knew it was a big discovery," says Kelly, a postdoctoral fellow at the University of California, Berkeley. He emailed his group about the find, and they have since confirmed it as a supernova whose image has been distorted by the cluster galaxy, which lies along the supernova's line of sight. Months of observations have classified this object as a type IIp supernova, which originated from a massive star.

The distant stellar explosion lies more than halfway across the observable universe. Its light left the supernova some 9.5 billion years ago. Along its path to Earth, the light encountered a massive member of the intervening galaxy cluster. The galaxy warps the fabric of space-time like a bowling ball warps a trampoline, and so the supernova's light follows those curves in space-time, detoured from its path to Hubble.

This "gravitational lensing" causes the light to appear to come from four different points instead of just one lone supernova. Norwegian astrophysicist Sjur Refsdal predicted this type of quadruple-lensed supernova 50 years ago. The 2014 discovery, published in the March 6, 2015, issue of *Science*, has been named Supernova Refsdal after that scientist.

In his 1964 paper, Refsdal said such a blast could help to measure the rate our universe is expanding. Because the explosion's images show up in four locations, light followed four different paths to arrive at Hubble. Astronomers can use each of those paths to map the distribution of normal material and unseen dark matter in the galaxy cluster. In addition, those different paths are related to the cosmic expansion rate.

Another spectacle awaits the team. All of those paths also take a different travel time. After creating a map of MACS J1149.6+2223, the astronomers realized that the supernova should have taken a fifth path, too. The light is still traveling and could appear as early as late 2015, says Kelly.

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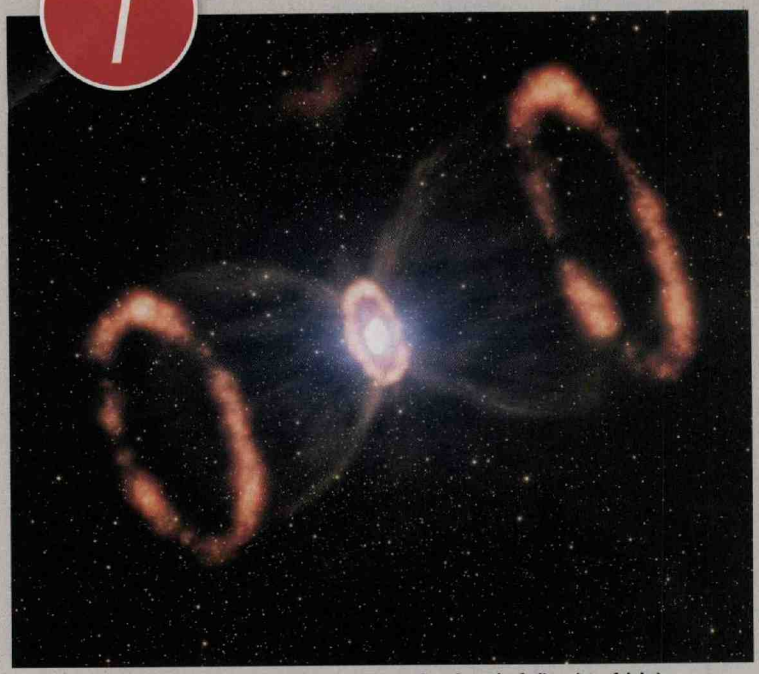
7 Deciphering a famous supernova



An artist's work depicts Supernova 1987A observations that show the fading ring of debris. ESO/L. CALÇADA

In February 1987, a brilliant new point of light shone in the southern sky. This turned out to be the explosive blast marking the death of a star and earned the name Supernova 1987A. Lying just 168,000 light-years from Earth, it is the closest supernova to explode since astronomers developed the tools to study such a blast. And that proximity makes it a perfect laboratory to watch how supernovae evolve. Several discoveries published in 2015 reveal changes to the blast site and uncover secrets of the explosion first seen 28 years ago.

SN 1987A is recognized by its ring of bright nodules, like shining diamonds along a band. These brilliant spots mark where the blast's shock wave is slamming into previously shed material. While astronomers had seen the diamonds brightening for the past 15 years, new observations show them fading for the first time. This means the blast's shock wave is passing through the ring of material, breaking it apart. Visible-light observations made by Stockholm University's Claes Fransson and colleagues using the Hubble Space Telescope show the ring is fading, while spots outside of the ring are beginning to light up. They described the observations in the June 10 issue of *The Astrophysical Journal Letters*.

X-ray images from the Chandra X-ray Observatory also show the ring's light changing. David Burrows, who has been watching SN 1987A evolve for 15 years, says the blast's high-energy light is plateauing.

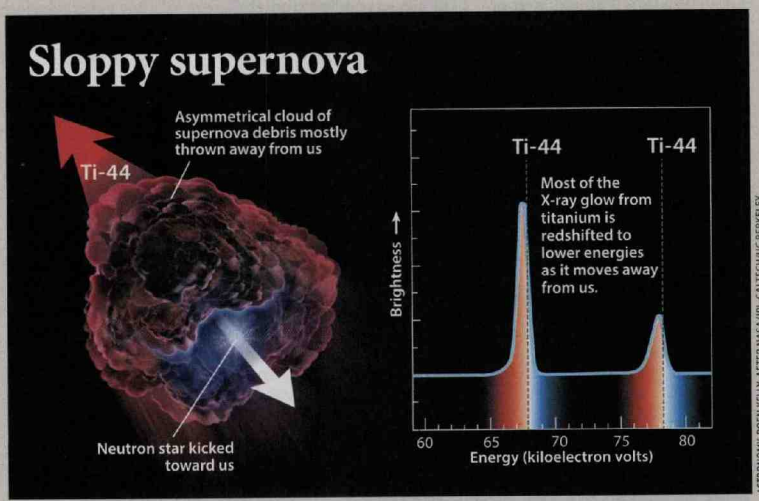
Another 2015 study focused on SN 1987A's guts.

When a star at least 10 times the Sun's mass explodes at the end of its life, the energies, temperatures, and pressures are so high that the supernova produces a range of heavy chemical elements. One of those is titanium-44 (Ti-44), which is an unstable radioactive isotope. "The isotope is produced deep in the core of the explosion, and its properties — mass, ejection speeds, and distribution — directly reflect the physics in the core," says Steve Boggs of the University of California, Berkeley.

Like all elements, Ti-44 glows with specific colors of light, so if scientists look for those colors, they can learn where that material is. But none of Ti-44's colors had been visible to astronomers until a recent X-ray telescope, the Nuclear Spectroscopic Telescope Array (NuSTAR), opened its eyes and began collecting data.

Boggs and colleagues described in the May 8 issue of *Science* their study using NuSTAR to map Ti-44 in SN 1987A. The element's distribution is clumpy and uneven, implying that the explosion was off-center. This is the second supernova remnant the team has been able to probe; the other is Cassiopeia A. Both explosions were asymmetrical, Boggs' team says, which means now astronomers have to rethink the theoretical models of these blasts.

Most computer models have assumed a symmetrical blast, but the new studies prove something more complex is happening.



X-ray observations mapping titanium-44 created during Supernova 1987A show that the explosion was a lopsided event, with the bulk of material streaming away from Earth.

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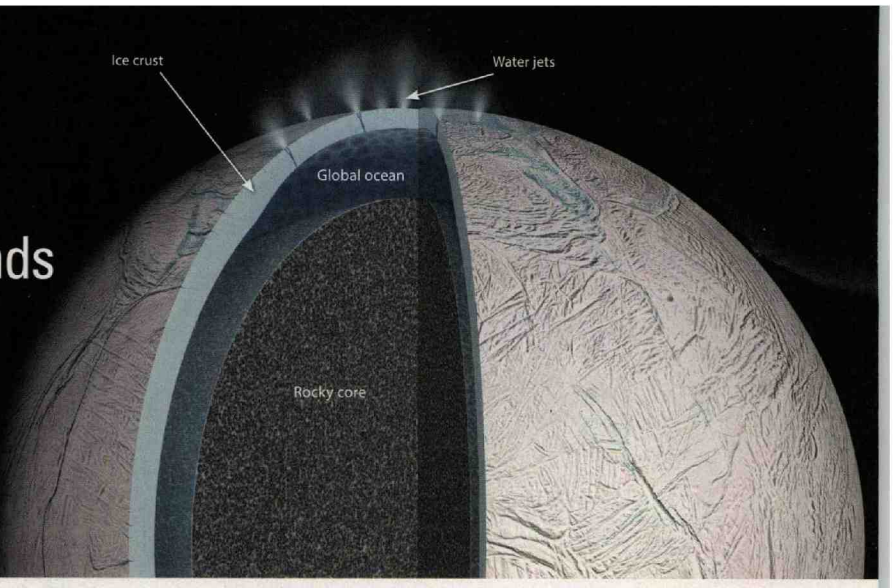
Water abounds in the outer solar system



Saturn's moon Enceladus is spewing out rocky silicate grains that researchers found form in hot acidic water — the same kind of hydrothermal vents where deep-sea life thrives on Earth. NASA/JPL-CALTECH

Saturn's moon Enceladus continues to show why it's one of the best bets in the solar system to search for life. Astronomers have suspected for years that salty water dredged up from a subsurface sea spews into space out of fissures near the moon's south pole. But an analysis, published online September 11 in the journal *Icarus*, of seven years of images from NASA's Cassini spacecraft indicates that Enceladus has a subsurface global ocean instead of merely a regional sea.

Cornell University planetary scientist Peter Thomas and colleagues measured a slight wobble in the moon's rotation. If Enceladus were solid, its mass would dampen that motion. The researchers believe, instead, that a liquid water ocean lies between the moon's icy surface layer and the rocky interior. They say the ocean is deeper and the ice shell thinner at the south polar region, where Cassini has spied some 100 geysers of salt water.

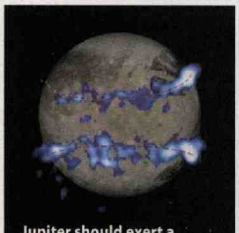
Scientists think that to keep any material in liquid state within Enceladus' interior requires the push-and-pull tidal energy from Saturn. A global ocean is harder to keep warm than a regional sea, and so this discovery could also indicate that the saturnian satellite has more tidal energy than originally thought. "If that is correct," says team member Carolyn Porco, "and its ocean has been around a long, long time, then it may mean that any life within it has had a long time to evolve."

Some of the material spewing from Enceladus' underground ocean flows out through the geysers, flows toward Saturn because of the planet's gravitational pull, and then orbits the planet as its E ring. In the March 12 issue of *Nature*, Frank Postberg at the universities of Heidelberg and Stuttgart in Germany and colleagues described how they used the Cassini spacecraft to study some of the material from the E ring. They saw silicon-rich molecules (called silicates) just a few nanometers wide. When this type of material is found in space, it almost always originates from rock being dissolved in water. But to learn the precise characteristics of that water-rock interaction, Postberg's team collaborated with researchers from Japan to mimic the conditions needed at Enceladus to produce the sizes and composition of silicate particles they observed. They found the water needs to be at least 194° F (90° C) and have a pH between 8.5 and 10.5. These characteristics imply hot-spring-heated water; the only other place where such hydrothermal vents have ever been seen is on Earth, and these sites host extreme organisms.

The chemical reaction that produces the silicates also creates molecular hydrogen, and a different instrument on board Cassini will look for this gas during a late 2015 flight through Enceladus' plumes. If it detects more molecular hydrogen than expected, it will confirm hydrothermal activity, says Postberg.

This year, astronomers also found the best evidence so far of water at yet another location in our solar system: Jupiter's large moon Ganymede. NASA's Galileo spacecraft, which studied the jovian system in the late 1990s and early 2000s, studied Ganymede's magnetic field to learn whether the moon holds a global ocean under its surface. But the analysis from only 20 minutes of flyby observations was inconclusive. Fast forward to the past year, when Joachim Saur of the University of Cologne and his colleagues studied data from two 7-hour Hubble Space Telescope observations.

Ganymede has an auroral belt in each hemisphere just like Earth does. Jupiter's magnetic field also influences these aurorae and causes them to rock during Jupiter's 10-hour rotation period. Saur's team knew that if Ganymede did not have an ocean, the aurora belts would change their positions slightly, tilting about 6°. "However, when a salty and thus electrically conductive ocean is present, this ocean counterbalances Jupiter's magnetic influence and thus reduces the rocking of the auroras to only 2°," says Saur. "We observed Ganymede with the Hubble Space Telescope for more than five hours and saw that the aurora barely moved and rocked by only 2°. This thus confirms the existence of an ocean." The researchers think the ocean lies about 90 miles (150km) below the moon's rock-ice crust and is about 60 miles (100km) thick. This strong evidence of Ganymede's ocean continues to increase the number of worlds in our solar system known to host water.



Jupiter should exert a strong influence on its moon Ganymede's magnetic field, causing its aurorae to rock. But astronomers see only a tiny effect, implying that an underground salt-water ocean is offsetting Jupiter's influence. NASA/ESA

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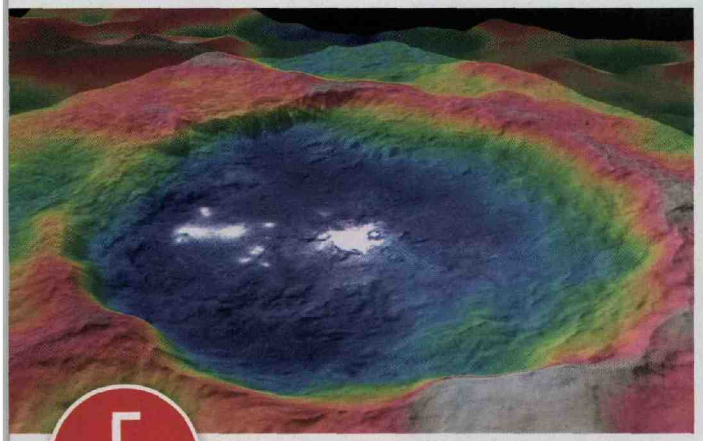

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Ceres is color-coded here to highlight the topography of Occator Crater with its bright spots. Low elevation is shown in blue and green and high regions in red and brown. NASA/JPL-CALTECH/UCLA/MPS/DLR/IDA

Ceres takes center stage

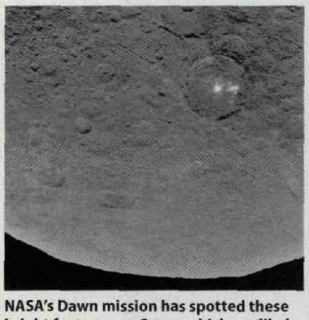
Since March 6, NASA's Dawn spacecraft has been in orbit around Ceres, the largest object in the asteroid belt lying between Mars and Jupiter. For a full recap of the spacecraft's adventures and discoveries, see "Dawn mission reveals dwarf planet Ceres" (p. 44). Dawn will continue its studies until June 2016. Ceres is the second asteroid Dawn has orbited; the first was Vesta, between July 2011 and September 2012.

Ceres' pockmarked surface is riddled with craters like those seen at Saturn's icy moons. "The features are pretty consistent with an ice-rich crust," said Dawn planetary geologist Paul Schenk of the Lunar and Planetary Institute in Houston in a press statement. The spacecraft has mapped the heights of surface features like craters and mountains.

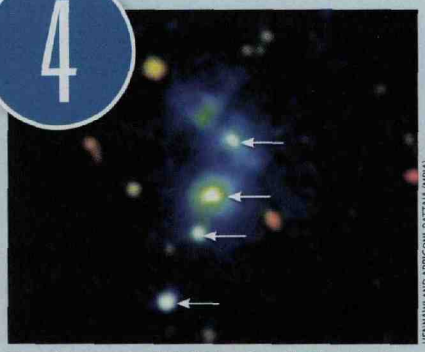
Bright spots on the dwarf planet's surface also have mystified planetary scientists. These reflective regions first came into view at the beginning of 2015 and have since resolved into a multitude of spots. They sit within Ceres' northern Occator Crater, which spans 57 miles (92km) and is 2.5 miles (4km) deep. Researchers at first believed they were ices or salts, but bad luck repeatedly stymied their efforts to gain spectra of the mysterious spots. Based on the reduced reflectivity of the spots, however, the consensus is turning to salt.

In August, Dawn had reached its penultimate orbit, circling Ceres from 910 miles (1,470km) out. A few months later, the spacecraft will have transitioned to its final science orbit, at just 230 miles (375km) above the surface.

In addition to mapping the surface and measuring the heights of the mountains and craters on Ceres, Dawn is working to learn about the composition of materials on the asteroid's surface. The spacecraft also is measuring how different locations on Ceres pull with more or less gravity. The answers will let scientists map the world's gravity and learn how the dwarf planet's rocky interior is distributed.



NASA's Dawn mission has spotted these bright features on Ceres, which are likely salt deposits. NASA/JPL-CALTECH/UCLA/MPS/DLR/IDA



4

HENNAWI AND ARRIGONI BATTAIA (MPIA)

These four quasars, the bright centers of active galaxies, are all the same huge distance from Earth. Their proximity to one another makes them the earliest galaxy cluster yet.

Youngest cluster of galaxies seen

The process of forming clusters of galaxies is not one that astronomers can watch in real time because it takes billions of years. Instead, they look for galaxy clusters at different stages in their development. Because light travels at a constant speed, the light collected from more distant objects means scientists are seeing those objects further back in time. In 2015, astronomers reported they had found the youngest cluster yet, still in an early stage of formation.

To find this protocluster, Joseph F. Hennawi of the Max Planck Institute for Astronomy in Heidelberg and colleagues searched for the extremely bright centers of galaxies hosting actively feeding supermassive black holes. These quasars, as they are known, are used in two ways: first, as markers for large galaxies, and second, as flashlights to see through nearby gas clouds. Such gas clouds glow because they absorb the active galaxy's light and then re-emit it. The researchers were looking for a specific color of light that energized hydrogen throws out, called Lyman alpha.

They spied four active galaxies near to one another on the sky. When they studied their light in more detail, they saw all four lie the same distance from Earth and the light from these objects has been traveling for 10.6 billion years. No one had ever seen, nor expected to find, four quasars in the same gravitationally bound group, so this discovery was a surprise.

The team also saw these galaxies embedded in an enormous cloud of hydrogen. The conglomeration existed when the universe was just about 3.2 billion years old, and the gas clump stretches about 1 million light-years across. "It's 100 percent clear that it's a protocluster," says team member J. Xavier Prochaska of the University of California, Santa Cruz. "It's a structure that will evolve into something like [the] Virgo [Cluster] today."

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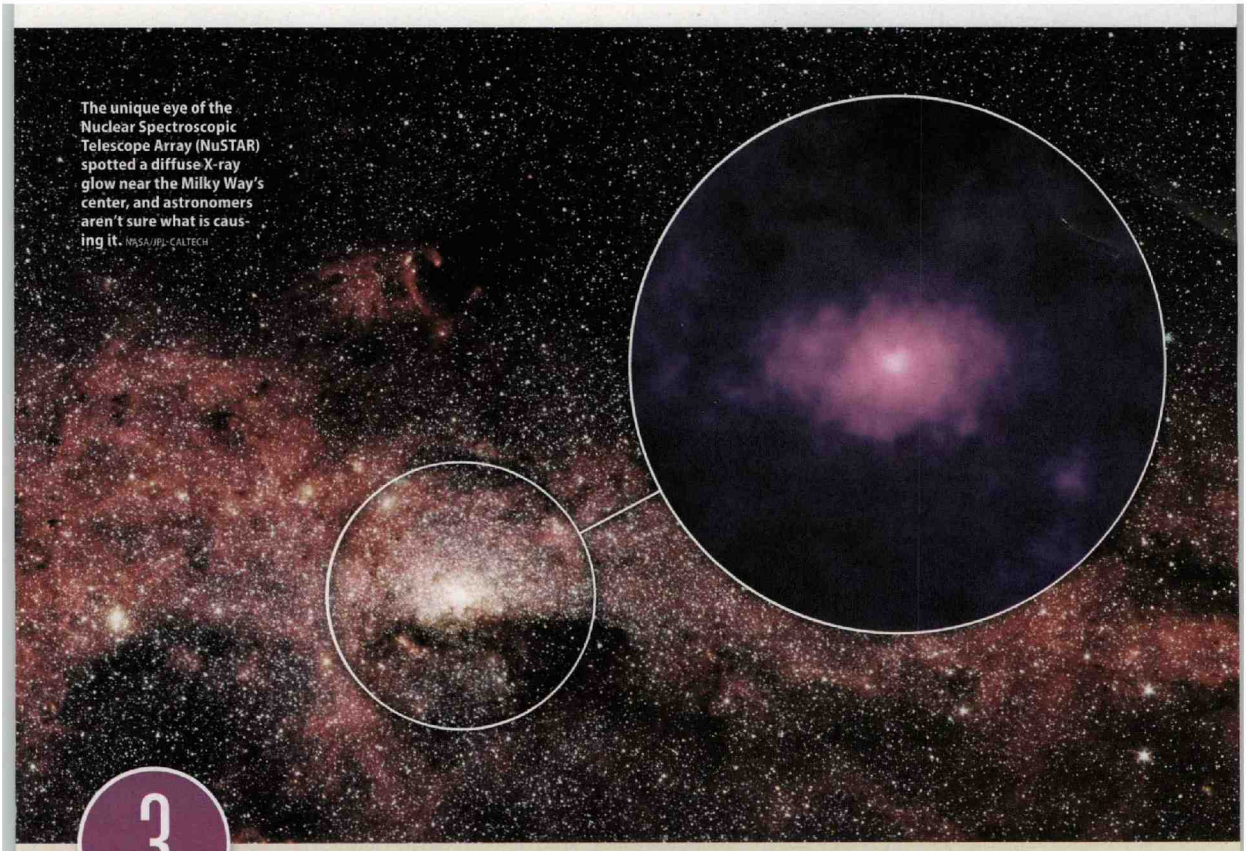

The unique eye of the Nuclear Spectroscopic Telescope Array (NuSTAR) spotted a diffuse X-ray glow near the Milky Way's center, and astronomers aren't sure what is causing it. NASA/JPL-CALTECH

3 A surprise glow at the galaxy's center

When astronomers have a new telescope that can resolve types of light never seen before, they can usually expect a surprise. And that's exactly what the Nuclear Spectroscopic Telescope Array (NuSTAR) uncovered when it collected a million seconds worth of high-energy X-ray light from the center of the Milky Way. Astronomers found a diffuse glow, but they can't pin down what's causing it.

Kerstin Perez was using NuSTAR data to study the glowing material around a neutron star lying in the galactic center. But she couldn't get rid of a pervasive signal in the central 13 light-years by 26 light-years. Once she convinced herself and her colleagues that this signal truly exists, they went to work to figure out what it could be.

NuSTAR doesn't just take pictures; it also spreads the light out in a spectrum, collecting information about the intensity of light at each individual color to make it easier to analyze. To figure out what creates the haze the researchers saw, they considered types of objects that would give a similar light pattern, says Perez. "And then you think, how many of those objects would you have to have in order to make up how bright we see it." This analysis led the NuSTAR team to four possibilities, which they described in an April 30 *Nature* article.

Three of the possibilities are stellar remnants stealing gas from a companion. As this material piles up, it ignites and glows in X-rays. The idea is that there are so many of these pairs that NuSTAR can't separate them from one another, so they appear as a haze.

One of these types of corpses could be thousands of white dwarf stars, each 90 percent of the Sun's mass. Another could be about a thousand black holes and neutron stars — the dense leftover cores of once massive stars. And the third option is some thousand millisecond pulsars, which are neutron stars that have had so much material dumped onto them by their companions that their rotation rates have sped up dramatically. The problem is that astronomers have no idea how so many of these objects — whatever they might be — could exist in a small region in the galactic center.

The fourth possibility is that as material falls toward the supermassive black hole at the center of the Milky Way, some of it gets shot out at high speed. This streaming material could be interacting with nearby clouds of gas, causing them to glow. But the hazy glow that NuSTAR sees doesn't look oriented in the right way for this explanation.

While scientists with NuSTAR hope that upcoming telescopic observations can help narrow down which of these possibilities is responsible for this emission, they don't expect to learn the answer soon.

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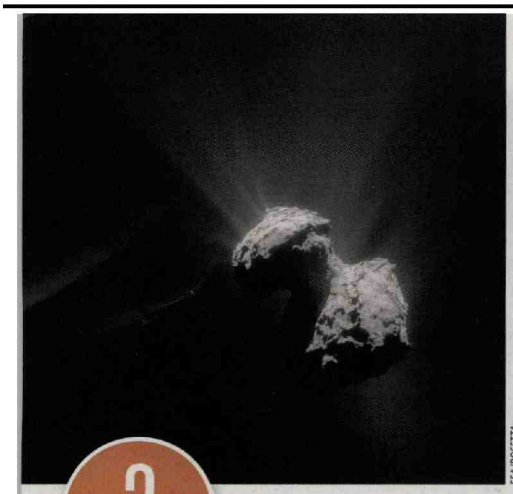
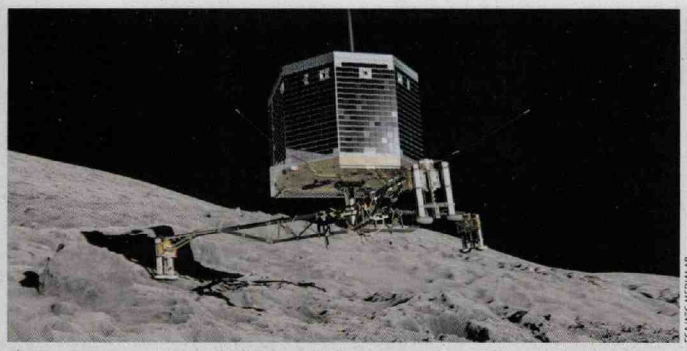


ESA/ROSETTA



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The European Space Agency's Philae lander (above) bounced several times before landing on Comet 67P/Churyumov-Gerasimenko (left) in November 2014, and then fell into deep hibernation. In 2015, it woke up again, but its final fate remains unknown.

2

Europe's visit to a comet

The European Space Agency's Rosetta spacecraft has been watching how Comet 67P/Churyumov-Gerasimenko changes as it passes through its closest approach to the Sun and then hurtles away. The history-making mission has revealed many cometary secrets.

Ever since Rosetta beamed back its first images of Comet 67P, scientists have wondered what made its unexpected double-lobed "rubber duck" shape. Now, they have an answer. According to a paper published October 15 in *Nature*, two separate objects collided to form the comet. To reach this conclusion, the researchers measured how regions were sloped, looked at the orientations of features on the surface, and calculated the local gravity across the surface.

Rosetta also has returned thousands of images of Comet 67P. It has photographed boulders balancing on just a small part of their surfaces, piles of rubble that seem to have come from falling rocks, and jets of gas spewing from pits dozens of feet across possibly created by sinkholes. The spacecraft also has spied about 120 bright areas several feet wide on the comet's surface, and scientists say these are most likely patches of water ice reflecting sunlight.

After analyzing data of one water-ice patch on the comet's "neck," scientists say the area seems to appear and disappear with the comet's 12-hour rotation. They think that as the region feels direct sunlight, ice on the surface and just an inch (a few centimeters) below are heated and turn directly to gas — a process called sublimation. The sunlight also warms the layers of ground beneath the region, and so further-buried ice makes its way as gas to the surface. As the patch rotates into darkness, the surface cools again and the just-risen gas turns to ice. The scientists, who reported this water cycle in the September 24 issue of *Nature*, say the process repeats each cometary day.

Rosetta's refrigerator-sized Philae lander had also studied the comet's surface, even though the sequence of events to land this spacecraft didn't go as planned. After dropping from Rosetta on November 12, 2014, and bouncing several times before finally tumbling to rest, Philae stayed alert for just around 60 hours before falling into hibernation. Because of its unplanned bounces, the lander was able to compare two different sites on the comet's surface. The first landing site appears to have a soft dusty material about 8 inches (20cm) thick covering a much harder material, possibly icy or crystalline in nature. Philae's final resting spot, however, lacks that dusty coating.

At the first landing location, the craft "smelled" 16 organic compounds, including four never before detected on a comet. Another instrument detected several gases at the same location, like water vapor, carbon monoxide, and formaldehyde. Comets are expected to be pristine relics from the early solar system, but Comet 67P has more complex chemistry than expected, and some of the molecules discovered on the comet's surface are important for biology.

After hibernating for seven months, Philae surprised everyone when it woke up again June 13. Over the next few weeks, Philae and Earth had spotty conversations, with the last command sent and received July 9. Scientists have no way to know whether Philae still sits atop Comet 67P, or whether it has been pushed off by actively spewing jets of gas.

Rosetta will continue watching Comet 67P through September 2016, at which point mission scientists will most likely try to land the spacecraft on the comet for a last look.

STORIES TO WATCH FOR IN 2016

- The European Space Agency's LISA Pathfinder, a mission to test the technologies needed for a full-scale gravitational wave observatory, will begin to return results.
- The Japan Aerospace Exploration Agency will launch Astro-H to study the high-energy universe.
- NASA will launch its Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer (OSIRIS-Rex) asteroid sample-return mission.
- Astronomers will begin closing other telescopes on Hawaii's Mauna Kea in order to make way for the Thirty Meter Telescope slated to begin operations there in the early 2020s.
- Juno will arrive at Jupiter to peer through the giant world's thick clouds.
- Advanced Laser Interferometer Gravitational-wave Observatory (LIGO) will return data on gravitational waves.

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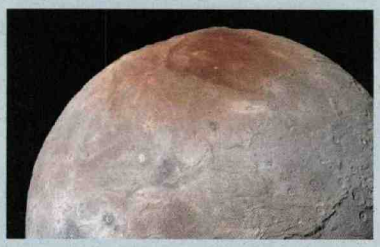
1

Pluto and its moons revealed

◄ 2015 was the "Year of Pluto," revealing the icy world and its moons in stunning detail and upending much of what we thought we knew about this system. NASA/JHUAPL/SwRI



► Pluto's largest moon Charon also came into sharper view, including glimpses of the dark region near its north pole informally known as Mordor Macula. NASA/JHUAPL/SwRI

Pluto's distinct haze layers are clearly visible in this image returned by New Horizons. The extent of the hazes was a surprise to astronomers expecting a more elusive atmosphere. NASA/JHUAPL/SwRI

When NASA's New Horizons spacecraft flew by Pluto, Earth watched and celebrated. "The target didn't disappoint," says Principal Investigator S. Alan Stern. "It's absolutely stunning." And even though the science collection lasted just months, the New Horizons mission had been decades in the making. NASA chose the mission in 2001, the spacecraft launched in 2006, and it reached Pluto on July 14, 2015.

Seeing the pixelated blobs of Pluto and its largest moon, Charon, evolve into complex worlds through the eye of New Horizons was rewarding, satisfying, and awesome, says Stern. That's because everything about Pluto surprised scientists. They expected a frozen, cratered, and long-dead world with an equally old-looking system of moons. Instead, Pluto's surface is young, with smooth frozen plains, icy mountains as high as the U.S. Rockies, topography that resemble dunes, a glacial lake, and ice that has recently flowed around other features in the same way that glaciers move on Earth's surface. The scientists estimate that the uncratered swaths of terrain are 100 million years old, while other regions are billions of years in age.

Pluto's varied surface with such youthful areas means that something internal must be warming it to make it pliable. And while all the objects in our planetary system would have been warm shortly after the solar system formed 4.5 billion years ago, scientists didn't think such a small object could stay warm all these years. "We expect small planets to typically run out of energy a lot sooner than the big planets. It's like a small cup of coffee cools off faster than a bucket of coffee," says Stern. But what New Horizons has revealed about Pluto, he adds, changes the expectations of planetary geology.

Scientists have also created a map of methane ice distribution, and this material seems to prefer a region of young terrain that scientists have informally named "Sputnik Planum." Outside of this area, methane is still present and congregates on crater rims and brighter regions but avoids crater centers and darker regions for unknown reasons.

The up-close photos of Pluto have also let scientists precisely measure the width of the dwarf planet: 1,473 miles (2,370km). This secures Pluto as the largest known object orbiting beyond Neptune.

After New Horizons flew by Pluto, it looked back and watched the dwarf planet eclipse the Sun. This alignment let scientists study Pluto's atmosphere as sunlight filtered through it. Above the surface lie distinct haze layers that extend to about 80 miles (130km) out, several times farther than researchers expected. And New Horizons detected wisps of a nitrogen-rich atmosphere 1,000 miles (1,600km) out.

While Pluto has been the main focus, Charon also has shown surprises. It too has a varied surface, with some regions void of impact craters. Cliffs stretch hundreds of miles across the surface, indicating the crust has fractured. A deep canyon, 4 to 6 miles (6 to 10 km) deep, also scours Charon's surface.

New Horizons snapped photos of Pluto's four smaller moons as well: Nix, Hydra, Styx, and Kerberos. While Charon is 751 miles (1,208 km) across, each of these four is just a few dozen miles wide.

Most of New Horizons' data is still on board the spacecraft and will be downloaded piece by piece over the next several months. Researchers will pore over the additional data in the next few years, learning more every day about Pluto and its moons. Even though humans saved this dwarf system for last in our exploration of the solar system, just the first views exceeded and upended expectations and have given researchers a treasure-trove of new science.

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