MICHELE BANNISTER *studies the solar system's minor planets at Queen's University, Belfast.*

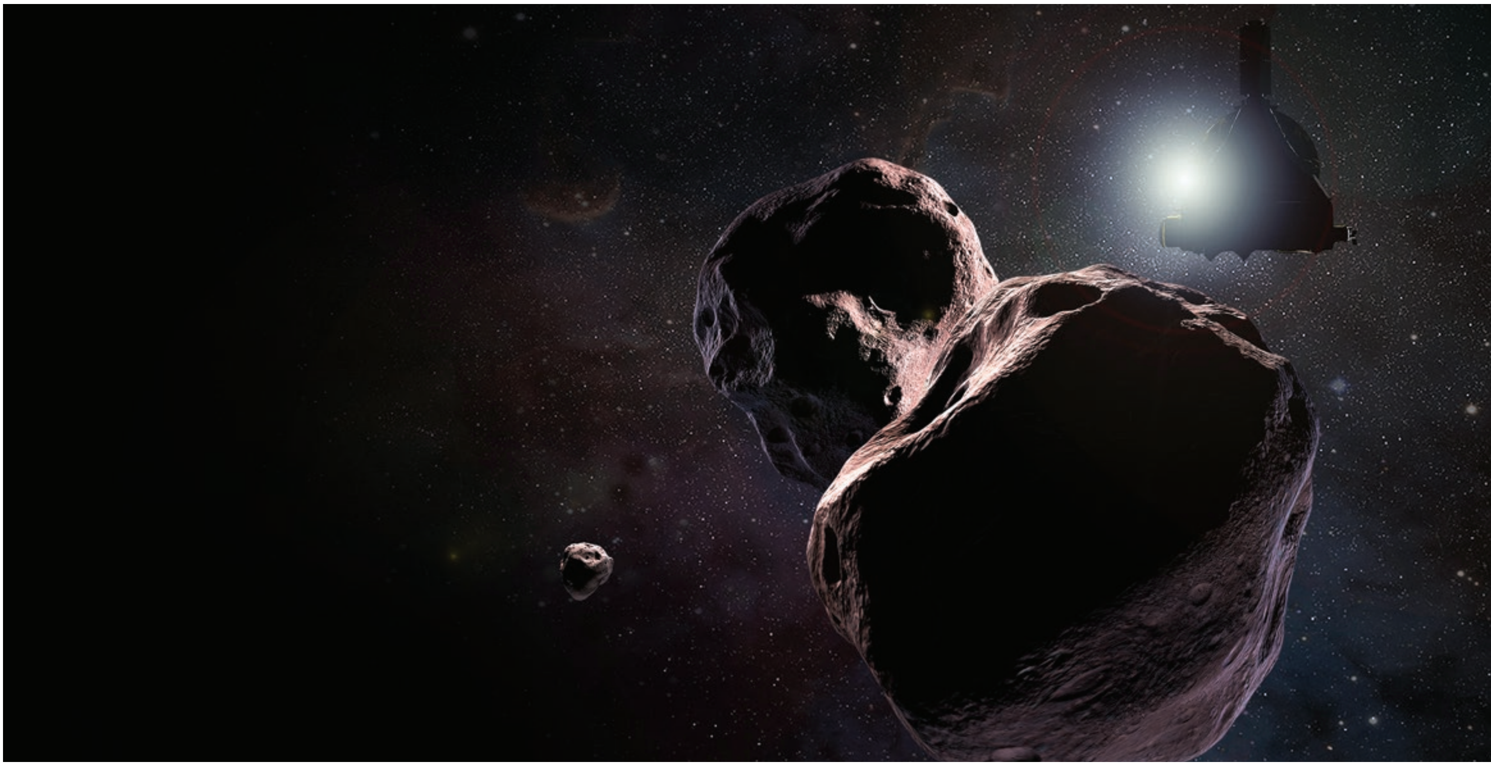


Illustration: NASA/JHU/SwRI/Steve Gribben

Beyond Neptune

Distant Minor Planets (840 of them!) Reveal the Outer Solar System

MAPPING THE OUTER solar system is a science that touches on art. For decades it has involved painstaking measurement of images by a combination of machine and person. The brassy gleam of the "blink comparator" of Clyde Tombaugh's time, a device for checking each point of light in paired images for motion over time, has given way to the digital era. Software now matches stationary stars and galaxies between images taken hours or days apart, discards the static dots of light, and keeps the ones that have shifted from one place to another. From these transient detections, we can piece together the slow tracks on the sky of tiny worlds, far from the Sun.

Trans-Neptunian objects (TNOs), orbiting at more than 30 times the distance between Earth and the Sun (the Earth-Sun distance = one astronomical unit, or AU, 150 million kilometers, or 93 million miles), are the remnant material of the early days of the solar system. Where we find TNOs provides evidence that the solar system as we see it today is not as it once was. Their present paths around the Sun pick out the traces of an ancient mystery: the outward migration of the outer planets, at least four billion years ago.

More than a fifth of trans-Neptunian bodies are in mean-motion resonances with Neptune. Resonant TNOs move in an orbital ballet of beat frequencies, where Neptune makes a round number of turns around the Sun for every orbit by these more distant worlds. Pluto is the best known of

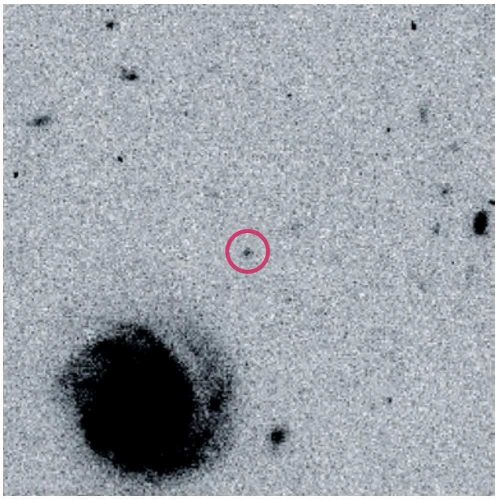
ABOVE *Studies of Trans-Neptunian Objects (TNOs) have revealed that Neptune has many of them entrained in resonant orbits. Soon, we will get a close-up view of MU69, a TNO first seen by the Hubble Space Telescope. As shown in this artist's concept,* New Horizons *will fly by MU69 in 2019.*

the resonant TNOs, at a mean distance of 39 AU, making two turns for every three by Neptune. Smaller kin in the 3:2 resonance are known as the "plutinos." Resonances appear on a map of orbits as thin regions that filigree the vast volume of the outermost solar system. Only a migration of Neptune, spiraling outward over millions of years, can have snowplowed so many of the TNOs out to orbits in these tiny volumes of strange, poised stability. What remains unknown is the way this migration happened. Was the ice giant Neptune thrust outward, by interactions with other giant planets and with the disk of tiny proto-planets—in a slow glide or perhaps a quick dart? The answer lies in the current pattern and populations of resonant TNOs.

DISTANT, TINY, AND HARD TO SPOT: HOW TO FIND MORE TNOs?

After two decades of mapping the sky, beginning in the 1990s, barely a thousand of the telltale TNOs had been discovered: a tiny fraction of the population that had to be out there. TNOs are faint and hard to find. They are on distant, often elongated, eccentric orbits, and have a steep luminosity distribution. Many are a few hundred kilometers in diameter or smaller; a few are larger, dwarf planets. Seen only by reflected sunlight, the smaller objects are hard to detect unless they are at perihelion, when they are closest and brightest. Every TNO discovery in the early years hinted at a much larger population, too faint to be seen. To describe how Neptune's migration happened was going to require many more discoveries.

An opportunity came at the 2011 meeting of planetary scientists in Nantes, France. Nearly two thousand astronomers and geologists gathered in one place. What better time to discuss how to take the next step in mapping the outer solar system? I was a graduate student at the time, just finishing up a survey of the southern hemisphere sky, looking for bright TNOs by analyzing images from a small telescope in Australia. The consensus of the community of interested scientists was clear: we needed a survey that imaged deeply and across a wide area of sky, at least 150 degrees square, near the plane of the solar system, where TNOs are found



RIGHT *The red circle surrounds the first sighting by human eyes of one of the 840 Trans-Neptunian Objects detected by OSSOS. The dark object nearby is a spiral galaxy.*

OPPOSITE PAGE *The small blue circle at the center of this tangle of TNO orbits represents the orbit of Neptune. This graphic illustrates the vast extent of the trans-Neptunian populations and the challenges of searching across such distances for small objects lit only by the Sun. Precise, triple-checked data made it possible to calculate and later confirm the orbits of TNOs spotted by OSSOS.*

Image: Canada-France-Hawaii Telescope, courtesy of the author

in the greatest numbers. Such a program would detect hundreds of faint TNOs, but to be awarded time on the highly competitive large telescopes for such a large scale survey would need a powerhouse of collaboration. The nascent program brought together nearly 50 researchers from around the world, including scientists from Canada, France, the U.S., Taiwan, the U.K., Finland, Slovakia, and Japan.

THE NEW NET GOES FISHING

The Outer Solar System Origins Survey (OSSOS) was approved as a Large Program

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on the 3.6-meter Canada-France-Hawaii Telescope (CFHT) on Maunakea, Hawaii, in 2012, and started observing in 2013. For the next five years, CFHT acquired images for OSSOS every month of the year.

We designed the survey to act as a fine-meshed net for distant icy worlds. TNOs move across the sky in large loops, like writing with a fountain pen, a pattern produced by the more rapid yearly motion of our Earth around the Sun. A snapshot of a patch of sky will snare a sample of TNOs. Over time, this "group" of TNOs will disperse, depending on their individual orbits. This predictable large-scale motion allowed us to automate our first year of observation for each survey region of sky. Instead of pointing the telescope at each TNO and trying to chase them all individually—which would have led to a lot of spillage from loss of TNOs on unusual orbits, wriggling away—we tracked four big, 20-degree square patches of sky, at the mean looping rate of TNO drift across the sky for the half-year that each patch was visible.

Our discoveries were fished out when each patch of sky came to its opposition point from the Sun. At this geometry, the TNOs' motion relative to Earth is at its speediest, making them easier to detect. Painstaking calibration of our software ensured we could quantify how precisely we were detecting TNOs with different rates of motion—from the speedy Centaurs to the slow-drifting Sednas. The exquisite calibrations mean OSSOS's great product is as much a matter of empty spaces where we know there was nothing to find, as the hundreds of TNOs we discovered.

Because CFHT is a queue-scheduled telescope, as the OSSOS operations lead, I would send programming to Waimea, Hawaii, from Victoria, BC, and the schedulers and observers in Waimea would plan and put into practice our requests. From the second year of observing onward, our eight-person OSSOS core team worked under a hectic pace of scheduling observations, adjusting the cadence if weather prevented observing success, and dealing with the stream of arriving observations. All the while we were analyzing the images for discoveries and piecing together their paths across the sky into confirmed new TNOs, ensuring all discoveries above a threshold brightness would be safely tracked. These icy worlds would then be imaged again each year with targeted snapshots, pinning them with 20 to 60 points on the sky, calibrated against the *Gaia* spacecraft's star maps. Each TNO was imaged until all their orbits had such

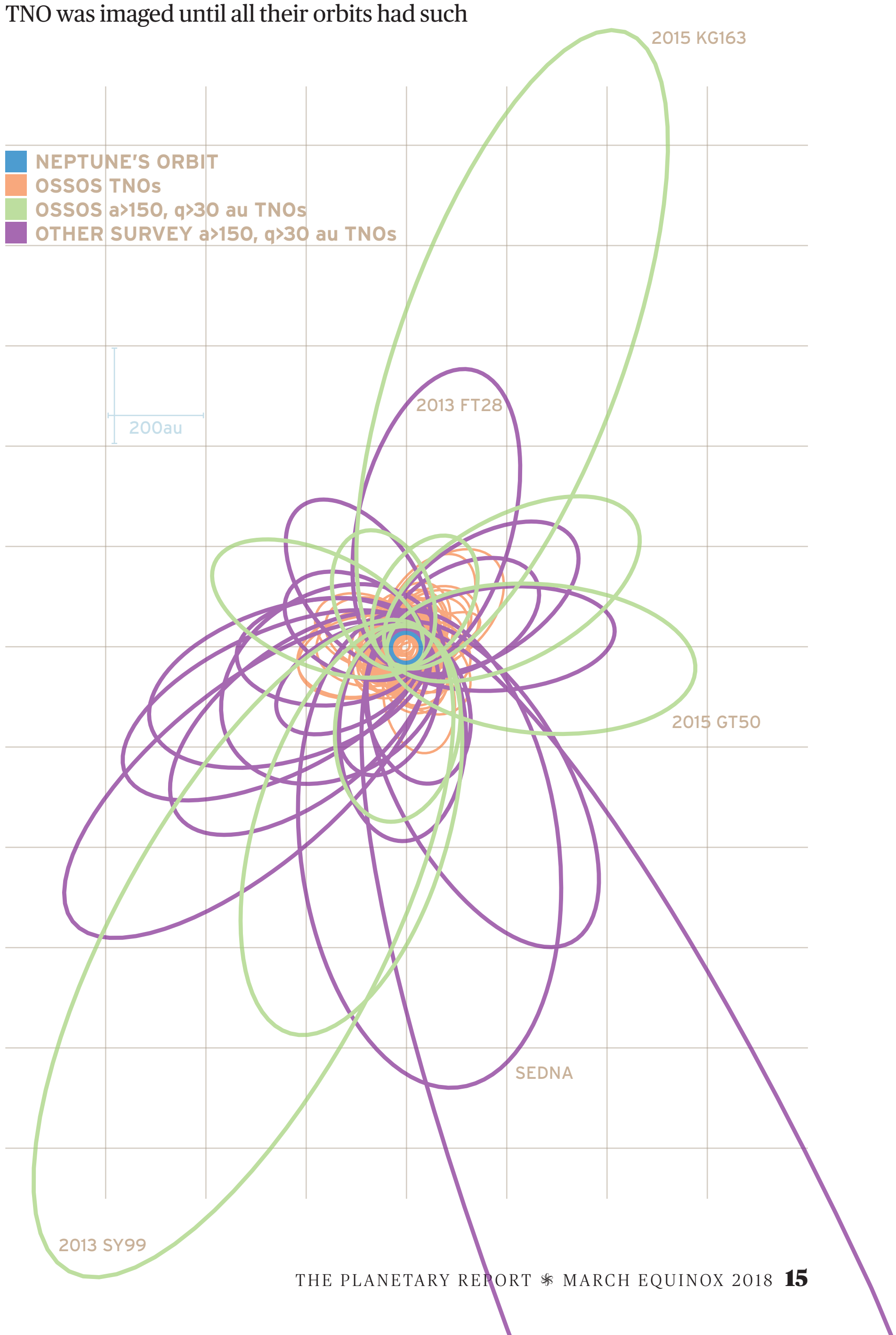

Illustration: Courtesy of the author/Loren A. Roberts/Hearken Creative small uncertainties that their membership in the various orbital populations (such as the TNOs in the thin threads of Neptunian resonance) could be held certain, with numerical simulations of their behavior over millions of years. In total, the whole effort required triple-checked measurements of more than 37,000 points of light.

The 2015 observations brought a new challenge—our best ever visibility. A combination of truly spectacular, crisply stable atmosphere on the discovery nights (with seeing down to 0.4 seconds of arc) and the arrival of a new, deeper camera filter, which let us see fainter TNOs, brought a wave of discoveries. Nearly half of OSSOS's discoveries showed up in 2015's autumn-winter semester. This abundance cranked our tracking efforts to a fever pitch. In retrospect, it's amazing we were able to track every object in our sample above the threshold brightness—at Kuiper Belt distances.

CRACKING THE KERNEL OF THE KUIPER BELT

The 840 detections from OSSOS increased the inventory of trans-Neptunian objects with accurately known orbits by 50 percent. The full data release will be in a special 2018 issue of the *Astrophysical Journal Supplement* series. Ten papers have analyzed the discovery set thus far.

The new TNOs add a lot of detail to our knowledge of the Kuiper Belt. OSSOS detects all objects down to magnitudes as faint as 24.1 to 25.2. OSSOS-defined orbits have exceptionally high quality, with an uncertainty of less than 0.1 percent, which lets us resolve the Kuiper Belt's structure with unprecedented precision. The significance of this structure is best described by the shapes of the TNOs' orbit ellipses. Orbit shapes may be characterized by four measurements: a semimajor axis, which averages how distant an orbit is from the Sun; an eccentricity, or distortion from a circle; an inclination, or tilt; and a distance of closest approach to the Sun, or perihelion. Our 437 non-resonant (or "classical") discoveries show that Kuiper Belt orbits have semimajor axes larger than 37 AU, with a lowest perihelion boundary of 35 AU. The distance from Neptune to the Sun is about 30 AU.

The Kuiper Belt has been known for nearly two decades to have two populations on different distributions of inclination to the ecliptic: there is a near-flat belt, with inclinations less than about 5 degrees, and a more broadly spread population on more tilted and eccentric orbits, with tilts up to about 30 degrees of inclination. We've confirmed that there is a concentrated population in the near-flat, almost perfectly round orbits of the "cold classicals." This population is nestled like a kernel in the midst of the low-inclination TNOs. Fortunately, in 2019 *New Horizons* will be visiting a "kernel" TNO—the little world known as MU69, found by Hubble.

A handful of precious OSSOS discoveries show that the low-inclination belt has an entirely unexpected feature: it continues out beyond the truncating 2:1 resonance with Neptune, with the semimajor axes of its orbits extending to about 50 AU. These orbits may be a stirred-out remnant of Neptune's last swing during its wild migratory days. Or they may hint at the primordial disk, left from the beginning of the solar system.

THOSE DISTANT RESONANT DANCERS

In the filigree regions of resonance with Neptune, OSSOS confirms more than 300 new TNOs, including a staggering 132 plutinos, which orbit in the 3:2 resonance, nearest the Sun. At perihelion, plutinos as small as 40 kilometers in diameter are detectable.

OSSOS discoveries also include TNOs in newly occupied resonances, with mean distances beyond 50 AU. Most distant of all, out at mean distances of 130 AU, two of our discoveries dance securely in the orbital ballet of the 9:1 resonance with Neptune. The precise calibration of OSSOS—telling us not only what is there but what is not—shows that 11,000 unseen worlds must also orbit in

For more information on the Outer Solar System Origins Survey, go to:
ossos-survey.org

the 9:1. Our computer simulations show these two TNOs have been at their dance a long while: they are stable in the resonance for as long as a billion years. Possibly they have become "stuck" to the narrow resonance, in a flypaper capture from long ago, when their orbits were interacting much more intensely with Neptune.

Rapidly changing orbits characterize a population known as the scattering disk, which is eroding down from much larger numbers, flung out by Neptune since its early days of migration. OSSOS shows the scattering disk must number some 90,000 objects larger than 100 kilometers, based on 68 scattering TNO discoveries.

THE MYSTERY OF 2013 SY99 AND FRIENDS

OSSOS finished its observational duties on December 25, 2017, with CFHT providing a last image of a TNO on one of the strangest orbits among our discoveries. This world is now known as 2013 SY99. It is one of nine such TNOs that OSSOS found; a third of all known TNOs in this unusual population were discovered during our survey. Their orbits have closest approaches to the Sun out beyond 30 AU, and semimajor axes of at least 150 AU. In SY99's case, its orbit has a perihelion of 50 AU and a mean distance of 730 AU, a perihelion exceeded only by those of Sedna and 2012 VP113.

These extreme TNOs take as long as 20,000 years to orbit the Sun, and the splay of their orbits in space has inspired new theories. One idea proposes an unseen large planet in an orbit at hundreds of AU. However, all nine of our extreme TNOs, together with OSSOS's calibrated ability to tell what it did not detect, remain consistent with a population in large orbits that are spread out smooth as butter on bread, rather than in the clumping we might expect from a big planet's shepherding. Formation mechanisms for this distant population are not yet clear, and it remains an area of active investigation.

The OSSOS discoveries form a unique set. It has half as many TNOs as the number of TNOs found in all the 40-plus surveys that went before. Together with perfect tracking efficiency for trans-Neptunian orbits, and a calibration for every survey bias, it will let the true scale of the TNO populations be precisely calculated. We're excited to see how people will use this powerful tool for understanding the inventory and history of our solar system.

ABOVE LEFT *Before being captured as a moon of Saturn, Phoebe was likely a TNO—as evidenced by its retrograde orbit and other characteristics. With a diameter of 213 kilometers (133 miles), Phoebe has the dark color, battered surface, and icy interior thought to be typical of primordial solar system bodies. This image is a mosaic of* Cassini *data collected just before the spacecraft's flyby in 2004.*

Image: NASA/JPL/Space Science Institute