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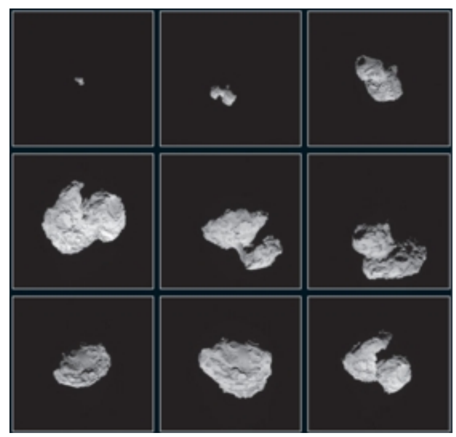
Kuiper Belt Missions Could Reveal the Solar System's Origins

For the first time, spacecraft will get an up-close look at comets, asteroids and dwarf planets from the distant Kuiper belt. These probes should reveal how the solar system came to be

Oct 14, 2014 | By Michael D. Lemonick |

January 20, 2014, was going to be either a very good or a very bad day for the men and women working on the Rosetta space probe. The 3,000-kilogram robotic spacecraft had been launched by the European Space Agency nearly 10 years earlier and was en route to an August encounter with an obscure comet bearing the unwieldy name 67P/Churyumov-Gerasimenko (67P for short). If all went according to plan, Rosetta would do something that has never been attempted before: it would loop into a tight orbit around the comet, deploy a lander named Philae to touch down on its surface, and shadow the frozen body as it crackled to life, warmed by the heat of the sun.



ZOOMING IN: As the Rosetta spacecraft approached Comet 67P/Churyumov-Gerasimenko, it captured these increasingly detailed views.

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But for any of that to happen, Rosetta first had to wake up. It had been placed into an energy-conserving state of hibernation more than two years before. At 11 a.m. Central European time on January 20, its internal alarm clock was set to go off. The scientists and engineers waiting in a control room at the European Space Operations Center in Darmstadt, Germany, were confident that the craft would report in as planned. But they were also mindful of the Mars Observer probe, which, in 1993, vanished from radio contact without a trace. For a few minutes, it seemed as though it might be happening again.

"I saw a lot of white faces around the room," recalls Holger Sierks of the Max Planck Institute for Solar System Research in Göttingen, Germany, who is in charge of the spacecraft's optical and infrared cameras. It felt like an eternity, although it was more like 15 minutes—but finally, an electronic ping reached Darmstadt from out beyond Jupiter. "It said, 'Here I am again,'" Sierks says, "and that was an enormous relief."

In the ensuing weeks it became clear that Rosetta was not just awake but fully functional and poised to answer crucial questions about the structure, composition, behavior and origin of comets—icy bodies that have remained largely unaltered since the solar system formed some 4.6 billion years ago. Later this month Rosetta will release its lander, which will drill down past the comet's surface to excavate the very history of the solar system.

Rosetta is not alone out there, either. In July 2015, after its own nine-year journey, nasa's New Horizons probe will perform another first: a close flyby of Pluto and its five known moons. “The spacecraft is in spectacularly good shape,” reports principal investigator Alan Stern of the Southwest Research Institute's office in Boulder, Colo. And although the two missions are independent, they are not unrelated. Astronomers now understand that Pluto and 67P are members of the Kuiper belt, a vast, largely uncharted swarm of billions of objects beyond Neptune, ranging in size from a few meters to more than 2,000 kilometers across.

These encounters will cap off a series of discoveries over the past two decades that have, as Stern puts it, “blown the doors off and literally rewritten everything we thought we knew about the architecture of the solar system.” Just a bit more than 20 years ago, in fact, nobody even knew that the Kuiper belt existed. Since then, planetary scientists have discovered a handful of frozen worlds that approach and even rival Pluto in size. They have seen evidence that points to a long-ago violent reshuffling of the orbits of Jupiter, Saturn, Uranus and Neptune—and maybe even to the existence of a lost fifth giant planet. They have analyzed the sizes and orbits of the 1,500 or so known Kuiper belt objects (KBOs) to get a handle on how the belt itself took shape—wondering whether crashing icefalls from the nascent Kuiper belt once bestowed oceans on a young, dry Earth.

Each of these observations has served as a narrow window into the origin and evolution of the Kuiper belt. Together, however, like the apocryphal story of the blind men and the elephant, they have begun to paint a more comprehensive picture of its structure, composition and evolution. And with two spacecraft nearing first-ever close encounters with two very different KBOs, that picture is about to become dramatically clearer.

Discovered Again

When a young astronomer named Clyde Tombaugh spotted a new body out beyond Neptune in 1930, he and the rest of the astronomical community had no doubt that he had found “Planet X,” the long-suspected ninth planet in the solar system. Initially the new object—named Pluto at the suggestion of an 11-year-old British schoolgirl named Venetia Burney—was calculated to have a mass similar to Earth's. By the 1970s, however, it was clear that Pluto was smaller and much less massive than Earth's moon. What Tombaugh had actually found was the brightest member of the Kuiper belt.

Nobody would realize until the 1980s, however, that such a thing as the Kuiper belt even existed. That included Gerard Kuiper, the Dutch-American astronomer whose name it bears. In the 1950s Kuiper proposed that the region just beyond Neptune might once have been filled with icy bodies. But he thought that the gravity of “massive” Pluto would have scattered them away into deep space. That part of the solar system, he wrote, should be mostly empty. “It was really an antiprediction,” says University of California, Los Angeles, astronomer David C. Jewitt, a pioneer in observations of the outer solar system.

At about the same time, Kuiper's countryman Jan Oort hypothesized that those widely scattered objects would have formed a spherical cloud of proto-comets orbiting as much as a light-year away from the sun. Occasionally, he suggested, one of them would be jostled loose and fall into the inner solar system, where it would burst into life as a comet. This scenario neatly explained the existence of long-period comets, which fall in from all directions and whose orbital paths take at least 200 years to complete.

But it did not explain shorter-period comets, which tend to zoom in along the relatively flat plane where the planets dwell. Oort thought these were just long-period comets that had been diverted into shorter orbits by close encounters with the giant planets, and nobody had a better idea. (Or almost nobody: back in the 1940s, Irish astronomer Kenneth Edgeworth had suggested the short-period comets came from a swarm of small bodies whose home was much closer in. But he made the suggestion in a general way and only in passing. “If you think that counts as a prediction, fine,” says Michael E. Brown, the California Institute of Technology astronomer whose 2005 discovery of the Pluto-size KBO Eris ended up demoting Pluto to the status of “dwarf planet” the following year. Brown clearly does not think it counts, and in any case, nobody paid any attention to Edgeworth's idea at the time.)

The first legitimate prediction of the Kuiper belt's existence, most planetary scientists now agree, came from Uruguayan astronomer

Julio Fernández. His 1980 paper "On the Existence of a Comet Belt beyond Neptune" made the same case Edgeworth had but with far more scrupulous detail. In 1988 Scott Tremaine, then at the University of Toronto, along with his colleagues Martin Duncan and Thomas Quinn, showed that the swarm of bodies Fernández had predicted would in fact explain the frequency and trajectories of short-period comets. They were the first to use the term "Kuiper belt," although, says Tremaine, now at the Institute for Advanced Study in Princeton, N.J., "it's probably the wrong term. Fernández is really the one we should have named it for."

While Tremaine, Duncan and Quinn were nailing down the theoretical case for the Kuiper belt, Jewitt and Jane X. Luu, then his student at the Massachusetts Institute of Technology, began looking for hard evidence. Their search was not motivated by the predictions: Jewitt and Luu did not know about Fernández's paper, and they began their search in 1986, two years before Tremaine and his colleagues published their results. "What encouraged us and motivated us," Jewitt says, "was this simple idea that it's just weird that the outer solar system would be so empty."

Of course, it was not empty. In August 1992, using a 2.2-meter telescope at the summit of the extinct volcano Mauna Kea in Hawaii, Jewitt and Luu found the first KBO, 1992 QB1, as part of what they called the Slow Moving Object survey. They found the second KBO about six months later, and while Jewitt and Luu were pretty much the only ones searching at the time, "the astronomical community wised up quickly," Jewitt says. Astronomers have now identified about 1,500 KBOs; based on these numbers, they estimate that the Kuiper belt is home to 100,000 objects more than 100 kilometers across and up to 10 billion larger than two kilometers across. "For every asteroid in the main asteroid belt," Jewitt says, "there are 1,000 objects in the Kuiper belt. It's staggering to me."

Many astronomers, however, are more shocked by what isn't in the Kuiper belt. According to their best models of planet formation, it should boast objects as big as Earth and even bigger. Yet while Pluto has been joined by objects that rival it in size—worlds such as Makemake, Haumea, Quaoar and Eris—nothing has yet been found that comes close to any of the planets. "There's a vast number of bodies out there," Jewitt says, "but all told, they only add up to a 10th of the mass of Earth. That's really kind of puny."

Something must have happened early in the solar system's history to snuff out the largest members of the Kuiper belt. For years planetary astronomers have argued about what it could be. With Rosetta and New Horizons, they should finally start getting some answers.

Ejection Model

By the time the Kuiper belt was discovered, physicists had already established how the solar system came to be. It began with a huge interstellar cloud of gas and dust, which collapsed to form a spinning disk. At its core, gravity pulled the disk into a knot of matter so dense and hot that it burst into thermonuclear fire, thus forming the sun.

The sun's heat and radiation drove most of the gases and some of the dust outward; closer in, the dust congealed into pebbles, then boulders, then asteroid-size bodies known as planetesimals. Finally, in the last states of planet formation, hundreds of Mars-size objects would have been flying around, smashing apart, slamming together again and ultimately forming the eight planets we see today—not just the rocky inner planets but also Jupiter, Saturn, Uranus and Neptune, which are basically chunks of rock with enough gravity to vacuum up enormous amounts of surrounding gas.

Beyond Neptune, the "dust" would have been mostly ice particles, which should have formed into planet-size objects by a similar process. There are two problems with this scenario. One is that astronomers simply do not see these planet-size objects (although, Brown says, for all we know, there might be a few objects as big as Mars out in the distant Oort cloud, where they cannot be detected with current technology).

The other problem is that there is not enough matter in the Kuiper belt to account for the existence of any objects of *any* size. If all of the material in all existing KBOs had started out as a primordial cloud of icy dust, that cloud would have been too widely dispersed to ever form into anything at all.

The very existence of the Kuiper belt therefore appears inconsistent with how theorists believe it must have formed. "The consensus solution," Jewitt says, "is that in the beginning there was far more material—30, 40 or even 50 Earth masses' worth" in the Kuiper belt.

This material did form into a gigantic swarm of objects, but that collection was whittled down somehow.

The most plausible mechanism for the “somehow,” first suggested by Renu Malhotra, a physicist at the University of Arizona, is that the solar system's four giant planets—Jupiter, Saturn, Uranus and Neptune—were once crowded much more closely together than they are now.

Malhotra and several of her colleagues argued that gravitational interactions between these tightly bunched planets and the primordial gaggle of KBOs pushed Saturn, Uranus and Neptune outward. At the same time, Jupiter, interacting with both KBOs and asteroids, moved inward.

These gravitational encounters would not only have shuffled the planets around but would also have flung many KBOs out to the far edges of the sun's gravitational influence, creating the distant Oort cloud, and have thrown many asteroids in toward the inner solar system. During their migration, moreover, Jupiter and Saturn would have found themselves, for a time, in a resonance with each other, a situation in which Saturn would have made exactly one orbit for every two of Jupiter's.

With the extra gravitational punch generated by having two planets lined up so precisely, KBOs would have been scattered with such vigor that more than 99 percent of them would have been swept away. Some would have ended up in the Oort cloud. Others would have smashed into the inner planets in a cataclysm known as the late heavy bombardment. “The solar system would have taken a savage beating,” Jewitt says.

At least one physicist, David Nesvorný of the Southwest Research Institute, takes the idea one step further. The solar system might, he argues, have once boasted a fifth gas-giant planet, which would have been ejected into interstellar space during this violent reshuffling.

If the reshuffling of the giant planets really happened, it could explain why the Kuiper belt has no truly large objects: the material that would have built them was prematurely swept away. The objects that did form, moreover, would have looked a lot like planetesimals—small proto-planets that later combined to form planets. In this view, the Kuiper belt is like a snapshot, frozen in time, of what the rocky inner solar system looked like just a few million years after the planet-formation process had gotten under way.

“The biggest uncertainty in how the existing planets formed,” says M.I.T. planetary scientist Hilke Schlichting, “is the formation of the planetesimals—how they came to exist and how big they were.” That information is long gone from the inner solar system, but using a combination of observations and models, she and her colleagues have shown that the size distribution of Kuiper belt objects can be explained if the icy planetesimals they came from were typically about a kilometer across—an insight that might apply to the inner planets as well. “We're beginning to learn,” she says, “after decades of speculation, about the initial conditions for planet formation.”

Pluto's Close-up

Models and remote observations have told planetary scientists an enormous amount about the structure and likely history of the Kuiper belt. That is no substitute for close-up observations, however, as scores of space probes to all the planets and dozens of moons and asteroids have shown. “A Hubble picture of Pluto is cool,” Stern says, “but it's just a couple of pixels across.” By next June, “Pluto will come rushing up to us as a real world,” he adds.

That world was still a planet when New Horizons launched in January 2006; its demotion to dwarf planet did not come until the next summer. But whatever you call it, Stern and his co-investigators will try to learn as much as they can as the craft speeds toward and past Pluto and its moon Charon at nearly 40,000 kilometers an hour, coming within just 10,000 kilometers of its frozen surface.

One goal will be to count the craters that are virtually certain to pockmark Pluto's icy surface, noting not just their overall number but also how many there are of a given size. That information will provide astronomers with an independent measure of the sizes of KBOs themselves, which would have smashed into Pluto in proportion to their abundance in the belt.

“But it's even better than that,” Stern says. Over time, Pluto's craters get scoured away by the same processes that create its wispy atmosphere: the repeated heating and cooling of its surface as the dwarf planet moves through its elongated orbit. Charon, however, has no atmosphere, which means that all its impacts have been preserved. “You can compare those two,” Stern says, “and find out how the impact history has changed, what the size range of projectiles is today versus what it was in the ancient Kuiper belt.”

New Horizons will also seek signs of a subsurface ocean. Planetary scientists have already found oceans tucked under the thick icy shells of some of the moons of Jupiter and Saturn: Europa, Ganymede, Enceladus and Titan. If Pluto has ice geysers or volcanoes, that is a clue that the interior is warm and watery—perhaps as the result of radioactive decay in a rocky core. And even if there are not outward signs of heat, the probe's infrared cameras can detect warm spots on the surface. The idea that life could exist inside Pluto is utterly speculative—but because liquid water is considered a necessary ingredient for biology as we know it, its discovery would at least make such speculation legitimate.

The spacecraft will do all this and more in just five months, with the most intense study coming in the day or so it takes to whiz past the dwarf planet. But it will take some 16 months for the data to be relayed, bit by bit, over the nearly five billion kilometers back to Earth.

Dance with a Comet

Rosetta will spend almost that long orbiting just above the surface of 67P. In contrast to New Horizons, which will zip past Pluto at high speed, Rosetta will fly in formation with its target for 15 months, enabling it to answer all kinds of questions about 67P's precise chemical makeup and its internal structure—valuable clues to understanding the nature of the gas and dust that originally built the Kuiper belt and the way KBOs were assembled. Scientists' current understanding is so rudimentary at this point that there is no “smoking gun” that could plausibly vindicate one theory and destroy the competition. What Rosetta finds, however, could help researchers put together a convincing theory for the first time.

The journey will also give Rosetta and its lander Philae a front-row seat as the comet awakens as it comes closer to the sun. “We'll be alongside the comet right through the summer of 2015, when activity is at a maximum and the nucleus is expelling 1,000 kilograms of material per minute,” says Matt Taylor of the European Space Agency, who is the principal investigator for the mission as a whole. Researchers still do not know if this material will come from all over the comet's surface or whether it will spray from small hotspots. A year from now that question will be answered, helping planetary scientists understand how and why comets eventually lose their ices and burn out.

Rosetta should also be able to address questions about us. In particular, where did Earth's water come from? Many planetary scientists believe that a storm of comets early in the solar system's history first delivered water to Earth. Rosetta will test this hypothesis by measuring whether the H2O locked up in 67P's ice is chemically identical to the H2O on Earth. There is already evidence from the Herschel Space Observatory that at least some comets carry water with the same ratio of hydrogen to its heavier isotope, deuterium, as the water in Earth's oceans. But Rosetta's instruments will get a far closer and more leisurely look at the comet's water and other constituents, including carbon-rich organic compounds that may have played a role in the origin of life.

Philae and Rosetta will also work together to settle the question of whether comets are simply large chunks of dirty ice or groups of smaller chunks that stick together relatively loosely under their own gravity. When the Rosetta orbiter is on the opposite side of the comet from Philae, it will beam a radio signal down through the body of the comet to Philae, where it will be reflected back. It is analogous to a CT scan, and it will show the scientists the inner structure of a comet for the first time.

Unfortunately for most of us, 67P will never be visible to the naked eye. Just as with Pluto and the vast majority of KBOs, you need artificial magnification even to know the comet is there. It is therefore no wonder that astronomers have only recently come to understand that the Kuiper belt exists at all and to appreciate its potentially crucial role in the history and architecture of the solar system.

By the end of next year, thanks to two probes that set out on their journeys nearly a decade ago, we will understand incomparably more.

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ABOUT THE AUTHOR(S)

Michael D. Lemonick is a writer at Climate Central, a nonprofit news site, and author of *Mirror Earth: The Search for Our Planet's Twin* (Walker Books, 2012). For 21 years he was a science writer for *Time* magazine.

MORE TO EXPLORE

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SCIENTIFIC AMERICAN ONLINE See video animations of Rosetta's and New Horizons's journeys at ScientificAmerican.com/nov2014/kuiper-belt