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SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

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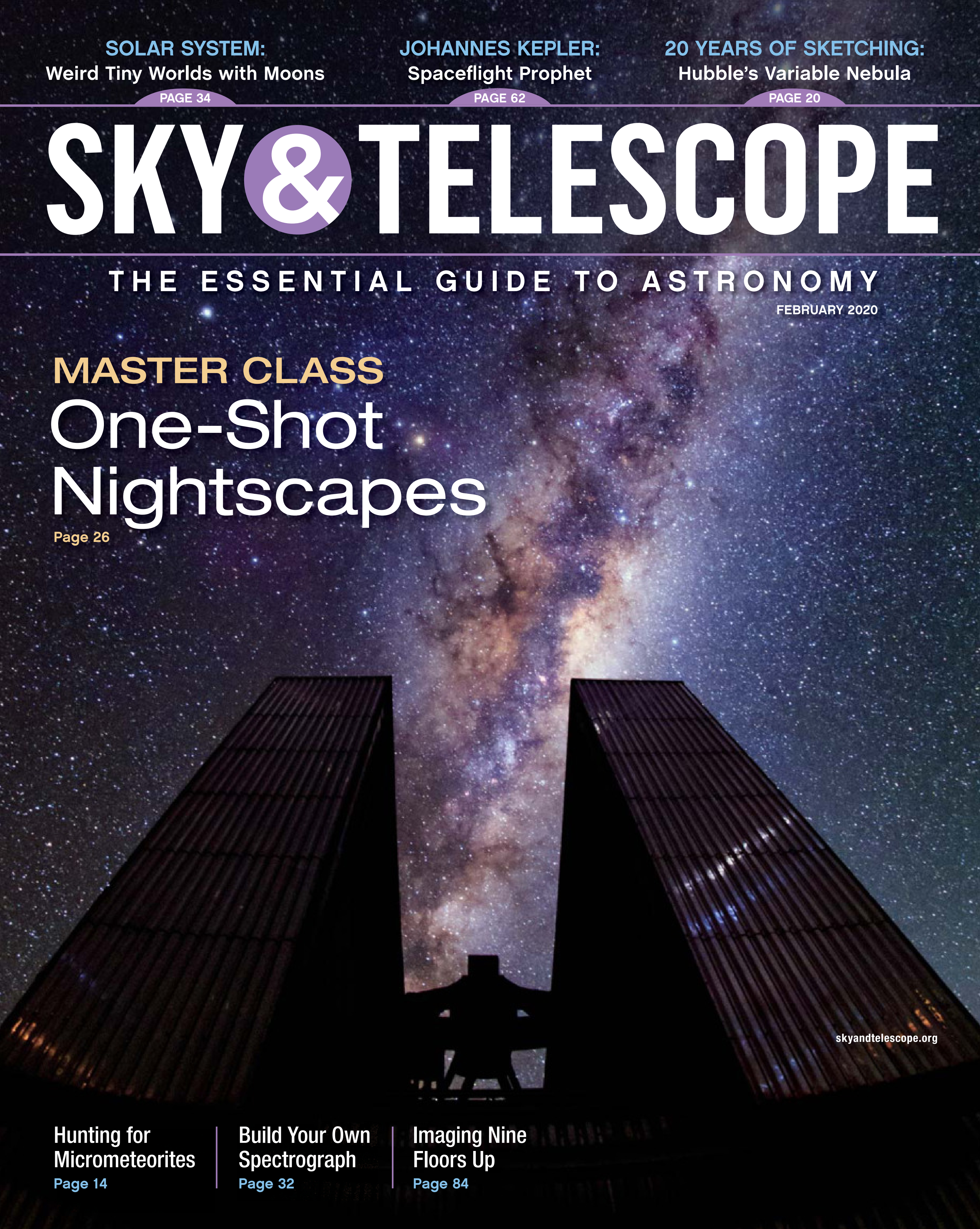

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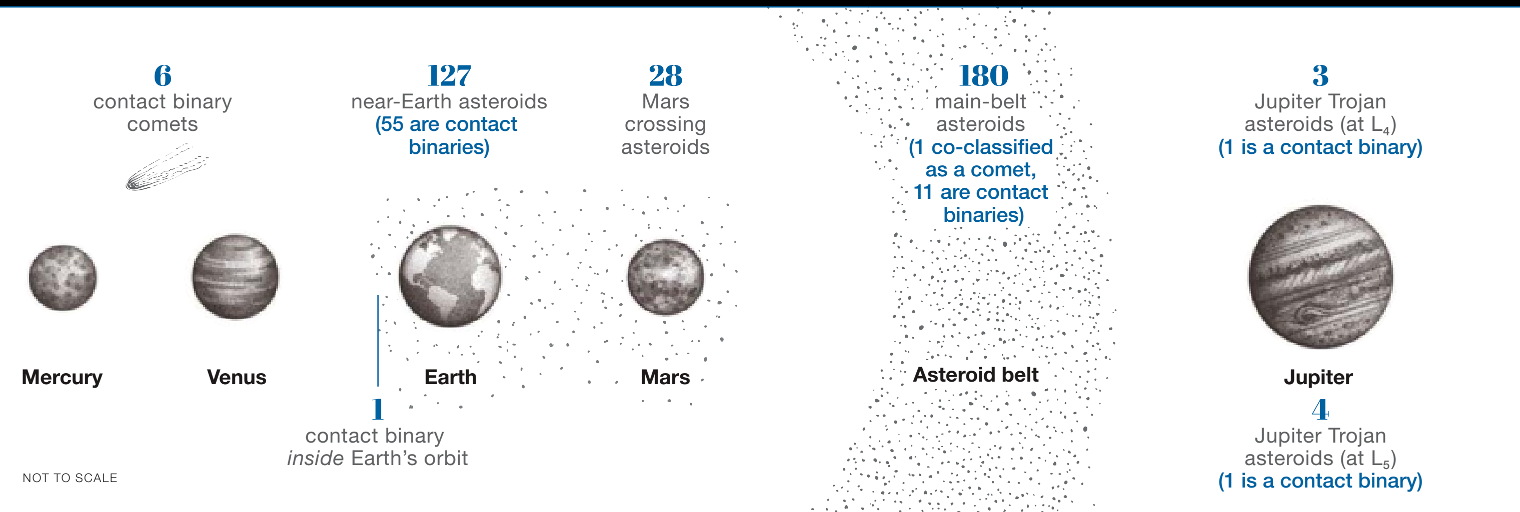
 by Jeff Hecht

PRIMITIVE WORLD The Kuiper Belt object 2014 MU_{69} (now officially named Arrokoth) is a contact binary, each lobe a hodgepodge of smaller regions. Scientists think this is the most unchanged object from the solar system's formation that a spacecraft has so far encountered.

Binary Worlds



The wide variety of binary objects in the solar system not only surprised astronomers but is now also helping us understand the birth of planetary systems.

Astronomers had hoped to see something interesting when they steered the New Horizons spacecraft on course to visit a Kuiper Belt object soon after it flew past Pluto. They chose the object 2014 MU_{69} because its nearly circular orbit beyond Neptune marked it as among the most primordial objects known in the solar system, and its path put it within reach for New Horizons. They nicknamed it Ultima Thule, "beyond the known world." On November 8, 2019, its official name became Arrokoth, meaning "sky" in the Powhatan Algonquian language.

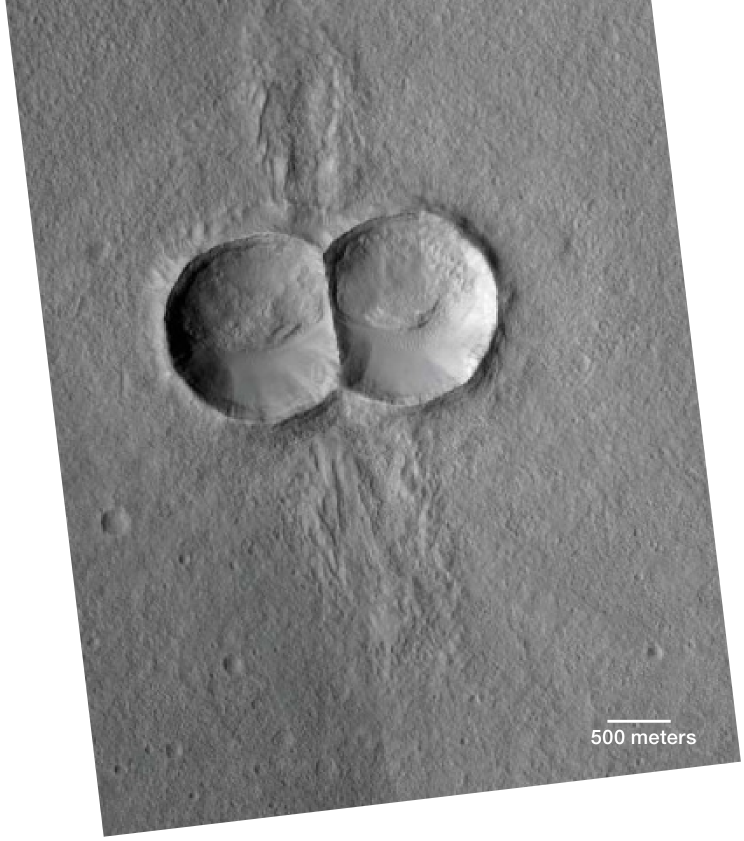
All Hubble recorded was a tiny spot in the sky, but when astronomers watched Arrokoth occult a distant star, the little world's silhouette hinted at a pair of objects orbiting close to, or even touching, each other. So controllers were both hopeful and anxious as the spacecraft bore down on Arrokoth for its close encounter early on New Year's Day 2019.

Our first close-up view of Arrokoth bore out those hints: It showed a contact binary shaped like a giant snowman. The two lobes seem to have bumped very slowly into each other sometime early in their history and stuck together. Subsequent images revealed that the two reddish lobes are fairly oblong, joined on their long ends, with brighter stuff spread around the junction almost like glue.

Arrokoth is not alone in its strange shape. Observers have found many binaries in the solar system, both contact binaries like Arrokoth and ones in which the members don't touch but orbit each other. They appear in the Kuiper Belt, the main asteroid belt, and even among comets and the objects that come near Earth. Some scientists wonder if binaries might have been a standard stage of planet formation.

Yet just 30 years ago, most astronomers doubted these binary worlds existed.

ARROKOTH: NASA / JHU APL / SWRI / NOAO; INFOGRAPHIC: TERRI DUBÉ / *S&T*, SOURCE: JOHNSTONSARCHIVE.NET; PLANETS: MARINAT197 / SHUTTERSTOCK.COM; DOUBLET CRATER: NASA / JPL / UNIVERSITY OF ARIZONA

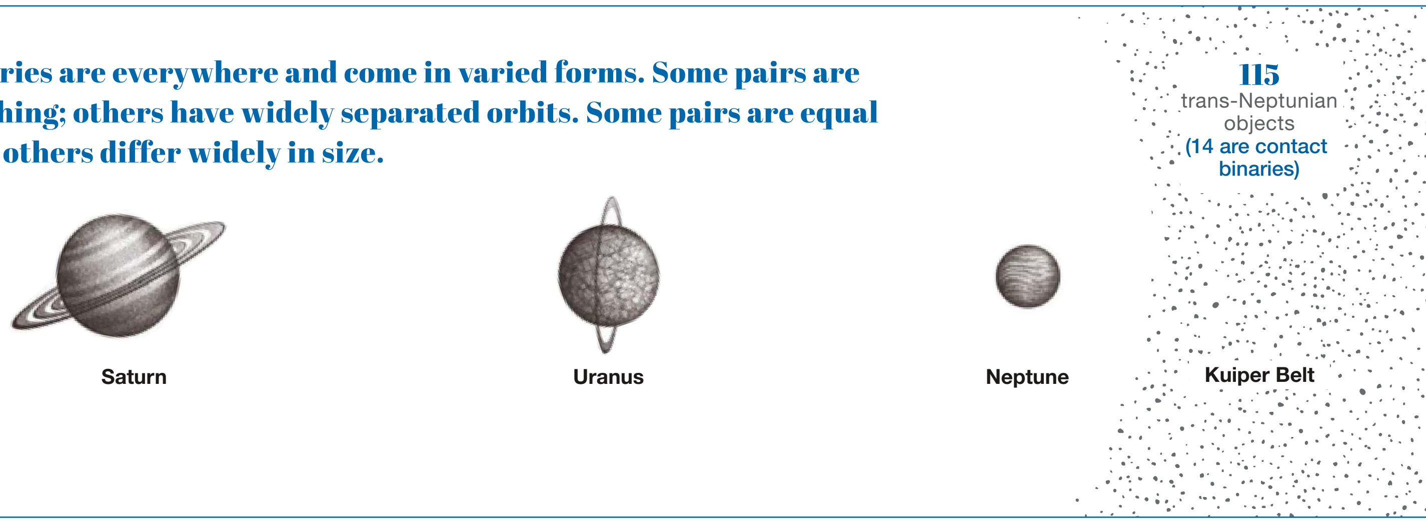


▲ **DOUBLE CRATER** The shared rim and plume-like ejecta of this Martian double crater formed when two objects hit simultaneously. The impactor may have consisted of two loosely connected objects of the same mass.

Discovering Binaries

The first hints came in the 1970s, when observers recording the light curves of stars occulted by asteroids saw unexpected variations before or after the asteroid passed in front of the star. Geologists found a few terrestrial craters that appeared to have formed in pairs. And in August 1989, Steven Ostro (Jet Propulsion Laboratory) and colleagues used the 305-meter (1,000-foot) Arecibo radio telescope to reveal the peanut shape of the potentially hazardous near-Earth asteroid 4769 Castalia (1989 PB). His team suspected the 1.4-kilometer asteroid might be a contact binary rotating every four hours.

Binaries are everywhere and come in varied forms. Some pairs are touching; others have widely separated orbits. Some pairs are equal size; others differ widely in size.

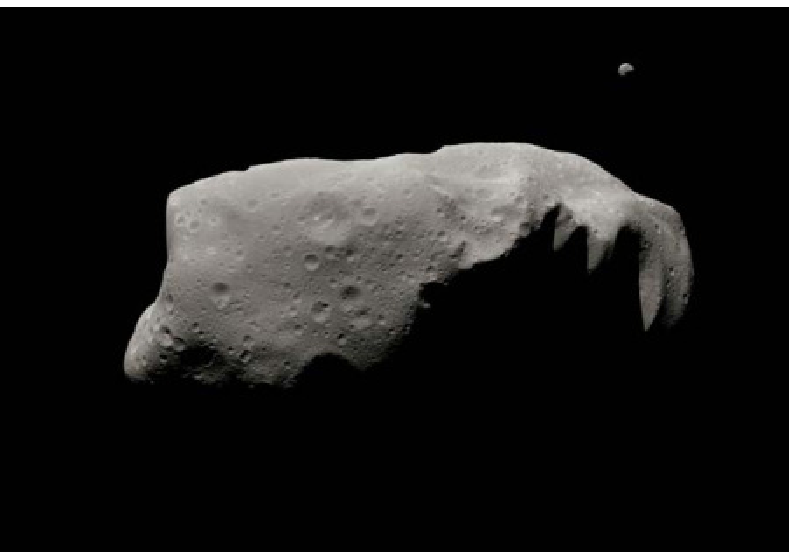


The first convincing evidence of a pair of asteroids orbiting each other, however, was a byproduct of NASA's Galileo mission to Jupiter. The spacecraft had to pass through the main asteroid belt, so planners arranged flybys of two asteroids. The second, on August 28, 1993, revealed that the 60-km oblong asteroid 243 Ida was orbited by a 1.5-km moon, later dubbed Dactyl. The images of little Dactyl moving along with the much larger Ida were finally enough to convince Brian Marsden, the long-time director of the Minor Planet Center at the Harvard-Smithsonian Center for Astrophysics, that binary asteroids existed.

More discoveries followed. Some have involved radar, others were made using ground-based telescopes with adaptive optics or the Hubble Space Telescope, which can resolve separate bodies if their orbits take them far enough from each other. Often the best data come from spacecraft exploring objects up close, like Galileo's visit to Ida and New Horizons' flybys of Pluto and Arrokoth. The Rosetta mission to famous "rubber duck" Comet 67P/Churyumov-Gerasimenko, for example, showed us spectacular close-ups of a contact binary nucleus (*S&T:* May 2017, p. 14). But extremely precise measurements from far away of how an object's brightness changes over time have identified more than half of known binaries.

As of November 2019, astronomers had identified 375 asteroids and trans-Neptunian objects with at least one companion: 359 have one, 15 have two, and the record holder, Pluto, has five. These objects are spread throughout the solar system: 72 near-Earth asteroids, 28 Mars crossers, 169 objects in the main asteroid belt (one of them a comet), five Jupiter Trojans, and 101 beyond Neptune. An additional 67 inner solar system and main-belt asteroids, two Jupiter Trojans, 14 trans-Neptunian objects, and six comets are contact binaries, including Arrokoth.

▼ **IDA AND DACTYL** This mosaic shows asteroid 243 Ida and its moon, Dactyl, as seen by the Galileo spacecraft en route to Jupiter. The moon's discovery shocked much of the planetary science community when announced in 1994.



The YORP effect can spin up a rubble-pile asteroid enough for the centrifugal force at its equator to exceed the body's gravitational attraction, and pieces can drift away.

That adds up to quite a diverse bestiary. Binaries are everywhere and come in varied forms. Some pairs are touching; others have widely separated orbits. Some pairs are equal size; others differ widely in size. Some rubble piles spin off chunks that orbit the main body for a while, then slowly return to merge with it. Astronomers think their differences reflect where they formed and where they have wandered since.

To sort through the bestiary, we will start with near-Earth binaries and move outward through the solar system to Arrokoth and other objects in icy orbits beyond Neptune.

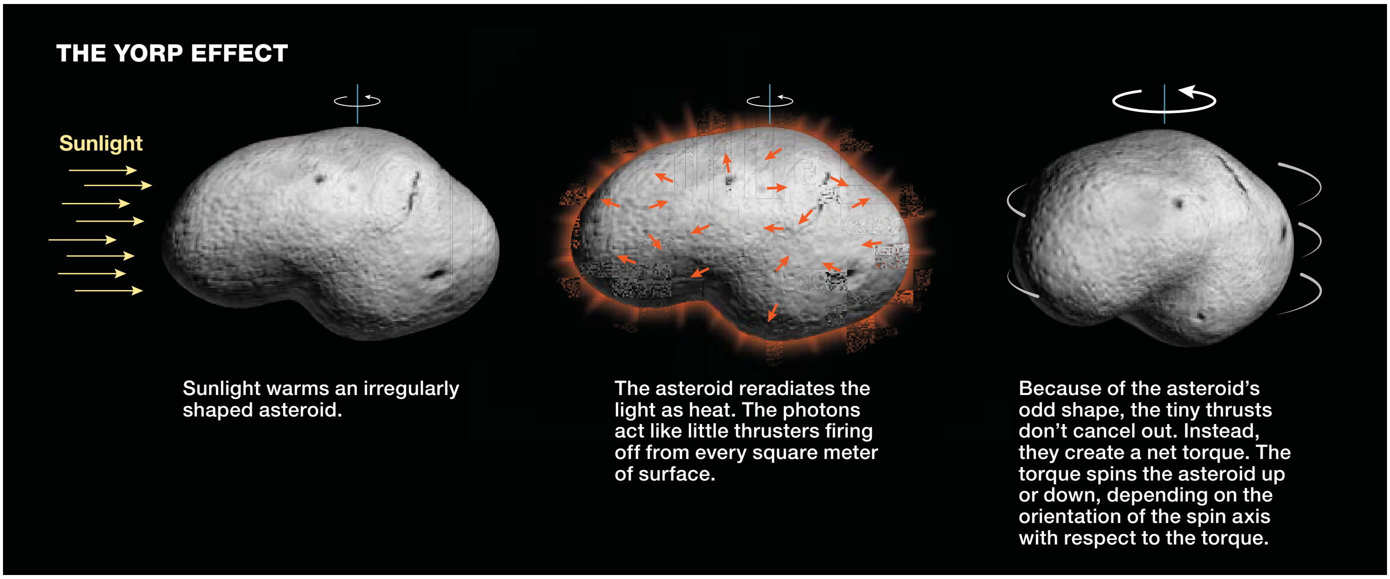
Near-Earth Binaries and the YORP Effect

Radar has discovered about three-quarters of the multi-member near-Earth asteroids, says Patrick Taylor (Lunar and Planetary Institute). Maximum size is a few kilometers. He says that one-sixth of near-Earth asteroids wider than 200 meters are binaries; another one-sixth are contact binaries like Castalia and Arrokoth, with two similar-size lobes touching each other and rotating jointly.

The separate members of near-Earth binaries generally orbit only a few kilometers from each other, or a few times the size of the primary. The bigger objects tend to spin fast, with "days" lasting only 2.2 to 4.5 hours. The smaller components typically are 4% to 58% the sizes of the primaries.

Near-Earth orbits are chaotic, and objects normally stay in them for only around 10 million years before colliding with a planet or the Sun or being ejected out of the region. Most near-Earth objects are "rubble piles," accumulations of material held together loosely by gravity, which makes them vulnerable to three processes that can break them apart before they are lost. Collisions can knock pieces out of the rubble pile, which then drift back to form binaries with their parent bodies. Close gravitational encounters with planets can tear apart both asteroids and comets, as happened when Comet D/Shoemaker-Levy 9 passed near Jupiter on July 7, 1992.

The third process relies on far weaker forces, but over time it is far more effective because it is powered by sunlight. Light carries momentum that it can transfer to objects when reflected or absorbed and reradiated, and the induced torque can change the spin of an irregularly shaped object. The process is called the *YORP effect*, and depending on the object's rotational orientation it can either speed up or slow down its rotation. "It's very weak, a measurable force but not a huge force," says Daniel Scheeres (University of Colorado,



Boulder). Over long periods, the YORP effect can spin up a rubble-pile asteroid enough for the centrifugal force at its equator to exceed the body's gravitational attraction, and pieces can drift away.

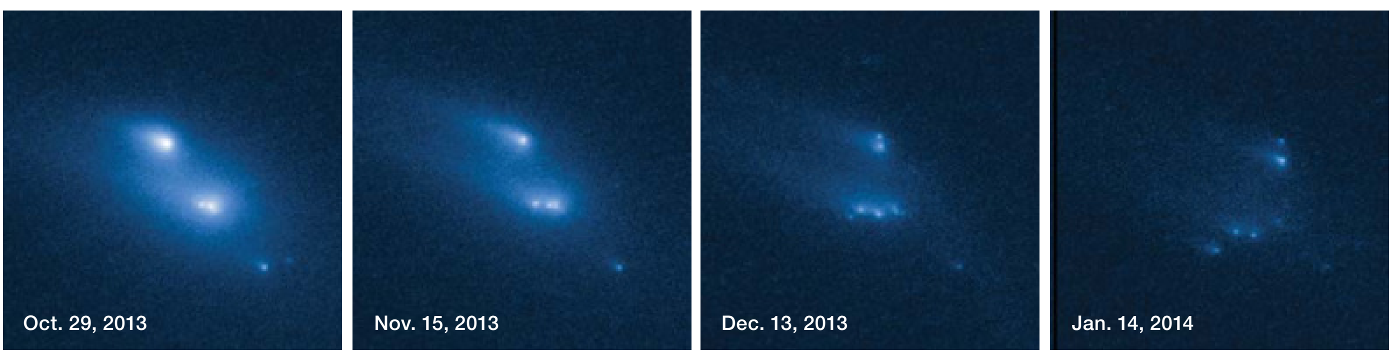
The strength of the effect depends on the intensity of the incident light. It's stronger for near-Earth objects and much weaker in the main belt, which lies farther from the Sun. Also, the smaller the object, the more a given amount of sunlight can increase its spin. "This means that these effects are only active on small bodies," Scheeres says. His students have measured the YORP effect as it spun up small defunct artificial satellites in geostationary orbit within months to years. Asteroids are more massive, so it takes hundreds of thousands to hundreds of millions of years to spin them up. But the Sun shines relentlessly. Many single near-Earth asteroids are spinning nearly fast enough to start shedding material, and all the near-Earth binaries have close orbits, both outcomes expected from the YORP effect.

Asteroid rubble that has spun off may drift away, but it generally does not escape permanently. Instead, it goes into orbit around the asteroid, where in theory escaped pieces might accrete to form a smaller, stable companion for the original asteroid. Details are unclear, including how much material would escape, how much would stay to form the resulting binary companion, and how large it would be. However, Scheeres says, formation of a new object in orbit could in theory trigger the related "binary YORP effect," which can cause the pair to either spiral in or out depending on details. If the two spiraled out, they could become separate objects. But if they spiraled in, they could merge with each other to re-form a single object, even though some mass would be lost.

Main Belt and Comets

The YORP effect is much weaker farther out in the main asteroid belt, so other effects are likely responsible for most of its 169 orbital binary asteroids. Estimates of the fraction of binaries in the main belt vary widely because few have been observed closely enough to detect whether these are multiple objects. Main-belt binaries include a wide variety of relative sizes and orbital spacings, and many are much larger and more widely spaced than objects with orbits near Earth's.

▼ **ASTEROID BREAKUP** Main belt object P/2013 R3 disintegrated unexpectedly in 2013. Each piece has its own comet-like dust tail. Researchers suspect the YORP effect might have spun the asteroid up until it flew apart.



YORP EFFECT: GREGG DINDERMAN / *S&T*; ASTEROID BREAKUP: NASA / ESA / D. JEWITT (UCLA)

Collisions are known to happen in the main belt, a region of space that is much more stable and densely populated than the region of near-Earth orbits. Collisions could form widely separated pairs with a large primary and a very small secondary, like Ida and Dactyl.

Only about 10 contact binaries have been spotted in the main belt, most detected by radar. That number includes a peculiar object among the Trojan asteroids that share Jupiter's orbit, 624 Hektor. It's a large contact binary orbited by a smaller moon. Ground-based adaptive optics show the larger body is a peanut-like contact binary measuring about 400 by 200 km, orbited by a 12-km moon. That makes Hektor both a contact binary and an orbital binary. In 2014 Franck Marchis (SETI Institute) and colleagues calculated that the moon's orbit is stable. They proposed that two 200-km components had collided, forming a contact binary and ejecting a fragment that became the moon.

▲ **624 HEKTOR** Artist's concept of the Trojan contact binary Hektor and its 12-km moon. The primary body is about 400 km long and may be a porous mixture of rock and ices.

Although we think of asteroids as rocky objects, some two dozen objects originally designated main-belt asteroids have been reclassified as comets after they began spouting comas or tails. One, P/2013 R3, broke up into several pieces that went their separate ways in 2013. Another, initially designated asteroid 2006 VW_{139} and later numbered 300163, has now been recognized as the first orbital binary comet. In 2017, a team led by Jessica Agarwal (Max Planck Institute for Solar System Research, Germany) published Hubble images showing two roughly kilometer-size objects in an elongated orbit around each other that spanned 100 kilometers. No binary asteroid has the same combination of wide separation, similar-size members, high orbital eccentricity, and cometary emissions. Agarwal says the binary may have formed either when the two pieces split from a single collision fragment, or when two fragments from a collision hooked up gravitationally in the aftermath. Intriguingly, it is one of 11 objects in main-belt orbits traced to the breakup of a 10-km object 7.5 million years ago. Yet none of the others has shown similar cometary emissions.

▶ **BINARY COMET** This series of Hubble images reveals that the nucleus of 2006 VW_{139} is made of two objects revolving around each other. Astronomers think that the main-belt object has only been a binary for about 5,000 years. (The tail's changing orientation is due to the change in the Sun-Earth-object alignment between observations.)

Contact binaries are common in comets. Four of the six comets imaged by spacecraft have two distinct lobes. The most impressive images are from Comet Churyumov-Gerasimenko, which show that ices began eroding from both lobes of the rubber duck after the incoming comet passed Jupiter's orbit. Close-ups near the "neck" show networks of cracks where the two lobes meet, a sign of weakening that might be linked to stress or ice sublimation.

How such an object forms remains a big question. Comets are thought to have formed 20 to 30 astronomical units from the Sun, then to have been pushed far beyond Neptune's orbit dur-

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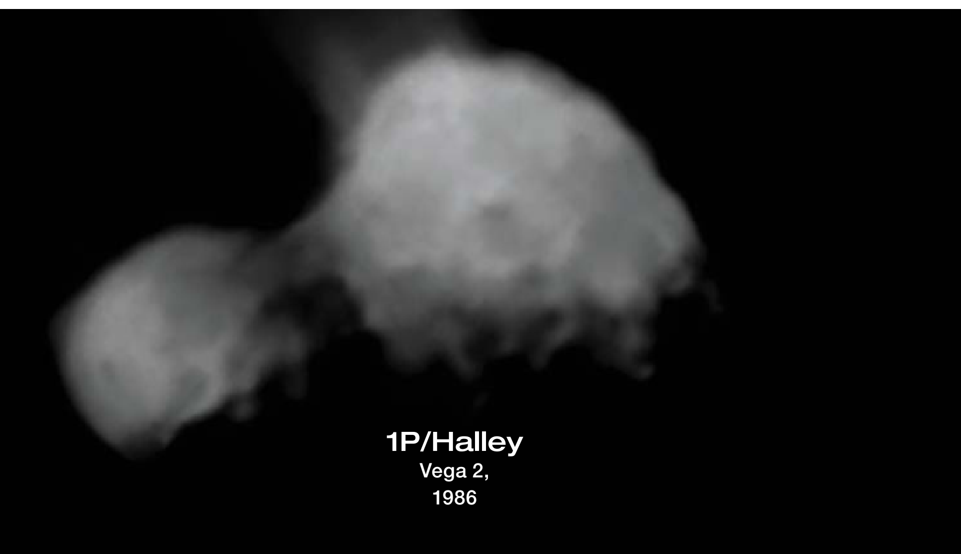


UP CLOSE Spacecraft have imaged six comet nuclei up close. Four of these have a bilobe shape, including Comet Churyumov-Gerasimenko *(above right)*.

ing the time of planetary migration. They stay there until perturbations send them inward to the planetary region, where encounters with the giant planets make them the periodic comets we see in the inner solar system. Comet Churyumov-Gerasimenko, for example, now has a 6.44-year orbit that takes it just beyond Jupiter.

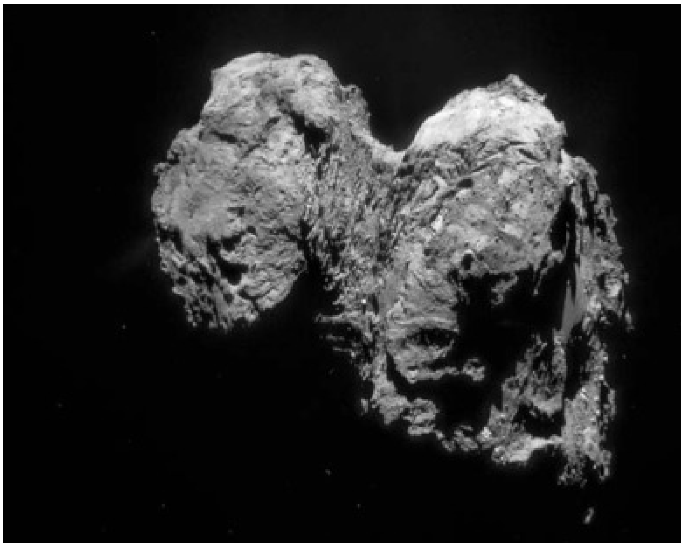
David Nesvorný (Southwest Research Institute) says mergers like those that produced Arrokoth in the Kuiper Belt might produce an object shaped like Comet Churyumov-Gerasimenko. But he doubts that the process could occur often enough to explain why two-thirds of the nuclei imaged so far are contact binaries.

Primordial Planetesimals on Ice

The New Horizons spacecraft launched in January 2006 to explore Pluto and the other objects in the Kuiper Belt that stretches beyond the orbit of Neptune. So far it has delivered spectacular close-up images of two Kuiper Belt binaries: Pluto with its five moons and the contact binary Arrokoth. The two share many features that come from having spent billions of years in the icy fringes of the solar system. However, even before New Horizons reached Arrokoth, we had learned that the Kuiper Belt is a refuge for a diverse range of objects that differ in their orbits, origins, and early histories.

Discovered 90 years ago this month, Pluto is the exemplar of a class of objects called *plutinos* that formed closer to the Sun, were scattered when Neptune migrated outward, and became locked into an orbital resonance with Neptune. Pluto's largest moon, Charon, was discovered in 1978 and is so large that the duo's center of mass lies outside Pluto entirely — the two bodies orbit a common center. The system likely formed when a giant impact on proto-Pluto blasted debris into orbit that accreted to form Charon.

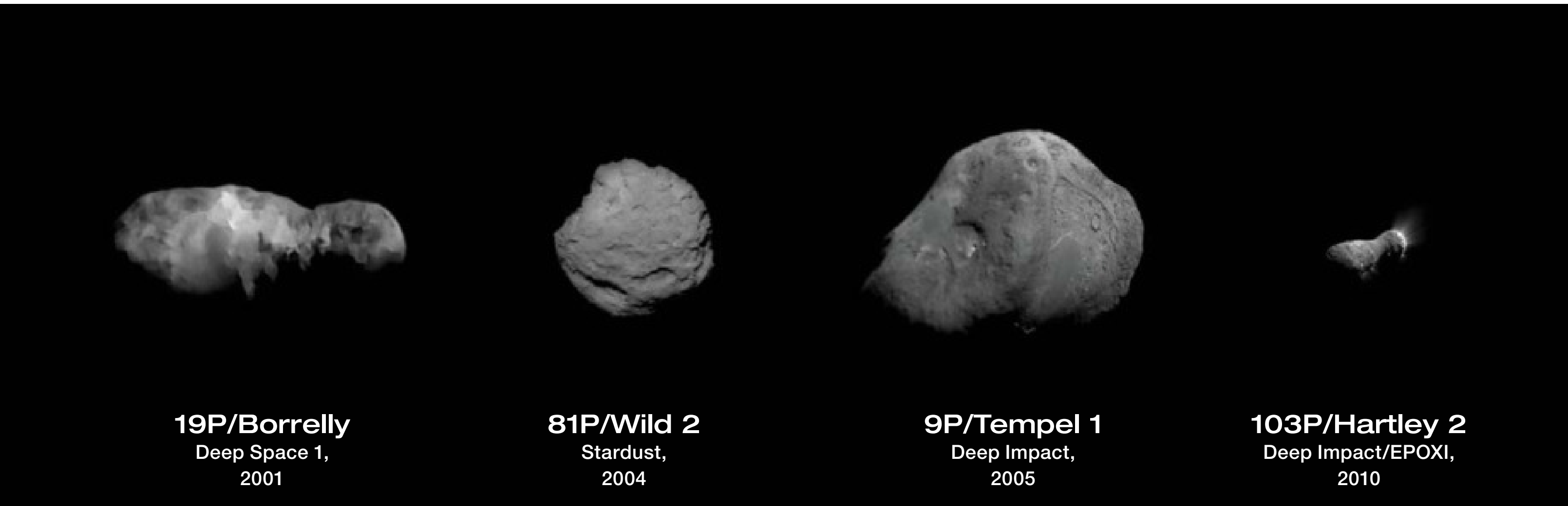
Hubble spotted two small new moons in the spring of 2005, soon before the New Horizons launch. The discovery of two more followed in 2011 and 2012. The four small moons are neatly spaced with orbital periods about three, four, five, and six times Charon's. Nesvorný says how they formed remains "a big puzzle."



▲ **COMET CHURYUMOV-GERASIMENKO** This post-perihelion Rosetta image reveals the linear, rugged terrain of the southern neck region, called Sobek. Cracks in this region might be due to the two lobes straining against each other. The nucleus is a couple of kilometers wide.

David Jewitt (then University of Hawai'i) and Jane Luu (then University of California, Berkeley) discovered the second of more than 2,000 known Kuiper Belt objects in 1992. Initially called 1992 QB_1 — and recently renamed 15760 Albion — it is smaller and fainter than Pluto. Albion's orbit is also more circular and lies almost flat in the plane of the solar system. Many more such bodies have been found in similar orbits and are called *cold classical objects* because their orbits are more planet-like than Pluto's.

Cold classical objects are thought to have formed directly from the outer part of the protoplanetary disk and remained unaltered for the past 4.6 billion years. That makes them the most pristine planetesimals we've found. Astronomers wanted



New Horizons to visit one, but Albion was out of its path so they searched for another and found Arrokoth in 2014. The images showed their choice was right. Arrokoth "is as primordial as it gets," says William McKinnon (Washington University in St. Louis). "It has not been disturbed and was not part of any large-scale rearrangement or orbital scattering."

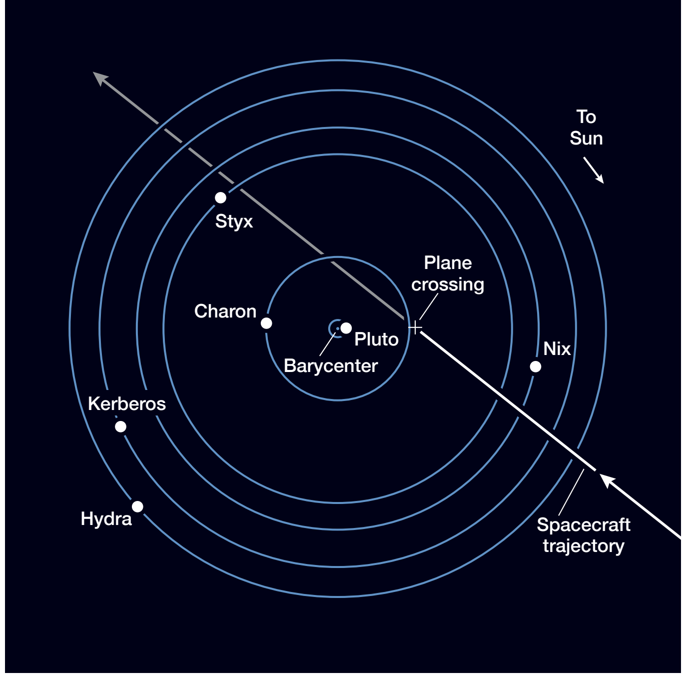
When initial images revealed Arrokoth was a contact binary, observers first assumed the two lobes were round. As more photos gave better perspective, Audrey Thirouin (Lowell Observatory) recalls, the squashed shapes "kind of surprised all of us." Two flattened oblong disks, 22 kilometers and 14 kilometers long, respectively, had collided end to end with no obvious deformation. They're spinning around an axis that passes through the larger one, close to the contact point. They also show several distinct topographic regions, which may be remnants of smaller pieces that accreted to form each lobe. Astronomers saw similar units on comets Churyumov-Gerasimenko and 9P/Tempel 1.

Scientists had predicted that about a third of all trans-Neptunian objects should be contact binaries. By studying light curves, Thirouin and Scott Sheppard (Carnegie Institution for Science) found that 10% to 25% of cold classical objects may be contact binaries made of equal-size members, lower than the 40% to 50% they found for *plutinos*. But we are still in the early days; observations are difficult and uncertainties are large.

The fraction of objects with companions in this region is high. Most of the largest objects found have at least one moon. "Binaries are much more common in the Kuiper Belt than anyone had appreciated," says McKinnon.

Curiously, more binaries have been found among 100-kilometer cold classical objects than had been expected. "We are talking about the majority of 100-kilometer objects being binaries," says Nesvorný. "That's really interesting."

The result shows intriguing similarities to computer models of the solar system's formation, which predict building blocks of the same size range. The models show that, as gas and dust collapse under their own gravitation into 100-kilometer-class bodies, an effect called the *streaming instability* mixes the stuff in a way that helps it stick together. Conditions in the collapsing cloud cause the clumps to form binaries with similar-size components.



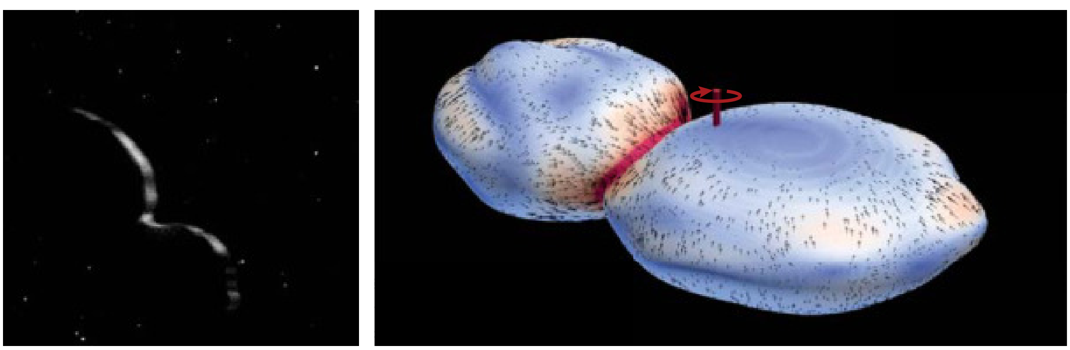
▲ **SEXTUPLE SYSTEM** Pluto and its five moons orbit the *barycenter* (center of gravity) of the Pluto-Charon binary. The outer four moons' shapes suggest they assembled from smaller fragments.

In both the model and for real trans-Neptunian binaries, 80% of the time the two bodies circle each other in the same direction as the pair revolves around the Sun. Nesvorný says the theory applies over a wide range of conditions, so the streaming instability could seed planetesimal formation around other stars, too.

More painstaking measurements and analysis are needed to identify binaries and to extract information on their orbits. Theoretical models need further analysis and more computer power. And more is on the way from New Horizons, which will not finish sending its Arrokoth data until September 2020 and may yet fly by a third Kuiper Belt object. Yet the dramatic close-ups of Arrokoth in the Kuiper Belt and Comet Churyumov-Gerasimenko closer to us have already shown us the richness of the minor planets that not too long ago were just faint dots in even our best telescopes.

■ **JEFF HECHT** writes about science and technology and is a fellow of the Optical Society. His most recent books are *Understanding Lasers* and *Lasers, Death Rays, and the Long, Strange Quest for the Ultimate Weapon*.

▶ **STRANGELY FLAT** Backlit views of Arrokoth *(left)* provided an outline of the part hidden in shadow during New Horizons' flyby. The profile helped scientists estimate the contact binary's shape *(right)*. Redder colors indicate steeper slopes, with the steepest at the neck. Black arrows show which direction is downslope — basically, which way a ball set on the surface would roll.



PLUTO SYSTEM: LEAH TISCIONE / *S&T*, SOURCE: SIMON PORTER ET AL.; BACKLIT VIEW OF ARROKOTH: NASA / JHU APL / SWRI / NOAO; SHAPE: NASA / JHU APL / SWRI