The Kuiper Belt

Rather than ending abruptly at the orbit of Pluto, the outer solar system contains an extended belt of small bodies

by Jane X. Luu and David C. Jewitt

After the discovery of Pluto in 1930, many astronomers became intrigued by the possibility of finding a 10th planet circling the sun. Cloaked by the vast distances of interplanetary space, the mysterious "Planet X" might have remained hidden from even the best telescopic sight, or so these scientists reasoned. Yet decades passed without detection, and most researchers began to accept that the solar system was restricted to the familiar set of nine planets.

But many scientists began seriously rethinking their notions of the solar system in 1992, when we identified a small celestial body—just a few hundred kilometers across—sited farther from the sun than any of the known planets. Since that time, we have identified nearly three dozen such objects circling through the outer solar system. A host of similar objects is likely to be traveling with them, making up the so-called Kuiper belt, a region named for Dutch-American astronomer Gerard P. Kuiper, who, in 1951, championed the idea that the solar system contains this distant family.

What led Kuiper, nearly half a century ago, to believe the disk of the solar system was populated with numerous small bodies orbiting at great distances from the sun?

OUTER EXTREMITIES of the solar system preserve primordial material remaining from the time the planets first formed. During that early era, Pluto (*foreground*) may have captured its satellite, Charon (*right*), while casting a third body (*top*) away into space. At the time, the region would have been thick with dust and rife with growing Kuiper belt objects.

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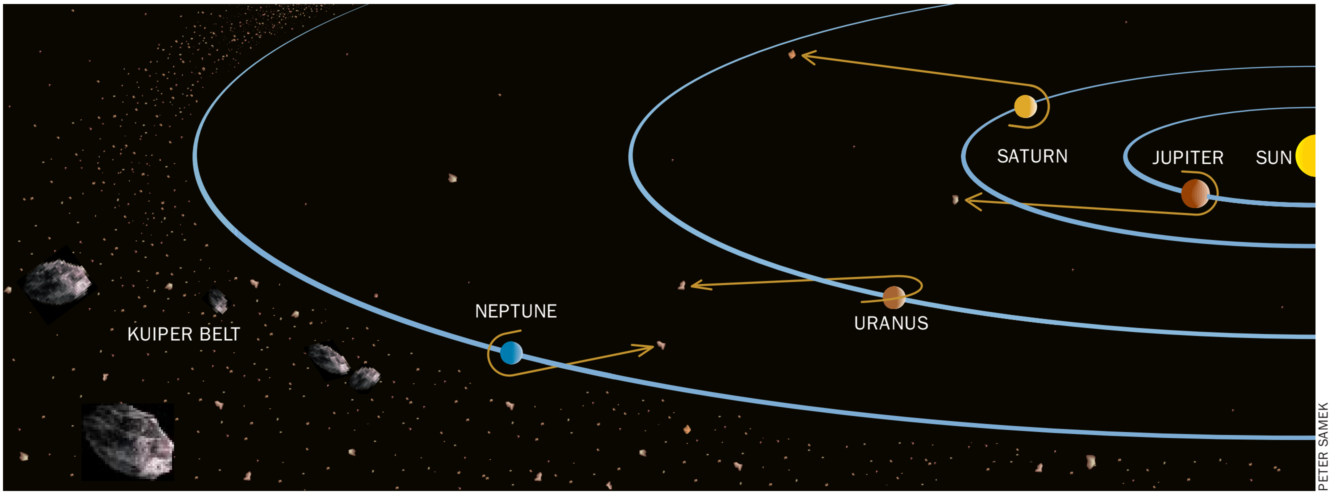
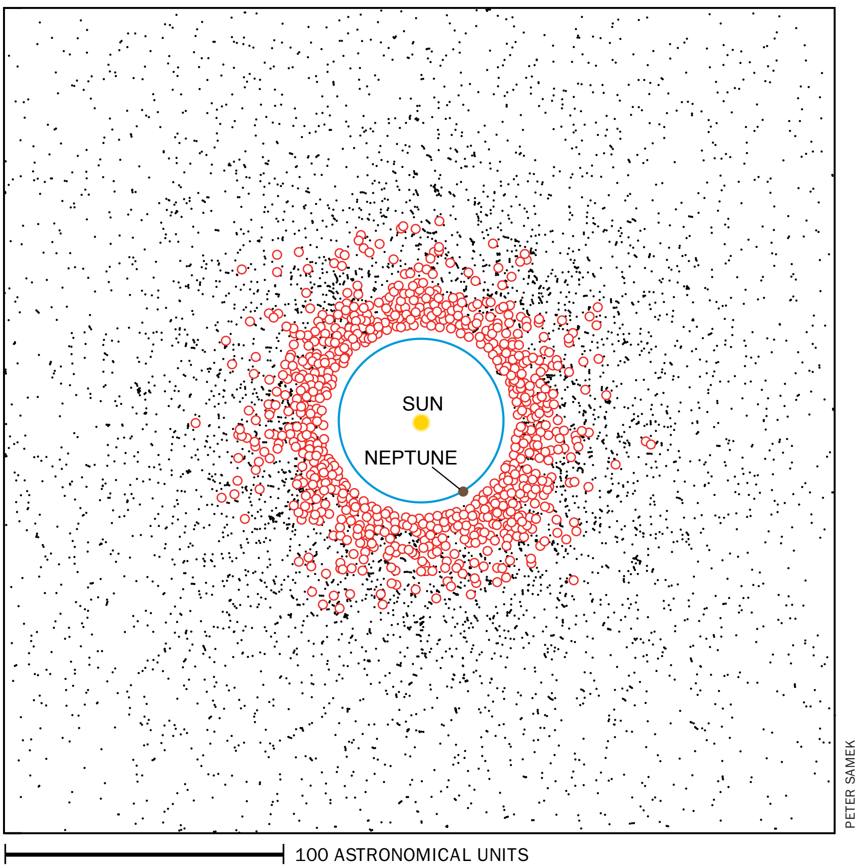


GRAVITY OF THE PLANETS acted during the early stages of the solar system to sweep away small bodies within the orbit of Neptune. Some of these objects plummeted toward the sun; others sped outward toward the distant Oort cloud (*not shown*).

His conviction grew from a fundamental knowledge of the behavior of certain comets—masses of ice and rock that on a regular schedule plunge from the outer reaches of the solar system inward toward the sun. Many of these comparatively small objects periodically provide spectacular appearances when the sun's rays warm them enough to drive dust and gas off their surfaces into luminous halos (creating large "comae") and elongate tails.

Astronomers have long realized that such active comets must be relatively new members of the inner solar system. A body such as Halley's comet, which swings into view every 76 years, loses about one ten-thousandth of its mass on each visit near the sun. That comet will survive for only about 10,000 orbits, lasting perhaps half a million years in all. Such comets were created during the formation of the solar system 4.5 billion years ago and should have completely lost their volatile constituents by now, leaving behind either inactive, rocky nuclei or diffuse streams of dust. Why then are so many comets still around to dazzle onlookers with their displays?



COUNTLESS OBJECTS in the Kuiper belt may orbit far from the sun, but not all of those bodies can be seen from Earth. Objects (*circles*) that could reasonably be detected with the telescope on Mauna Kea in Hawaii typically lie near the inner border of the belt, as seen in this computer simulation of the distribution of distant matter.

Guiding Lights

The comets that are currently active formed in the earliest days of the solar system, but they have since been stored in an inactive state—most of them preserved within a celestial deep freeze called the Oort cloud. The Dutch astronomer Jan H. Oort proposed the existence of this sphere of cometary material in 1950. He believed that this cloud had a diameter of about 100,000 astronomical units (AU—a distance defined as the average separation between Earth and the sun, about 150 million kilometers) and that it contained several hundred billion individual comets. In Oort's conception, the random gravitational jostling of stars passing nearby knocks some of the outer comets in the cloud from their stable orbits and gradually deflects their paths to dip toward the sun.

For most of the past half a century, Oort's hypothesis neatly explained the size and orientation of the trajectories that the so-called long-period comets (those that take more than 200 years to circle the sun) follow. Astronomers find that those bodies fall into the planetary region from random directions—as would be expected for comets originating in a spherical repository like the Oort cloud. In contrast, Oort's hypothesis could not explain short-period comets that normally occupy smaller orbits tilted only slightly from the orbital plane of Earth—a plane that astronomers call the ecliptic.

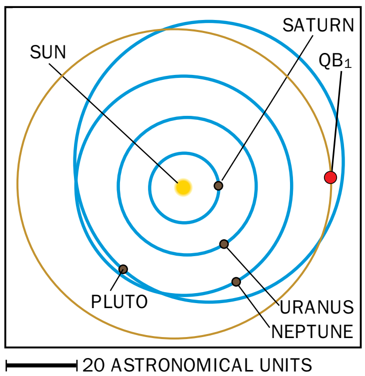
Most astronomers believed that the short-period comets originally traveled in immense, randomly oriented orbits (as the long-period comets do today) but that they were diverted by the gravity of the planets—primarily Jupiter—into their current orbital configuration. Yet not all scientists subscribed to this idea. As early as 1949, Kenneth Essex Edgeworth, an Irish gentleman-scientist (who was not affiliated with any research institution) wrote a scholarly article suggesting that there could be a flat ring of comets in the outer solar system. In his 1951 paper, Kuiper also discussed such a belt of comets, but he did not refer to Edgeworth's previous work.

Kuiper and others reasoned that the disk of the solar system should not end abruptly at Neptune or Pluto (which vie with each other for the distinction of being the planet most distant from the sun). He envisioned instead a belt beyond Neptune and Pluto consisting of residual material left over from the formation of the planets. The density of matter in this outer region would be so low that large planets could not have accreted there, but smaller objects, perhaps of asteroidal dimensions, might exist. Because these scattered remnants of primordial material were so far from the sun, they would maintain low surface temperatures. It thus seemed likely that these distant objects would be composed of water ice and various frozen gases—making them quite similar (if not identical) to the nuclei of comets.

Kuiper's hypothesis languished until the 1970s, when Paul C. Joss of the Massachusetts Institute of Technology began to question whether Jupiter's gravity could in fact efficiently transform long-period comets into short-period ones. He noted that the probability of gravitational capture was so small that the large number of short-period comets that now exists simply did not make sense. Other researchers were, however, unable to confirm this result, and the Oort cloud remained the accepted source of the comets, long and short period alike.

But Joss had sown a seed of doubt, and eventually other astronomers started to question the accepted view. In 1980 Julio A. Fernández (then at the Max Planck Institute for Aeronomy in Katlenburg-Lindau) had, for example, done calculations that suggested that short-period comets could come from Kuiper's proposed trans-Neptunian source. In 1988 Martin J. Duncan of the University of Toronto, Thomas Quinn and Scott D. Tremaine (both at the Canadian Institute for Theoretical Astrophysics) used computer simulations to investigate how the giant gaseous planets could capture comets. Like Joss, they found that the process worked rather poorly, raising doubts about the veracity of this well-established concept for the origin of short-period comets. Indeed, their studies sounded a new alarm because they noted that the few comets that could be drawn from the Oort cloud by the gravitational tug of the major planets should be traveling in a spherical swarm, whereas the orbits of the short-period comets tend to lie in planes close to the ecliptic.

Duncan, Quinn and Tremaine reasoned that short-period comets must have been captured from original orbits



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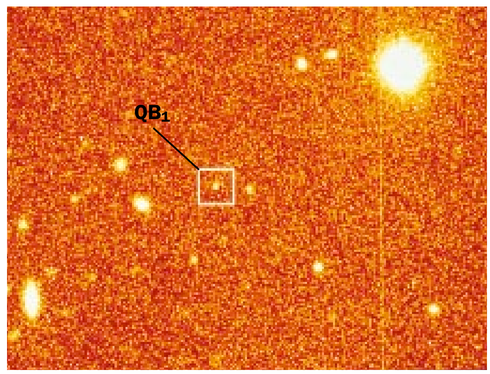

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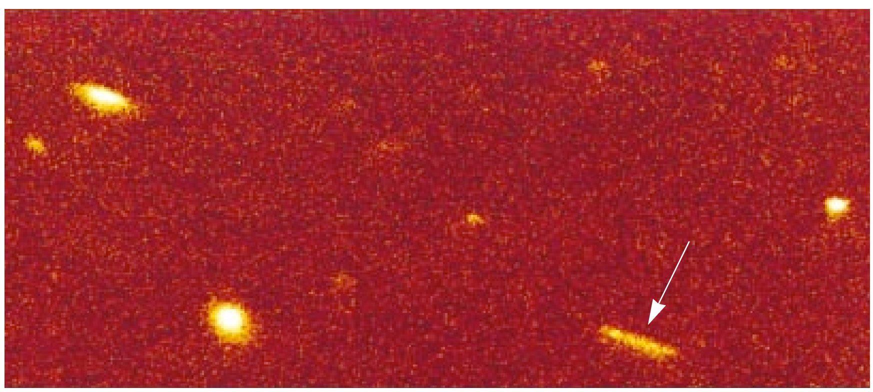

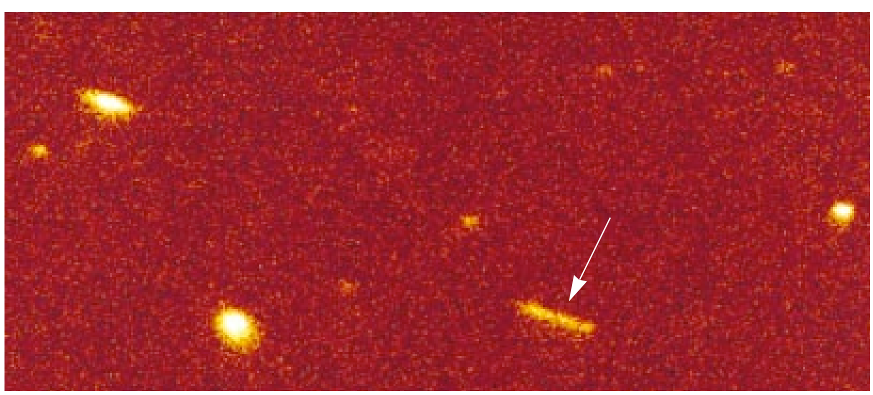
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SEQUENTIAL CCD EXPOSURES from 1992 revealed Kuiper belt object QB_1 clearly against the background of fixed stars (*middle* and *bottom*). This pair of images covers only a small part of the complete CCD frame (*top right*) that had to be analyzed before the authors could identify QB_1 (*arrows*) and determine its orbit (*top left*).

that were canted only slightly from the ecliptic, perhaps from a flattened belt of comets in the outer solar system. But their so-called Kuiper belt hypothesis was not beyond question. In order to make their calculations tractable, they had exaggerated the masses of the outer planets as much as 40 times (thereby increasing the amount of gravitational attraction and speeding up the orbital evolution they desired to examine). Other astrophysicists wondered whether this computational sleight of hand might have led to an incorrect conclusion.

Why Not Just Look?

Even before Duncan, Quinn and Tremaine published their work, we wondered whether the outer solar system was truly empty or instead full of small, unseen bodies. In 1987 we began a telescopic survey intended to address exactly that question. Our plan was to look for any objects that might be present in the outer solar system using the meager amount of sunlight that would be reflected back from such great distances. Although our initial efforts employed photographic plates, we soon decided that a more promising approach was to use an electronic detector (a charge-coupled device, or CCD) attached to one of the larger telescopes.

We conducted the bulk of our survey using the University of Hawaii's 2.2-meter telescope on Mauna Kea. Our strategy was to use a CCD array with this instrument to take four sequential, 15-minute exposures of a particular segment of the sky. We then enlisted a computer to display the images in the sequence in quick succession—a process astronomers call "blinking." An object that shifts slightly in the image against the background of stars (which appear fixed) will reveal itself as a member of the solar system.

For five years, we continued the search with only negative results. But the technology available to us was improving so rapidly that it was easy to maintain enthusiasm (if not funds) in the continuing hunt for our elusive quarry. On August 30, 1992, we were taking the third of a four-exposure sequence while blinking the first two images on a computer. We noticed that the position of one faint "star" appeared to move slightly between the successive frames. We both fell silent. The motion was quite subtle, but it seemed definite. When we compared the first two images with the third, we realized that we had indeed found something out of the ordinary. Its slow motion across the sky indicated that the newly discovered object could be traveling beyond even the outer reaches of Pluto's distant orbit. Still, we were suspicious that the mysterious object might be a near-Earth asteroid moving in parallel with Earth (which might also cause a slow apparent motion). But further measurements ruled out that possibility.

We observed the curious body again on the next two nights and obtained accurate measurements of its position, brightness and color. We then communicated these data to Brian G. Marsden, director of the International Astronomical Union's Central Bureau of Astronomical Telegrams at the Smithsonian Astrophysical Observatory in Cambridge, Mass. His calculations indicated that the object we had discovered was indeed orbiting the sun at a vast distance (40 AU)—only slightly less remote than we had first supposed. He assigned the newly discovered body a formal, if somewhat drab, name based on the date of discovery: he christened it "1992 QB_1." (We preferred to call it "Smiley," after John Le Carré's fictional spy, but that name did not take hold within the conservative astronomical community.)

Our observations showed that QB_1 reflects light that is quite rich in red hues compared with the sunlight that illuminates it. This odd coloring matched only one other object in the solar system—a peculiar asteroid or comet called 5145 Pholus. Planetary astronomers attribute the red color of 5145 Pholus to the presence of dark, carbon-rich material on its surface. The similarity between QB_1 and 5145 Pholus thus heightened our excitement during the first days after the discovery. Perhaps the object we had just located was coated by some kind of red material abundant in organic compounds. How big was this ruddy new world? From our first series of measurements, we estimated that QB_1 was be-

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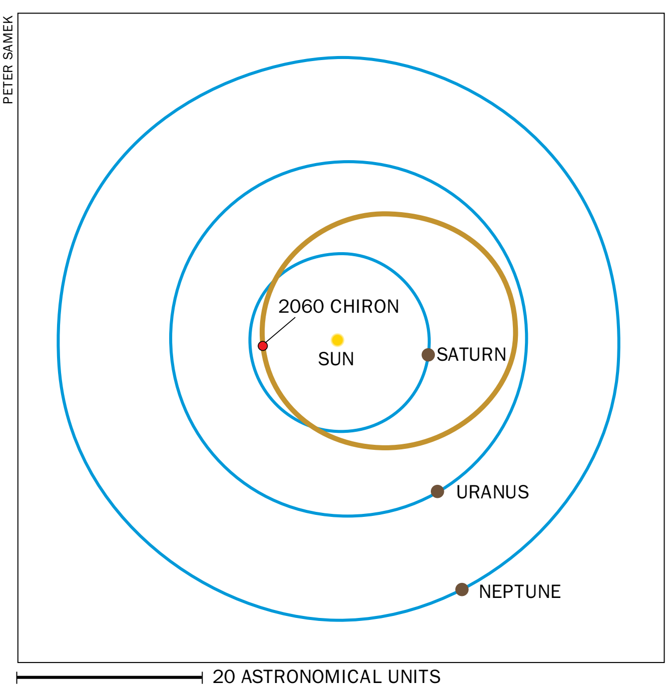
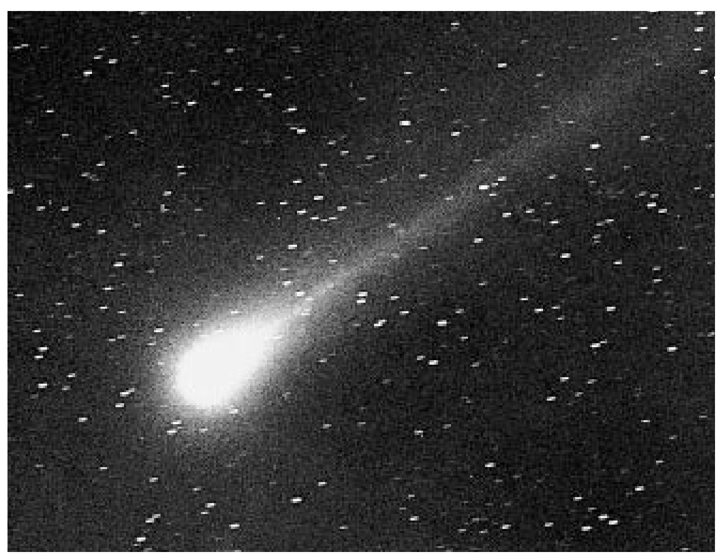




YERKES OBSERVATORY

2060 CHIRON may have escaped from the Kuiper belt into its current planet-crossing orbit (*left*). Although quite faint, the subtle glow surrounding 2060 Chiron (*far right*) marks this object as a celestial cousin to other "active" bodies, such as Comet Peltier (*above*).

tween 200 and 250 kilometers across—about 15 times the size of the nucleus of Halley's comet.

Some astronomers initially doubted whether our discovery of QB_1 truly signified the existence of a population of objects in the outer solar system, as Kuiper and others had hypothesized. But such questioning began to fade when we found a second body in March 1993. This object is as far from the sun as QB_1 but is located on the opposite side of the solar system. During the past three years, several other research groups have joined the effort, and a steady stream of discoveries has ensued. The current count of trans-Neptunian, Kuiper belt objects is 32.

The known members of the Kuiper belt share a number of characteristics. They are, for example, all located beyond the orbit of Neptune, suggesting that the inner edge of the belt may be defined by this planet. All these newly found celestial bodies travel in orbits that are only slightly tilted from the ecliptic—an observation consistent with the existence of a flat belt of comets. Each of the Kuiper belt objects is millions of times fainter than can be seen with the naked eye. The 32 objects range in diameter from 100 to 400 kilometers, making them considerably smaller than both Pluto (which is about 2,300 kilometers wide) and its satellite, Charon, (which measures about 1,100 kilometers across).

The current sampling is still quite modest, but the number of new solar system bodies found so far is sufficient to establish beyond doubt the existence of the Kuiper belt. It is also clear that the belt's total population must be substantial. We estimate that the Kuiper belt contains at least 35,000 objects larger than 100 kilometers in diameter. Hence, the Kuiper belt probably has a total mass that is hundreds of times larger than the well-known asteroid belt between the orbits of Mars and Jupiter.

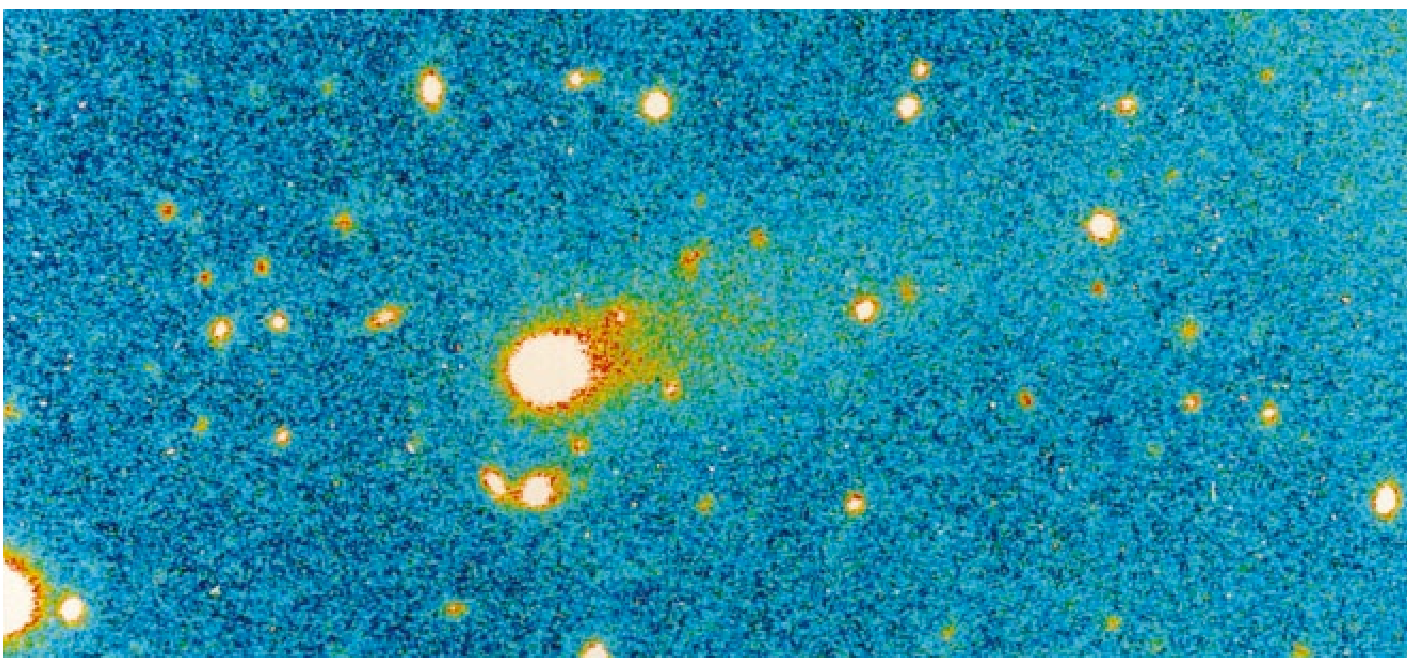
Cold Storage for Comets

The Kuiper belt may be rich in material, but can it in fact serve as the supply source for the rapidly consumed short-period comets? Matthew J. Holman and Jack L. Wisdom, both then at M.I.T., addressed this problem using computer simulations. They showed that within a span of 100,000 years the gravitational influence of the giant gaseous planets (Jupiter, Saturn, Uranus and Neptune) ejects comets orbiting in their vicinity, sending them out to the farthest reaches of the solar system. But a substantial percentage of trans-Neptunian comets can escape this fate and remain in the belt even after 4.5 billion years. Hence, Kuiper belt objects located more than 40 AU from the sun are likely to have held in stable orbits since the formation of the solar system.

Astronomers also believe there has been sufficient mass in the Kuiper belt to supply all the short-period comets that have ever been formed. So the Kuiper belt seems to be a good candidate for a cometary storehouse. And the mechanics of the transfer out of storage is now well understood. Computer simulations have shown that Neptune's gravity slowly erodes the inner edge of the Kuiper belt (the region within 40 AU of the sun), launching objects from that zone into the inner solar system. Ultimately, many of these small bodies slowly burn up as comets. Some—such as Comet Shoemaker-Levy 9, which collided with Jupiter in July 1994—may end their lives suddenly by striking a planet (or perhaps the sun). Others will be caught in a gravitational slingshot that ejects them into the far reaches of interstellar space.

If the Kuiper belt is the source of short-period comets, another obvious question emerges: Are any comets now on their way from the Kuiper belt into the inner solar system? The answer may lie in the Centaurs, a group of objects that includes the extremely red 5145 Pholus. Centaurs travel in huge planet-crossing orbits that are fundamentally unstable. They can remain among the giant planets for only a few million years before gravitational interactions either send them out of the solar system or transfer them into tighter orbits.

With orbital lifetimes that are far shorter than the age of the solar system, the Centaurs could not have formed where they currently are found. Yet the nature of their orbits makes it practical-



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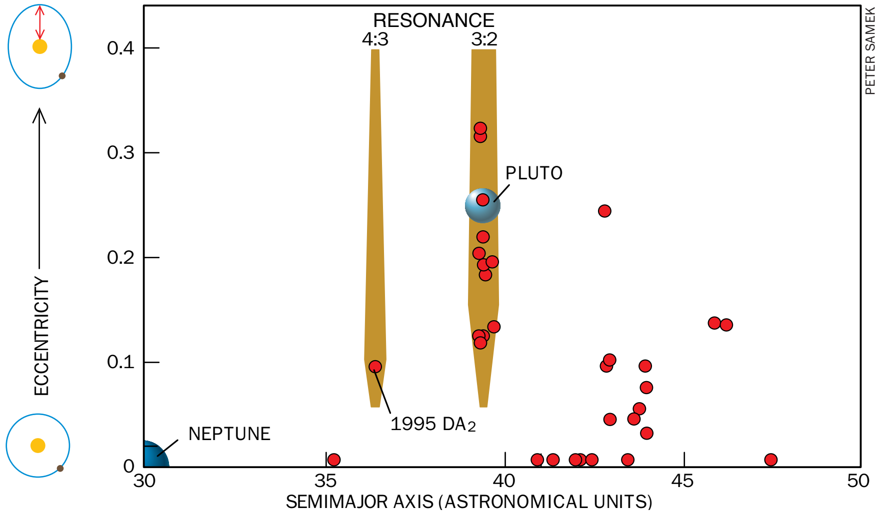

MEAN-MOTION RESONANCE governs the size and shape of the orbits of many Kuiper belt objects. Orbits are described by eccentricity (deviation from circularity) and semimajor axis (*red arrow*). Like Pluto, about half the known Kuiper belt bodies (*red points*) circle the sun twice while Neptune completes three orbits—a 3:2 resonance. The object 1995 DA_2 orbits in one of the other resonances. Renu Malhotra of the Lunar and Planetary Institute in Houston suggests that this pattern reflects the early evolution of the solar system, when many small bodies were ejected and the major planets migrated away from the sun. During these outward movements, Neptune could have drawn Pluto and a variety of smaller bodies into the resonant orbits that are now observed.

ly impossible to deduce their place of origin with certainty. Nevertheless, the nearest (and most likely) reservoir is the Kuiper belt. The Centaurs may thus be "transition comets," former Kuiper belt objects heading toward short but showy lives within the inner solar system. The strongest evidence supporting this hypothesis comes from one particular Centaur—2060 Chiron. Although its discoverers first thought it was just an unusual asteroid, 2060 Chiron is now firmly established as an active comet with a weak but persistent coma.

As astronomers continue to study the Kuiper belt, some have started to wonder whether this reservoir might have yielded more than just comets. Is it coincidence that Pluto, its satellite, Charon, and the Neptunian satellite Triton lie in the vicinity of the Kuiper belt? This question stems from the realization that Pluto, Charon and Triton share similarities in their own basic properties but differ drastically from their neighbors.

A Peculiar Trio

The densities of both Pluto and Triton, for instance, are much higher than any of the giant gaseous planets of the outer solar system. The orbital motions of these bodies are also quite strange. Triton revolves around Neptune in the "retrograde" direction—opposite to the orbital direction of all planets and most satellites. Pluto's orbit slants highly from the ecliptic, and it is so far from circular that it actually crosses the orbit of Neptune. Pluto is, however, protected from possible collision with the larger planet by a special orbital relationship known as a 3:2 mean-motion resonance. Simply put, for every three orbits of Neptune around the sun, Pluto completes two.

The pieces of the celestial puzzle may fit together if one postulates that Pluto, Charon and Triton are the last survivors of a once much larger set of similarly sized objects. S. Alan Stern of the Southwest Research Institute in Boulder first suggested this idea in 1991. These three bodies may have been swept up by Neptune, which captured Triton and locked Pluto—perhaps with Charon in tow—into its present orbital resonance.

Interestingly, orbital resonances appear to influence the position of many Kuiper belt objects as well. Up to one half of the newly discovered bodies have the same 3:2 mean-motion resonance as Pluto and, like that planet, may orbit serenely for billions of years. (The resonance prevents Neptune from approaching too closely and disturbing the orbit of the smaller body.) We have dubbed such Kuiper belt objects Plutinos—"little Plutos." Judging from the small part of the sky we have examined, we estimate that there must be several thousand Plutinos larger than 100 kilometers across.

The recent discoveries of objects in the Kuiper belt provide a new perspective on the outer solar system. Pluto now appears special only because it is larger than any other member of the Kuiper belt. One might even question whether Pluto deserves the status of a full-fledged planet. Strangely, a line of research that began with attempts to find a 10th planet may, in a sense, have succeeded in reducing the final count to eight. This irony, along with the many intriguing observations we have made of Kuiper belt objects, reminds us that our solar system contains countless surprises. SA

The Authors

JANE X. LUU and DAVID C. JEWITT came to study astronomy in different ways. For Jewitt, astronomy was a passion he developed as a youngster in England. Luu's childhood years were filled with more practical concerns: as a refugee from Vietnam, she had to learn to speak English and adjust to life in southern California. She became enamored of astronomy almost by accident, during a summer spent at the Jet Propulsion Laboratory in Pasadena. Luu and Jewitt began their collaborative work in 1986 at the Massachusetts Institute of Technology. Jewitt was a professor there when Luu became a graduate student. Jewitt moved to the University of Hawaii in 1988. It was during Luu's postdoctoral fellowship at the Harvard-Smithsonian Center for Astrophysics that Luu and Jewitt discovered the first Kuiper belt object. In 1994 Luu joined the faculty of Harvard University.

Further Reading

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