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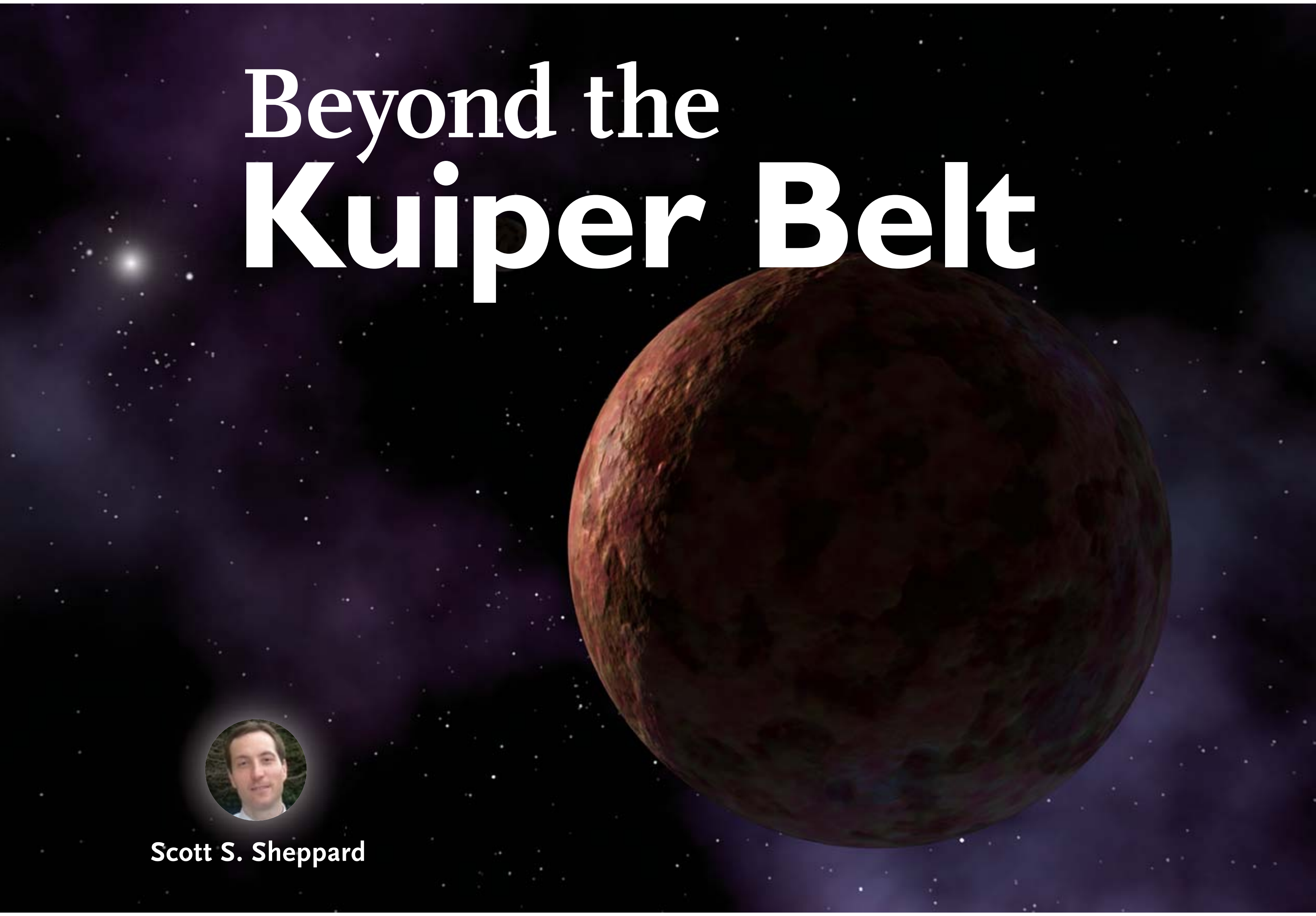
Beyond the Kuiper Belt



Scott S. Sheppard

NASA / JPL-CALTECH / ROBERT HURT (SSC)

Many bodies likely lurk in the sprawling emptiness that fringes our solar system. Where are they, and how did they get there?

In 1781 William Herschel discovered Uranus, the first planet not easily observable with the naked eye. Astronomers found Uranus's orbit to be peculiar, as if a more distant planet's gravity pulled on it. A search for this unseen planet led to the discovery of Neptune in 1846. Neptune's motion was also thought to be peculiar, which led to the discovery of Pluto in 1930.

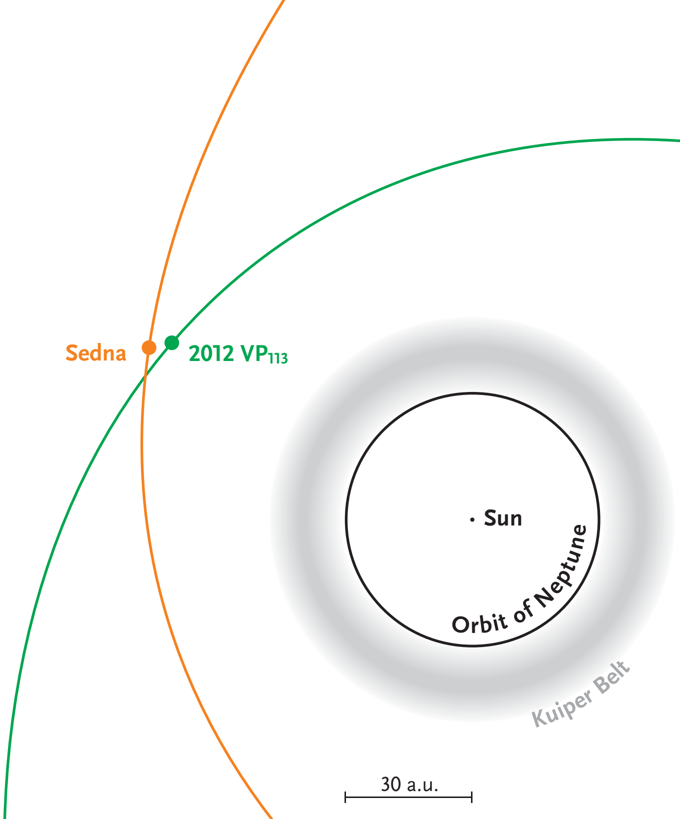
But astronomers have now determined that Pluto is only about 2,322 km (1,443 miles) in size, which is smaller than Earth's Moon, and not massive enough to affect Neptune's orbit. Later observations revealed that Neptune's motion was as expected, and no massive perturber was called for.

DISTANT ENIGMA Sedna (above, in an artist's conception) was discovered in 2003 far beyond Pluto and the classical Kuiper Belt. Do other large bodies like Sedna exist in the far reaches of our solar system? Astronomers are avidly searching for them.

Our exploration of the outer solar system was just beginning, however, and it continues today, with new discoveries and new mysteries arising all the time. Beyond Neptune lies an expanse of icy bodies, only a relative handful of which we've detected. And we're still figuring out how these mini worlds wound up where they are today.

The Kuiper and the Oort

Some 2,000 objects are known to orbit in the area near Pluto, which is now called the Kuiper Belt (*S&T*: Feb. 2014,



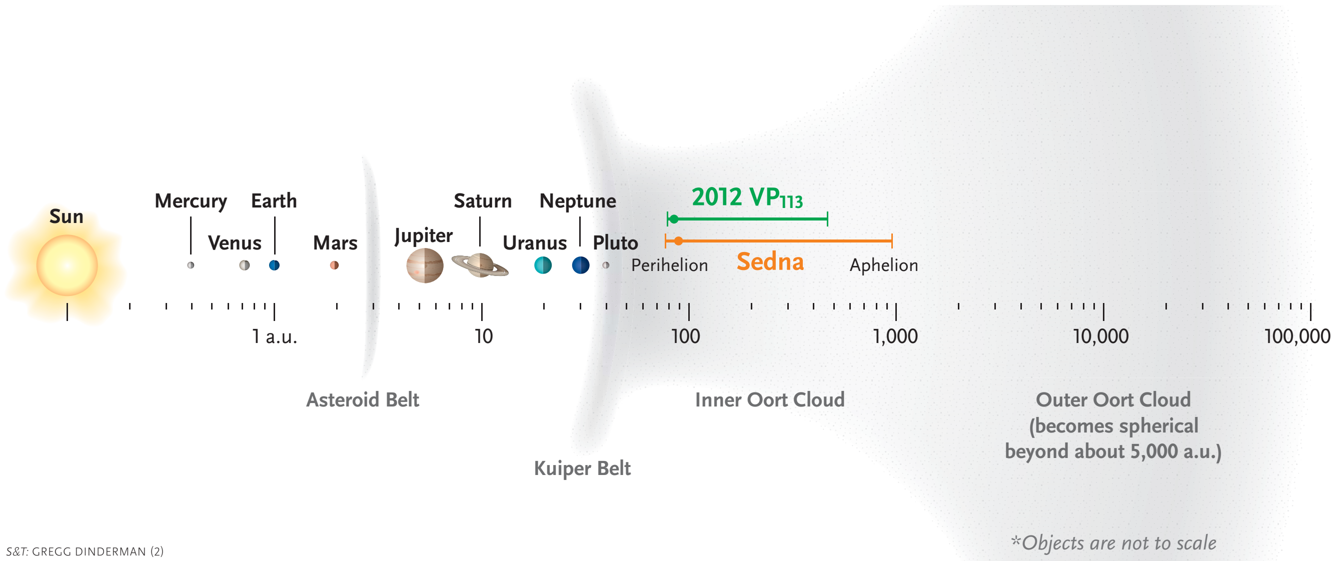
PATH NOT TAKEN The orbits of Sedna and 2012 VP_{113} lie entirely outside of Neptune's. But their highly elliptical orbits mean they interacted with *something* in the past.

p. 18). The Kuiper Belt appears to have an edge around 48 astronomical units, or 48 times the Sun-Earth distance, at which point the number of objects falls off sharply. The Kuiper Belt is a remnant of the original solar nebula out of which our planetary system formed, but it is made of the material that couldn't coalesce into a planet due to the large volume of space and low density of matter so far from the Sun. In fact, it is so hard to form objects in the outer solar system that Uranus and Neptune likely didn't form where they are now but were pushed out through interactions with Jupiter and Saturn.

Short-period comets, which have semi-major axes of only a few to tens of a.u. and low-inclination orbits, are likely recent escapees from the Kuiper Belt. Although the main Kuiper Belt ends around 48 a.u., there is another large reservoir of objects in the distant solar system from which the long-period comets originate. Long-period comets generally have semi-major axes of tens of thousands of a.u. and have orbits tilted every which way compared with the planets' nearly flat orbital plane (the planets essentially all lie in the ecliptic).

The reservoir that supplies these comets is called the Oort Cloud after Jan Oort, the Dutch astronomer who first proposed such a reservoir in 1950. The Oort Cloud extends over one-third of the way to the nearest stellar system, Alpha Centauri, or about 100,000 a.u. It likely contains around a trillion objects larger than 1 km across, with orbital periods of a few million years. It is well beyond the heliosphere, the region that ends where the solar wind gives way to the interstellar medium and through which the Voyager probes are now passing at around 120 a.u.

The Oort Cloud likely arose during our solar system's planet-building epoch. During our solar system's formation, many sizable objects formed in the giant planet region. Most of these objects became incorporated into the planets, but gravitational interactions with the growing planets tossed some from the region. The majority of these objects were ejected from the solar system into interstellar space, but 1 to 10 percent would not have had



S&T: GREGG DINDERMAN (2)

TOWARDS THE OORT As this diagram shows, Sedna and 2012 VP_{113} lie in a far-flung region of our solar system that some astronomers refer to as the inner Oort Cloud (IOC). Experts suspect that the population of objects in the IOC may be larger than that of the Kuiper Belt.

enough energy to escape and thus would have ended up in the distant outer solar system.

An object thrown outwards that does not escape the Sun's gravity will have an elliptical orbit that might take it to thousands or tens of thousands of a.u. But the orbit will still have a closest approach to the Sun (perihelion) that brings it back to the location from which it was originally scattered out. Thus any scattered object will still have part of its orbit within the giant planet region (5-30 a.u.) and at some point will strongly interact with the massive planet again. This will lead to either an eventual collision or complete ejection from the solar system.

The Oort Cloud assembled from these eccentric objects at thousands to tens of thousands of a.u., where they are weakly bound to our star. This is where the gravity of the Sun wanes to the point that the gravitational influence of nearby stars, the galactic center, and the Milky Way's disk start to be significant. This tidelike effect can move an object's perihelion out far enough past the planets to a point beyond any further strong interactions with Jupiter and its kin. This interaction randomizes inclinations and orbits of Oort Cloud objects over time, and it causes some of them to be lost into interstellar space while others are thrown back into the planetary arena to be observed as long-period comets.

The inner solar system may actually experience comet showers from random close stellar encounters. These are rare events when a star passes within about 100,000 a.u. of our Sun. Such events, which happen every few tens of millions of years or so, likely only increase the comet flux by a few tens of percent. The next known close encounter will be with the star Gliese 710, which will pass about 70,000 a.u. from our Sun in 1.5 million years. Researchers have suggested these stellar encounters could cause extinction events here on Earth by triggering a storm of comet impacts on the surface, but the interactions are very difficult to predict.

The Inner Oort Cloud

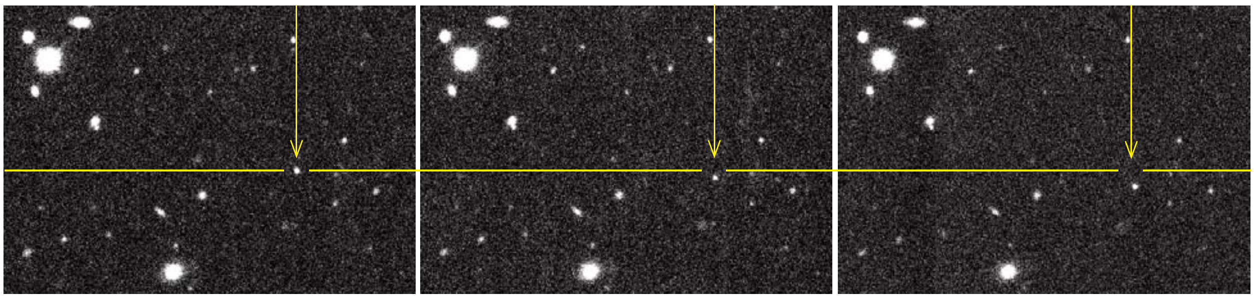
So what about the no man's land between the Oort Cloud at thousands to tens of thousands of a.u. and the Kuiper Belt at a few tens of a.u.? Astronomers had thought no objects would exist with orbits entirely in this middle region, since here the galactic tide is not strong enough to move the perihelion of an object out of the planetary region.

Then Sedna was discovered in 2003, in a shallow survey using the 1.2-meter Samuel Oschin Telescope at Palomar that covered most of the observable sky in the Northern Hemisphere. About 1,000 km in size, Sedna became the first object known to occupy this empty quarter for its entire orbit, with a perihelion of 76 a.u. and semi-major axis of 532 a.u. It was so unusual and unexpected that astronomers had to rethink the formation of our solar system. Ten years later, Chad Trujillo (Gemini Observatory) and I discovered 2012 VP_{113}, which has a perihelion even farther away than Sedna's at 80 a.u., though surprisingly it has a smaller semi-major axis (265 a.u.). Both objects are on very stable orbits. These objects currently do not interact significantly with any known mass in our solar system, including Neptune. However, their highly elliptical orbits mean that they must have interacted with *something* at some point in time.

Some astronomers have called these inner Oort Cloud (IOC) objects, since they are not susceptible to the galactic tide like the more distant outer Oort Cloud objects at thousands of a.u. IOC objects thus follow orbits that have remained stable from primordial times and are essentially fossilized imprints from their formation mechanism.

Theorists have proposed several viable IOC formation scenarios, all of which require the solar system to have been in a state vastly different than it is now. One theory is that a small rogue planet, tossed out of the giant planet region, could have dragged smaller objects with it or perturbed objects out of the Kuiper Belt and into the IOC on its way out. This planet could have been entirely ejected from the Sun's family of bodies or still be lurking in the distant solar system today.

Another theory is that IOC objects are captured objects that were ejected from other star systems that happened to be near our Sun during its formation in the original birth cluster (*S&T*: Mar. 2012, p. 30) and were then swept up by our star. A third, related theory is that a close stellar passage to our Sun sometime over the age of the solar system could have created objects like we see in the IOC



SCOTT SHEPPARD / CARNEGIE INST. FOR SCIENCE

FAINT TRAVELER On November 5, 2012, the author, together with Chad Trujillo, discovered the inner Oort Cloud object known as 2012 VP_{113}. The discovery images above were taken about two hours apart with the Dark Energy Camera on Cerro Tololo in Chile.

GOOD EYE **The Blanco 4-meter telescope at the Cerro Tololo Inter-American Observatory in Chile. The author and Chad Trujillo used the telescope's Dark Energy Camera to take the discovery shots shown on page 28.**

either by tugging objects in our solar system outwards or losing objects to our Sun (or both), but such a passage would have to have been within a few hundred a.u. This is very unlikely and would probably have disrupted the outer Oort Cloud.

But the leading scenario is that the IOC objects are native to our Sun and came to inhabit the region they do during a time when the gravitational tugs from outside were much stronger on the solar system than they currently are. This stronger tide would have perturbed objects closer to the Sun and been able to move their perihelia out to our system's outer reaches. A stronger tide would have occurred during our Sun's genesis in its birth cluster, as many other star systems were nearby. Theorists have simulated such a situation, finding that if our Sun originated in at least a moderately dense birth cluster (with a core packing 300 solar masses or more in a single cubic light-year), the gravitational interaction of our system with other stars could have produced IOC objects like Sedna and 2012 VP_{113}. Thus the creation of the IOC suggests our Sun grew up with a lot of siblings, which today are dispersed throughout the galaxy.

All the above theories are testable, with each predicting different orbital distributions for the IOC population. For instance, 2012 VP_{113} is more tightly bound to the Sun than is Sedna, meaning it would need a bigger outside perturbation to raise its perihelion. If IOC objects are captured extrasolar objects, they should have an assortment of orbital inclinations to the ecliptic, as capture should not strongly depend on the direction the objects came from. Objects scattered out from the inner solar system should show a flatter inclination distribution, reflecting their origin near the plane of the planets.

The modest inclinations of Sedna (12°) and 2012 VP_{113} (24°) suggest they formed within our solar system. Sedna's extremely red color also correlates well with the known classical Kuiper Belt objects. 2012 VP_{113}'s more moderately red color suggests it formed in the giant planet region. We need a bigger sample to say much more about the IOC objects.

What's Still Out There?

Sedna was discovered using the largest digital camera at the time to survey the sky efficiently. 2012 VP_{113} was discovered because astronomers are now placing these big digital cameras on larger telescopes. The Dark Energy Camera on the Blanco 4-meter telescope at the Cerro Tololo Inter-American Observatory, which Chad and I used to discover 2012 VP_{113}, covers about 2.7 square degrees per image. This is a factor of several times more sky area than any previous camera on a 4-meter or larger telescope, encompassing about 11 full Moons in one image. We are continuing our survey for distant objects and expect to find several more IOC objects in the next few years, but we will only cover a fraction of the sky. The Large Synoptic Survey Telescope, which the National Science Foundation is building in Chile, will cover a much larger portion of the sky and to the faint magnitudes needed to discover IOC objects in bulk. But it is still a decade away.

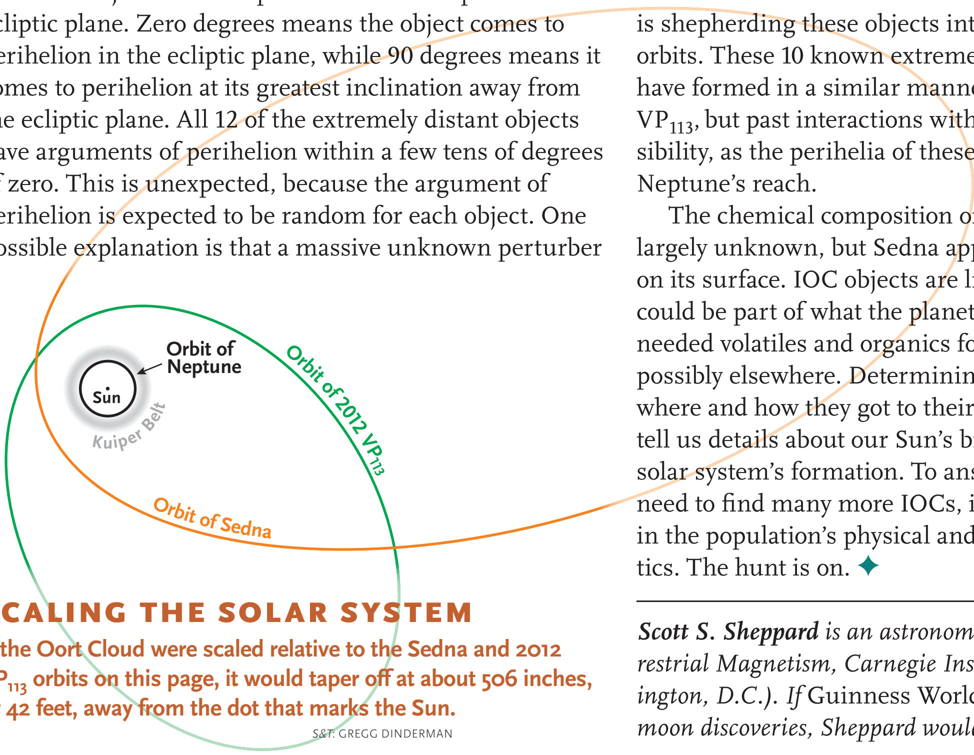
From the discovery of Sedna and 2012 VP_{113} and the small amount of sky searched to date, we believe about 1,000 objects larger than 1,000 km in size exist in the IOC, as well as many more smaller ones. The IOC population is likely larger than the main asteroid belt or Kuiper Belt. Several are probably bigger than Pluto, and some could even be bigger than Mars or even Earth. Objects get very faint at far distances, so big objects could easily lurk in the outer solar system (*S&T*: Mar. 2010, p. 20). We discover objects by their scattered sunlight, which has to travel out to the object, reflect off its surface, and travel back to Earth. An object twice as far away is 16 times fainter. Because of this, we can only detect Sedna and 2012 VP_{113} for a fraction of their orbits, when they happen to be near their perihelia. We would not spot these objects or even Mars-size objects on similar orbits most of the time because they would be too distant and thus too faint.

No more giant planets likely hide in our solar system, as NASA's Wide-field Infrared Survey Explorer spacecraft would have detected these large planets' warm atmospheres in the infrared. Giant planets give off more heat than they receive from the Sun, because their atmospheres are still dissipating energy they acquired from the planet's formation. Smaller worlds with minimal atmospheres, however, would be cold and frozen with no detectable heat signatures.

Some circumstantial evidence exists that a big object lies in the outer solar system. When looking at the orbits of Sedna and 2012 VP_{113} as well as 10 extreme Kuiper Belt objects near the outer edge of the Kuiper Belt, Trujillo and I noticed a similarity: a similar *argument of perihelion* for all 12 objects. The argument of perihelion is the angle at which an object comes to perihelion with respect to the ecliptic plane. Zero degrees means the object comes to perihelion in the ecliptic plane, while 90 degrees means it comes to perihelion at its greatest inclination away from the ecliptic plane. All 12 of the extremely distant objects have arguments of perihelion within a few tens of degrees of zero. This is unexpected, because the argument of perihelion is expected to be random for each object. One possible explanation is that a massive unknown perturber is shepherding these objects into these similarly angled orbits. These 10 known extreme Kuiper Belt objects could have formed in a similar manner to Sedna and 2012 VP_{113}, but past interactions with Neptune are also a possibility, as the perihelia of these objects are more within Neptune's reach.

The chemical composition of the distant objects is largely unknown, but Sedna appears to have methane ice on its surface. IOC objects are likely frozen ice balls that could be part of what the planets formed from, providing needed volatiles and organics for life here on Earth and possibly elsewhere. Determining their compositions and where and how they got to their present locations will tell us details about our Sun's birth environment and our solar system's formation. To answer these questions we need to find many more IOCs, in order to look for trends in the population's physical and dynamical characteristics. The hunt is on. ✦

WIDE-FIELD WONDER When operational, the Large Synaptic Survey Telescope facility, here shown in a photo-simulation composite, will provide time-lapse digital imaging of faint astronomical objects such as those found in the inner Oort Cloud.



SCALING THE SOLAR SYSTEM

If the Oort Cloud were scaled relative to the Sedna and 2012 VP_{113} orbits on this page, it would taper off at about 506 inches, or 42 feet, away from the dot that marks the Sun.

S&T: GREGG DINDERMAN

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