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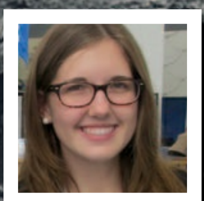

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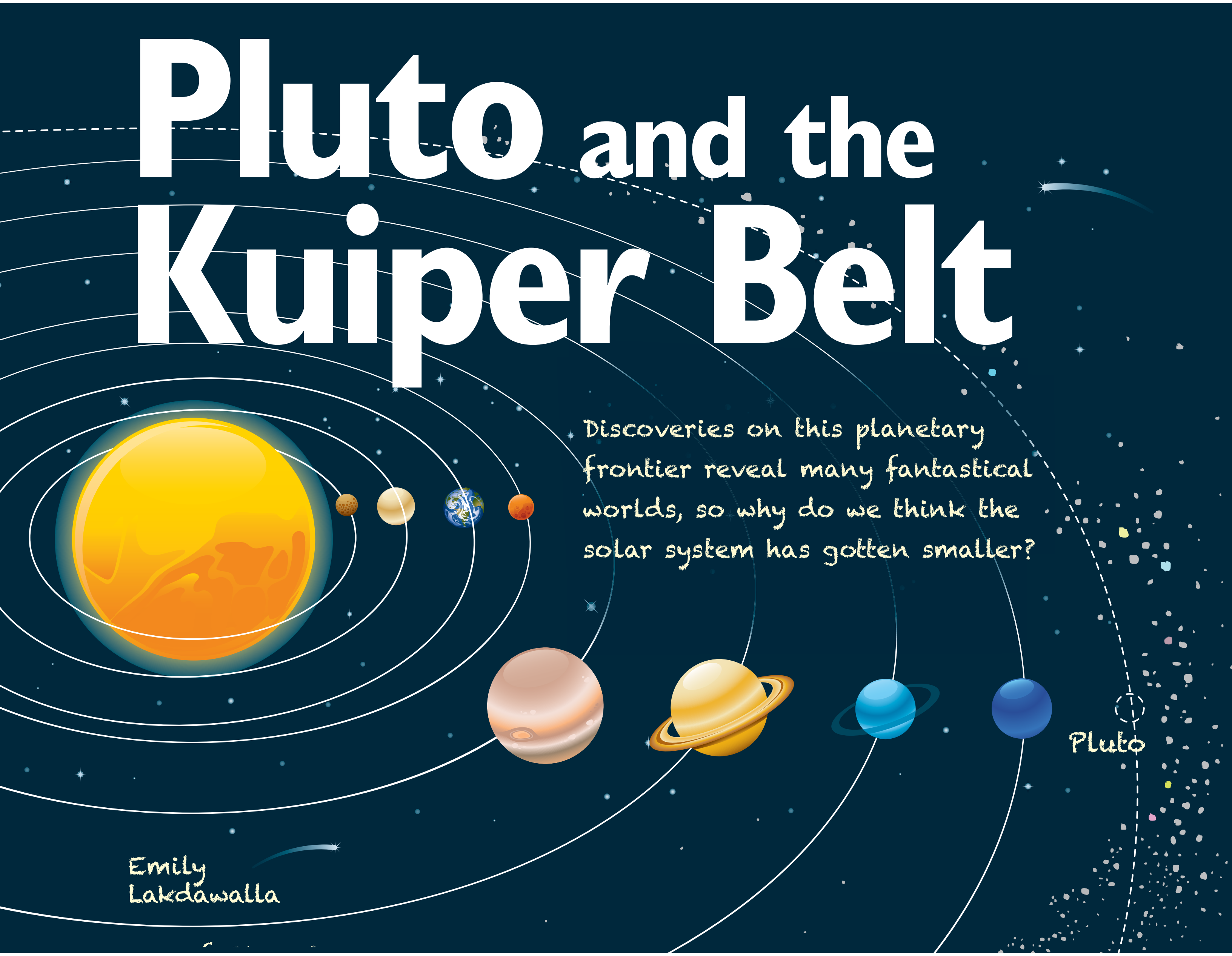
Pluto and the Kuiper Belt

Discoveries on this planetary frontier reveal many fantastical worlds, so why do we think the solar system has gotten smaller?



Emily Lakdawalla

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MY DAUGHTER was born three weeks before the International Astronomical Union held its fateful vote on the definition of the word "planet" (*S&T*: November 2006, page 34). As far as she has ever known, Pluto is not a planet. Her teachers also know that Pluto isn't a planet. But if it's not a planet, then what is it? Asked this question, every one of them has told her that Pluto is actually some kind of star!

While I find this statement astonishing, I can't blame teachers for not understanding what Pluto actually is. Being a space enthusiast, I'm well aware that its status has changed because of recent discoveries of more than 1,000 other bodies in Pluto's neighborhood, transforming our understanding of the shape of our solar system. However, as a parent, I've seen that Pluto's redefinition to "dwarf planet" has resulted in its swift redaction from children's books, games, and toys. The redefinition happened because we learned more about the solar system, but the change in status has resulted in us teaching our children (and, perhaps more importantly, their teachers) *less*.

As an educator, I wanted to correct the "some kind of star" error, but here I was halted by my own ignorance. I could name a few Kuiper Belt objects (KBOs), and I knew the solar system looked different from the orderly progression of nine worlds that my childhood books presented, but I didn't have a new mental picture of the solar system to go by. Where do all the newly discovered objects fit? Is the Kuiper Belt just a second, icier asteroid belt, or is it something different? Do we know Pluto's large neighbors as distinct worlds yet? What's going on out there beyond Neptune, anyway?

I've done some homework and have had lengthy conversations with several prominent astronomers, and I can now paint you (and me) a picture of the new solar system. Here's a spoiler: the Kuiper Belt is *not* just a second asteroid belt. Its present shape holds important clues to the puzzle of how the solar system formed. And if you're among those who think Pluto should still be called a planet, then I'll show you that there are at least a hundred other planets out there beyond the eight we now name.

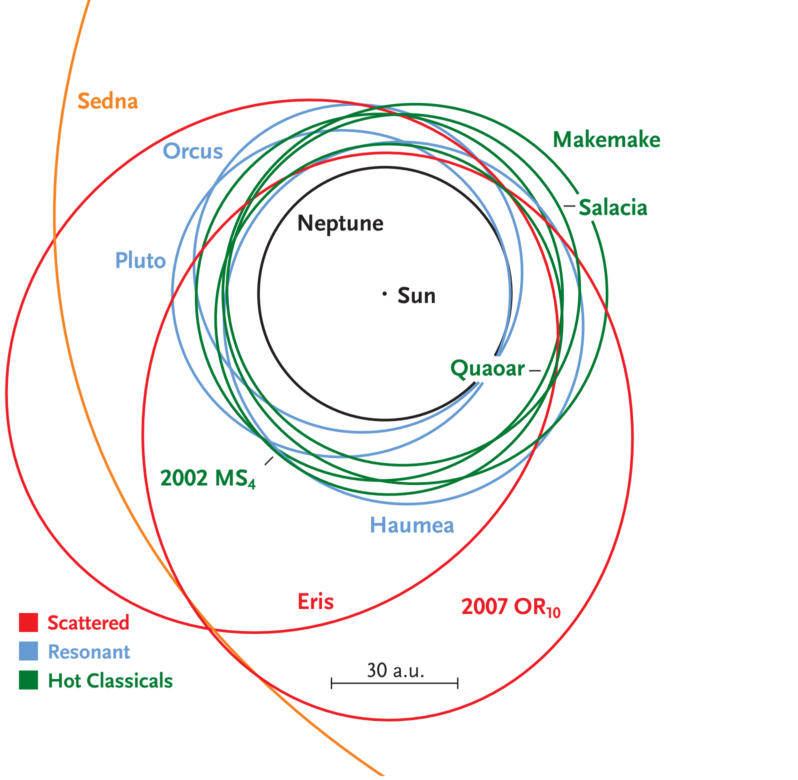
They're Everywhere

Studying the Kuiper Belt strains the capabilities of every observational method because the objects are so faint and so cold. At first, all astronomers could do was detect them and calculate their orbits. Pluto's orbit is typical of one large class of KBOs. It's quite elongated, inclined to the ecliptic plane that contains the orbits of the eight planets, and in a 2:3 orbital resonance with Neptune, going around the Sun twice every three Neptune years.

With the advent of CCD astronomy in the late 1980s, David Jewitt (now at University of California, Los Angeles) and Jane Luu (now at MIT Lincoln Lab) were able to perform the first modern survey of the sky for Pluto neighbors. They discovered the first in 1992. More discoveries followed every year. By the time that a few dozen trans-Neptunian objects had been found it was abundantly clear that Neptune ruled this region of the solar system: many of the icy worlds shared Pluto's 2:3 orbital resonance with Neptune, and even more were in the wider-ranging 1:2 resonance. Nearly all of the others orbited in between these two resonances, with semimajor axes filling in the space between 38 and 48 astronomical units.

As astronomers discovered more and more objects, other patterns and groupings emerged. There are some objects beyond the 48-a.u. cutoff. But even they are ruled by Neptune. All of them, save one, are on elongated orbits that eventually take them back to this dense part of the belt. No matter how far away they go, these "scattered" objects always come back.

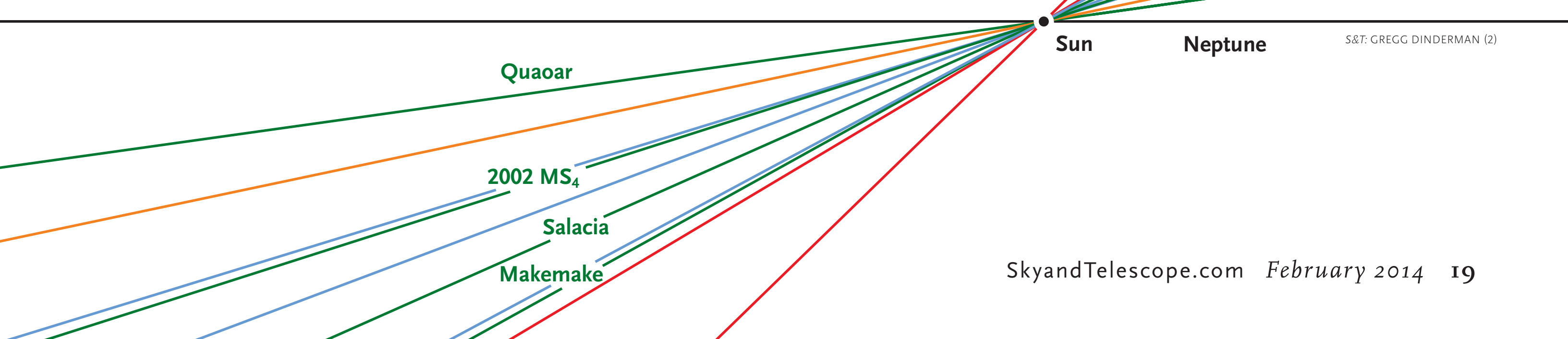
The single exception is a lonely world named Sedna, which I'll talk about later.



NOT REALLY A BELT. Kuiper Belt objects fall into distinct populations (Sedna is an oddball), distinguished by their orbits and surface hues. Shown above are orbits for the largest worlds as if the bodies traveled in the same plane as Earth does; below, the orbits' inclinations appear relative to Neptune's, which at this scale matches those of the other classical planets. Not shown are the "cold classicals": their orbits are shaped like the "hot" ones but have low inclinations.

As astronomers began to follow up discoveries with more detailed examinations of the objects' colors, they found another surprise: unlike in the asteroid belt, these icy worlds display a huge variety of colors, ranging from neutral gray to red. Colors often reveal an object's composition and, therefore, its history, but there was no immediately obvious relationship between KBOs' locations and colors.

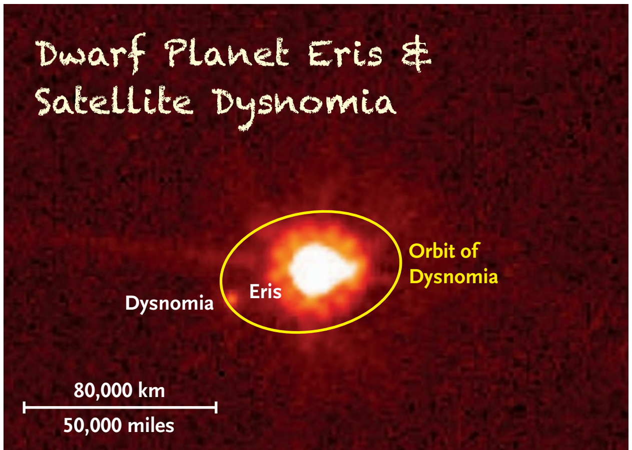
With more and more discoveries, dynamicists realized that the "classical" Kuiper Belt — the part between the 2:3 and 1:2 orbital resonances, from 38 to 48 a.u. — contained two totally distinct, overlapping populations. Objects in the "cold" classical belt have near-circular orbits with low inclinations; it's probably what you think of when you think of the Kuiper Belt. Objects in the "hot" classical belt also have circular orbits, but much higher inclinations. These



S&T: GREGG DINDERMAN (2)

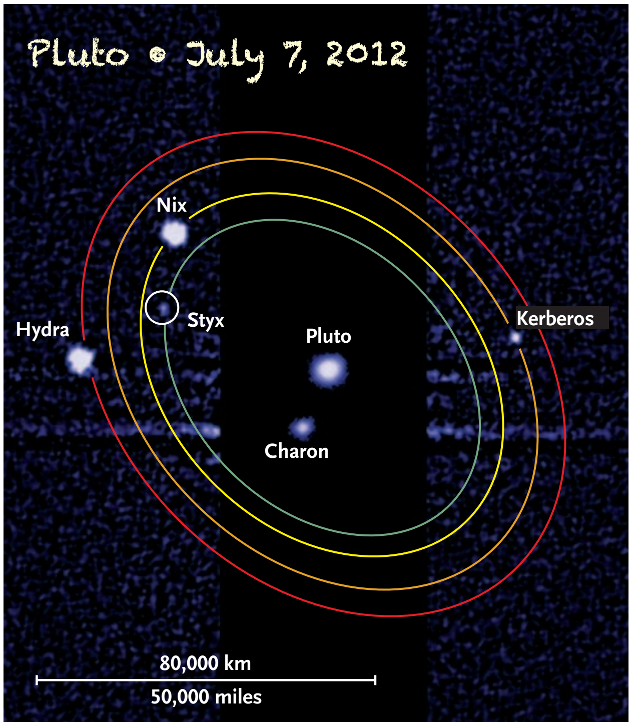
classifications aren't just astronomical hair-splitting: these are two populations that have distinctly different colors. The hot objects must have a different history from the cold objects — yet they're orbiting in the same region of space.

What did all of this mean? A major clue came from outside the solar system entirely. At the same time as the Kuiper Belt was first being surveyed, astronomers had also begun to discover planets around nearby stars. Many of these exoplanets were so-called "hot Jupiters," giant worlds on insanely tight orbits around their stars. Given what (little) we know about planet formation, these boiling-hot gas planets couldn't possibly have formed in their present locations. But that meant that, against conventional wisdom, these gigantic worlds must somehow have formed very far from their stars, then migrated inward.



DISTANT MYSTERY. This Hubble Space Telescope image from 2011 shows the dwarf planet Eris and its moon, Dysnomia. Eris and Pluto are the same size, but Dysnomia is only about one-tenth the size of Charon (see page 23).

NASA / ESA / MICHAEL BROWN (CALTECH)



PLUTO AND ITS KIDS. This composite of three sets of 3-minute-long exposures taken on July 7, 2012 with Hubble's Wide Field Camera 3 reveal all five of Pluto's known moons. Pluto and Charon's brightness are reduced, and the faint horizontal stripes are imaging artifacts.

NASA / ESA / MARK SHOWALTER (SETI INSTITUTE)

If exo-Jupiters can move inward, researchers reasoned, then perhaps the giant planets in our own solar system are not in their original locations. They saw that if Neptune had migrated *outward* since it formed and intruded into a primordial belt of cometlike objects, it would have eaten a few of them and scattered the rest like billiard balls, trapping some in orbital resonances and sending others inward toward the Sun.

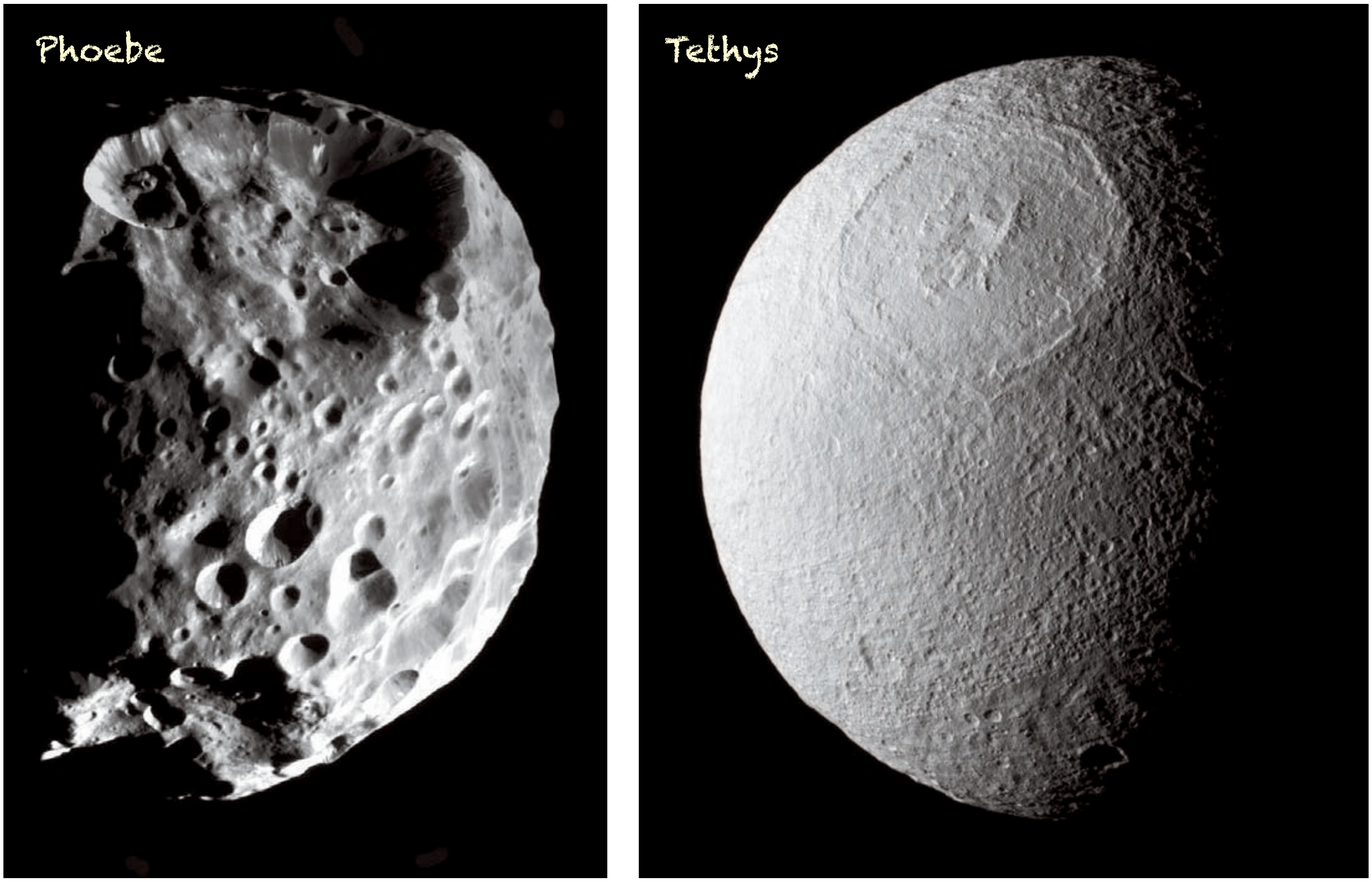
A few of the inward-moving objects stayed safely in the outer solar system as Trojans. But the majority of these travelers would have kept right on going. The resulting cascade of comets into the inner solar system could have contributed to the Late Heavy Bombardment, thought to have pelted the inner planets and moons a few hundred million years after the solar system formed (*S&T*: August 2011, page 20).

The present distribution of orbits in the Kuiper Belt is thus a crime scene, preserving evidence for the havoc wreaked when Neptune invaded its domain. Dynamicists still don't know exactly how Neptune perpetrated the crime, though — it's hard to write a history of Neptune's motion that can create the various "excited" populations in the Kuiper Belt (the resonant, scattered, and hot classical objects) while leaving the cold classical disk unscathed.

In the early 2000s, Mike Brown (Caltech), Chad Trujillo (Gemini North Observatory), and David Rabinowitz (Yale) began new CCD-assisted surveys specifically designed to detect large trans-Neptunian objects, resulting in the discoveries of several of the largest now known. The KBO discovery rate peaked in 2003, with nearly 200 discovered that year; in 2011, fewer than 20 were found. The discovery rate has dropped not just because we've found all the bright ones, but because the rarefied group of astronomers working on this distant part of the solar system has largely moved on from describing them as a population to studying them as individuals.

Size Matters

To discover the Kuiper Belt, astronomers used intermediate-size, wide-field telescopes. But to characterize its inhabitants, astronomers have moved to the biggest and smallest telescopes. Some are using the Hubble Space Telescope, the Very Large Telescope in Chile, and Keck on Mauna Kea to study the objects' colors and compositions in visible and near-infrared wavelengths. They are finding the population to be remarkably diverse in hue and



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A SORTING GAME. Kuiper Belt objects smaller than 400 km across probably resemble Saturn's moon Phoebe, a beat-up, icy body with similar surface chemistry. Those larger than 400 km might look more like Tethys, shown here with its 450-km-wide Odysseus Crater prominently displayed. These larger bodies are rounded by self-gravity and perhaps smoothed by icy outflows.

covered with a wide variety of ices taking an equally wide variety of forms.

Other astronomers use observations from the great space-based infrared telescopes, including Spitzer and Herschel, to measure KBOs' temperatures and sizes. The thermal infrared brightness, coupled with the visual magnitude, provides a tight constraint on the diameters and albedos of these worlds. This work has told us that KBOs are remarkably diverse in reflectivity, ranging from the bright white of new-fallen snow to pitch black.

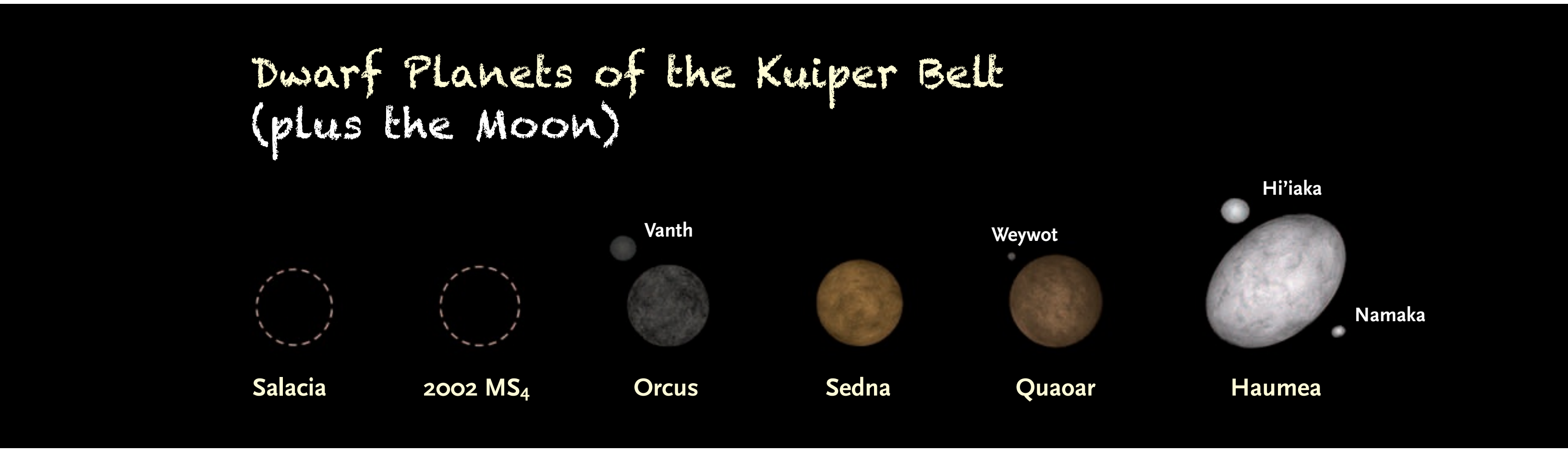
A few astronomers (including both professionals and amateurs) instead marshal as many telescopes as they can, of all sizes and all over the world, to watch as the distant, faint objects occult even more distant (but much brighter) stars. These stellar occultations give us the most precise diameter measurements, and they have also enabled us to probe Pluto's atmosphere, an atmosphere that, ironically, prevents us from precisely measuring the world's diameter from afar.

Astronomers aren't measuring diameters just to rank the objects by size. For the objects that have satellites (estimated to be as many as 30% of them), the orbital speed of those satellites tells us the objects' masses. Together, mass and diameter reveal density. The KBOs' densities, too, are all over the map, telling us that some are made of nearly pure ice, whereas others are mostly rock with only a thin ice veneer.

Of course there is a spacecraft headed to the Kuiper Belt: NASA's New Horizons mission, which will fly past Pluto in July 2015 and give us our first close encounter with this new region of the solar system (*S&T*: June 2010, page 30).

Family Portrait

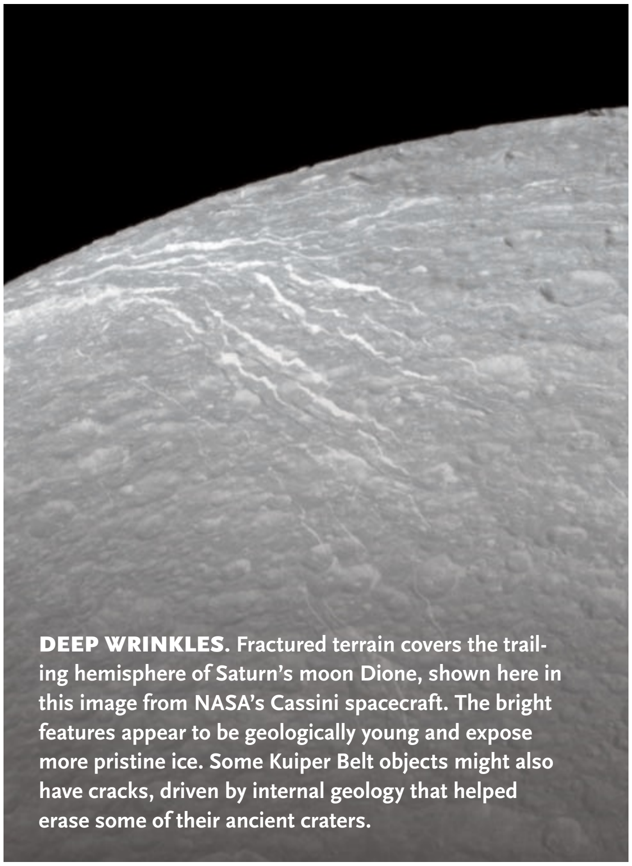
We now know enough about the sizes, albedos, and compositions to begin to develop an organized concept of the Kuiper Belt. The vast majority of objects are small (under 300 kilometers across), quite dark, and somewhat red. These are much too small to be dwarf planets and probably have changed little since they formed. They probably look a lot like Saturn's 220-km-diameter moon Phoebe, whose distant, retrograde orbit implies that it is almost certainly a KBO that was scattered inward by Neptune and then captured into its present position.



ALL IN THE FAMILY. The dwarf planets of the Kuiper Belt are a motley group. The colors and brightnesses shown are estimates by Alex Parker (University of California, Berkeley) based on the visible and near-infrared observations compiled in the Minor Bodies in the Outer Solar System database. Salacia and 2002 MS_4 are extremely dark, making their sizes uncertain: shown are potential diameters. The dark half of the Moon shows its albedo compared with the KBOs; the other half has been brightened to make familiar features visible.

The Cassini mission got a very good look at Phoebe on its way in to Saturn orbit and revealed it to be a battered, icy body showing signs of internal layering in its crater walls. Its surface displays a mixture of water ice, gunky organics, amorphous carbon, and rocky minerals. This cometlike combination of materials is a good match for the measured colors of the smaller KBOs, although scientists can't prove the kinship without better spectroscopic data.

Move up to the brighter (hence, larger) objects, though, and something changes. Brighter than absolute magnitude 5.6 — roughly equivalent to a diameter of 400 km — the surface composition changes. Whatever that composition change is, it makes the objects lighter in color. What could the difference be?



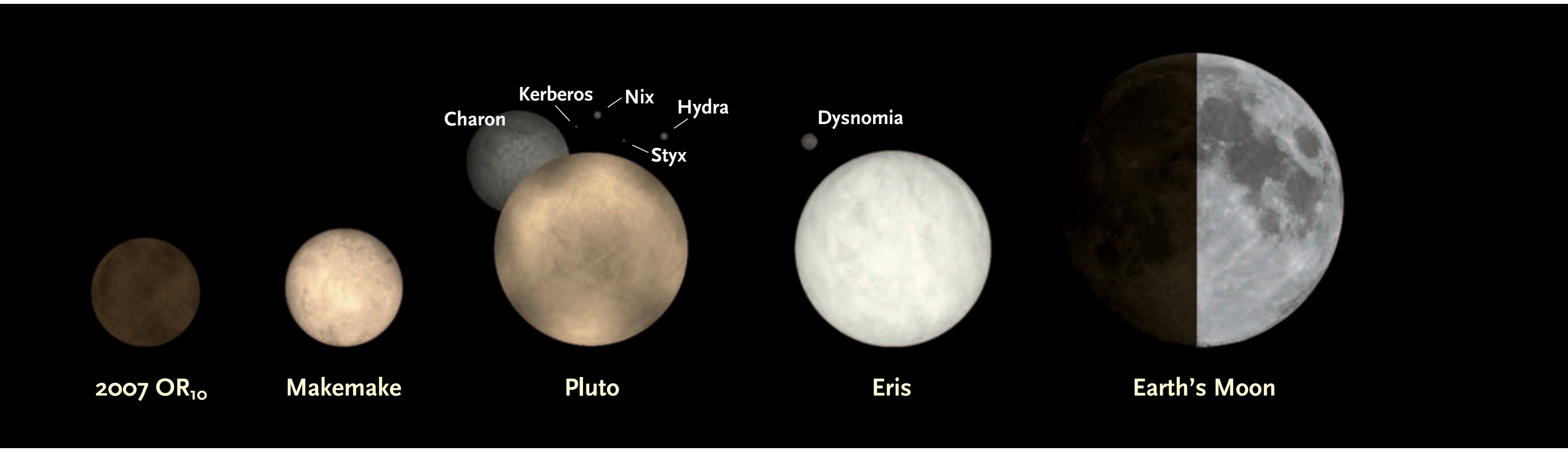
DEEP WRINKLES. Fractured terrain covers the trailing hemisphere of Saturn's moon Dione, shown here in this image from NASA's Cassini spacecraft. The bright features appear to be geologically young and expose more pristine ice. Some Kuiper Belt objects might also have cracks, driven by internal geology that helped erase some of their ancient craters.

NASA / JPL / SPACE SCIENCE INSTITUTE

Again, we can look at outer solar system moons for a clue. Under 400 km, we find objects such as Phoebe, Hyperion, Amalthea, and Puck, lumpy bodies shaped by their craters and passive slumps of surface material. Go larger than 400 km, and we are suddenly in the realm of the round icy moons, such as Uranus's Miranda and Saturn's Mimas and Enceladus.

Mimas is battered by craters but demonstrably round, and the surfaces of Miranda and Enceladus are clearly altered by internally driven geology (past or present) that has erased their ancient craters. It's tempting to think that a similar transition occurred on KBOs of the same size. Their self-gravity could have pulled them into round shapes, and they might have been just large enough for their heat of formation to melt some of their water — especially if they incorporated some ammonia, which lowers water's melting temperature. As they froze, their ice expanded, cracking near the surface and squirting pressurized "cryolava" (that is, liquid water) onto their surfaces, covering them with fresh, bright ice.

New Horizons's examination of Charon will provide the first close look at an object in this class. If the hypothesis is borne out by further examination — if these worlds are found to have enjoyed internally driven geology, and rounded themselves as a result — then they are all dwarf planets, and astronomers have already discovered more than a hundred of them.



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The Biggest Dwarfs

Among the (possibly) hundred-plus dwarf planets of the Kuiper Belt are at least ten notable individuals. In order of their discovery, they are Pluto, Quaoar, 2002 MS_4, Sedna, Orcus, Salacia, Haumea, Eris, Makemake, and 2007 OR_{10}. They are big enough for spectroscopy to yield data on their surface compositions. They stand out not only for their size, but also for their striking variety.

Pluto is large enough to hold on to an atmosphere made of nitrogen, methane, and carbon monoxide. Although the atmosphere is thin, it suffices to provide Pluto with weather and a climate that varies dramatically with its changing distance from the Sun. Jeff Kargel (University of Arizona) has even suggested that Pluto might have a nitrogen cycle just as Titan has a methane cycle and Earth has a water cycle: liquid nitrogen could rain into rivers and lakes at certain times during Pluto's year! New Horizons will investigate.

We know that Pluto has patches of different-colored terrain on its surface, and that those patches have shifted with time. Pluto is also notable for its large companion, Charon, which would be a dwarf planet if it orbited the Sun on its own. Charon is large enough that light reflected from it will illuminate Pluto's nightside sufficiently for New Horizons to photograph Pluto by Charonlight.

Eris is a twin to Pluto in diameter but significantly more massive, suggesting its history was different from Pluto's. It's currently the most distant observed object orbiting the Sun (although Sedna is usually farther), discovered only because of its intrinsic icy brightness. The bright surface is most likely frost: Eris probably has an atmosphere like Pluto's when it's closer to the Sun, but at its current position (about three times farther from the Sun than Pluto is at the moment) all gases are frozen to its cold surface. Thus Eris provides a snapshot of what Pluto will probably look like in a century as it approaches aphelion, its atmosphere hibernating through the long orbital winter.

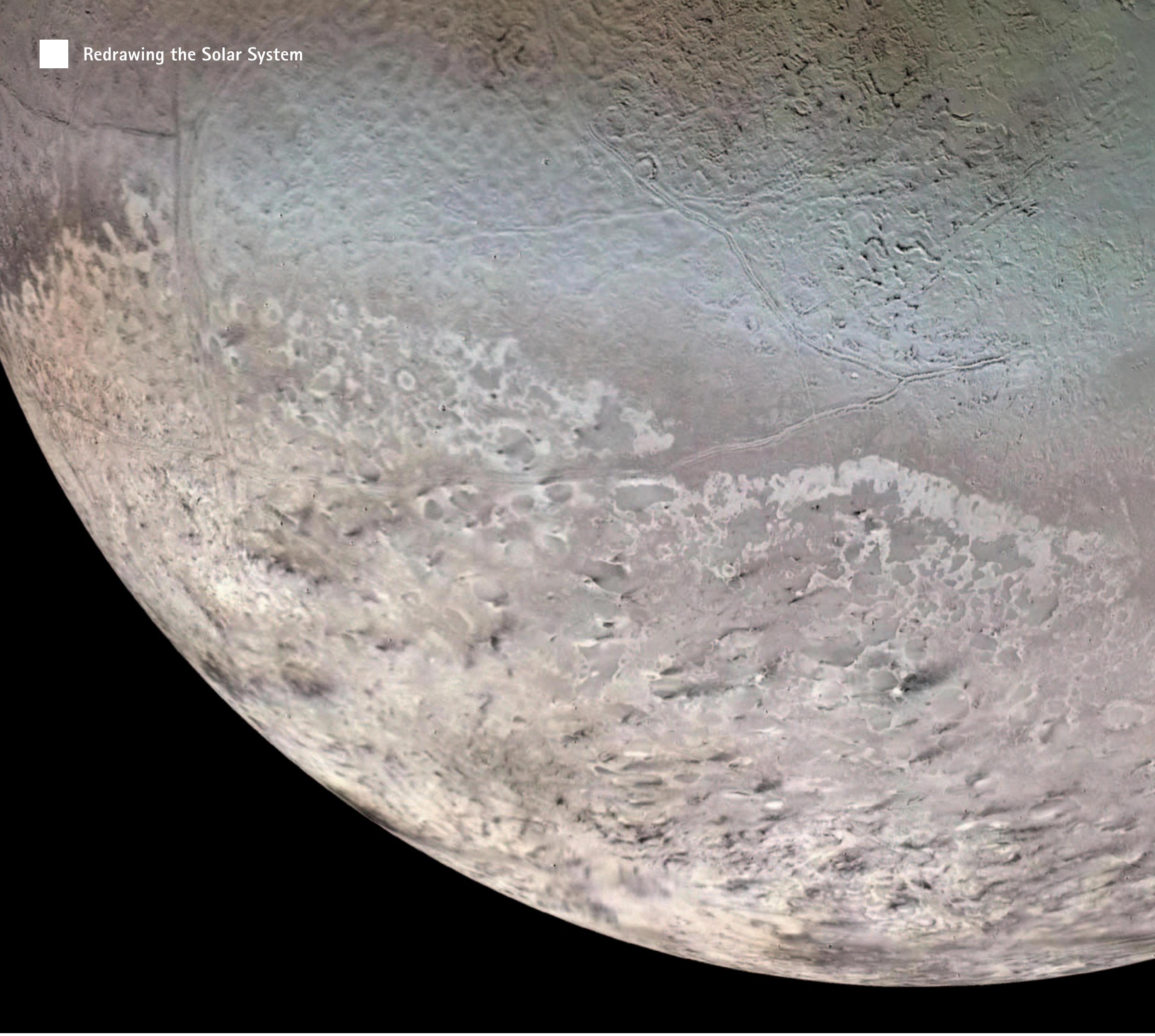
We can make a very good guess as to what Eris and Pluto look like by examining — you guessed it — an outer planet moon. Neptune's only large moon, Triton — which is larger than Pluto and nearly as big as Europa — has a bizarre-looking surface coated in bright frosts of nitrogen and methane. The resemblance between Triton, Pluto, and Eris is no accident: Triton almost certainly did not begin its existence circling Neptune. Its retrograde orbit, plus Neptune's curious lack of any other large moons, tells us that Neptune very likely captured huge Triton during its intrusion into the primordial Kuiper Belt. If Triton was independently orbiting the Sun, it, not Pluto or Eris, would be king of the Kuiper Belt.

At about half the diameter of Pluto and Eris, Makemake should have barely enough gravity to hold on to any nitrogen and carbon monoxide in its atmosphere. Its surface is dominated by methane, meaning that it must also have a methane atmosphere — at the ambient temperatures in this part of the solar system, methane ice will always have some gas above it, just as water ice on Earth always has some vapor above it. Peculiar shapes in Makemake's spectra suggest that its surface methane is not frost, but rather a solid slab of ice. The ice is dirtied with some amount of redder ethane and, very likely, smaller amounts of longer-chain hydrocarbons, much like those in Titan's atmosphere, only in solid form.

Quaoar and 2007 OR_{10}, somewhat smaller than Makemake, are similar in size and color. Their surfaces are known to bear methane ice or frost in a patchy coating on a mostly water-ice surface. So they, too, must have methane atmospheres, although these haven't been detected yet.

Sedna, too, bears methane. Sedna is similarly sized to Makemake, but much more distant. It never gets closer than 76 a.u. from the Sun — more than twice Neptune's distance. And its long, long orbit will eventually take it, 5,000 years from now, to an amazing 1,000 a.u. away.

Orcus, smaller and grayer than Quaoar and 2007 OR_{10}, shows tantalizing hints of ammonia on its surface. Geophysicists often invoke ammonia to explain long-lasting subsurface oceans on icy worlds (such as Europa),



because ammonia lowers water's freezing point. Ammonia on Orcus indicates that cryovolcanism has happened there. Like Pluto, it has an outsized companion, Vanth, more than a third Orcus's diameter.

Haumea is an odd duck. It's the fastest-rotating and most elongated, big round object in the solar system, with a day lasting only four Earth hours. It's one of the largest KBOs, about as wide as Pluto and Eris along one of its equatorial axes but only half as tall pole-to-pole. It has a bright surface of nearly pure, crystalline water ice, and so do its moons, Hi'iaka and Namaka. A whole family of smaller, similarly bright, crystalline icy objects follow orbits like Haumea's. These are probably bits of Haumea's mantle, shrapnel from an ancient collision that smashed away Haumea's crust, set the world spinning fast, and launched icy chunks into their own solar orbits.

Two more enigmatic worlds — 2002 MS_4 and Salacia — might belong on this list of dwarfs, too. Not much is known about them yet, except that they are extremely dark (see diagram, page 22). They might mark the extent of the major dwarf planets, at least for now: a recent search of the Southern Hemisphere sky netted no discoveries of other large objects, and work suggests that the inventory of large, bright KBOs is nearly complete.


NASA / JPL / USGS

CAPTURED KBO. Voyager 2 captured the images combined in this enhanced-color mosaic of Neptune's moon Triton. The moon's surface is mostly nitrogen ice, and the pink deposits might be created by sunlight-induced reactions in methane ice. Triton is probably a Kuiper Belt object caught by Neptune when the planet migrated outward early in the solar system's history.

The New Solar System

So here is my new mental picture of the solar system. We still have eight major planets on their sedate, nearly circular, nearly coplanar orbits. Jupiter herds a large family of little, lumpy asteroids in the main belt.

Beyond Neptune is another belt, this one made of several distinct but overlapping populations of worlds big enough to have their own unique histories. Don't imagine this belt as kin to the asteroid belt. It's more like a scattering of outer planet moons. Think of things like Triton, Rhea, Mimas, and Phoebe, some of them traveling in circles, others in wild, tilted ellipses, moving slowly when far from the Sun but more speedily when they're near Neptune's orbit.

These trans-Neptunian worlds far outnumber the 18 or so round icy moons of the outer planets. Think for a moment about how varied the appearances of these moons are, and then extrapolate that variety to the more than 100 spherical dwarfs wandering the vast region of trans-Neptunian space.

Some of these objects are as bright as Tethys, some darker than Umbriel. Some are gray, some red, some frosty white, some patchy. Several have atmospheres, with wind, weather, and seasons. Many have moons. A few of these moons are big enough to be included in our count of dwarf-planet-like moons.

They may not orbit a planet, but Neptune controls them all. Some travel to enormous distances from the Sun, but they always return to Neptune's neighborhood. Except one: Sedna.

Sedna's remarkably different orbit raises all kinds of questions. How did it get its elongated orbit way out there? Is it alone? Or is it analogous to Pluto, the easiest-to-find member of a whole new, unexplored population of objects? Does our Sun have another, much more distant planetary companion, herding an as-yet-undiscovered third belt of worlds?

One thing is certain: we have just barely begun the exploration of this wilderness in our planetary backyard, and there are many more worlds yet to find. It's almost certain that there are more bodies larger than Pluto, and it's in the realm of possibility that there's something as big as Neptune lurking out there, beyond our current ability to spot it (*S&T:* March 2010, page 20).

KBOs are dim, distant, and difficult to study. But let's not shrink from their great distance and bewildering variety by dropping Pluto from the record and telling kids that our solar system ends at Neptune. Pluto, Quaoar, Orcus, Haumea, Makemake, 2007 OR_{10}, Salacia, 2002 MS_4, Eris, and way-out Sedna are each unique and fascinating worlds, and they deserve places in our mental maps of our astronomical home.

And while we're adding round worlds to our kids' solar system posters, let's also include Ceres, Io, Europa, Ganymede, Callisto, Mimas, Enceladus, Tethys . . . ✦

Sky & Telescope *contributing editor* ***Emily Lakdawalla*** *is senior editor and planetary evangelist for The Planetary Society. She writes about space science and exploration at* ***planetary.org****.*