The Kuiper Belt: What We Know and What We Don’t

David Jewitt, UCLA, September 2012

The best indication of the significance of the Kuiper belt lies in its multiple connections to other aspects of the Solar system. The dust in the Zodiacal cloud, the rocks in the meteor streams, the nuclei of comets, the Centaurs, perhaps also the irregular moons of the planets and the Trojans that lead and trail planets in their orbits, are all related to the parent population in the Kuiper belt. Further afield, the dusty debris disks of other stars are likely produced by collisional shattering of parent bodies in unseen Kuiper belts about them. Because of these many connections, Kuiper belt science has already had significant impact on the study of the contents, origin and evolution of the Solar system, and on understanding the Solar system in the context set by other stars. While we know much more than we used to, we still don’t know many things about the Kuiper belt.

The Solar system formed from a flattened, rotating disk of gas and dust, itself produced by gravitational collapse from the interstellar medium. The explosion of a nearby massive star, a “supernova”, may have provided the initial compression causing the cloud to collapse, as suggested by the products of decay of short-lived radioactive elements (esp. 26Al) embedded in meteorites (Lee et al. 1977, Dauphas and Chaussidon 2011). Planets formed quickly in the dense inner portions of this disk but the process of growth in the rarefied outer regions was very slow. At large distances, growth times were so long that no major objects grew, instead leaving a large number of smaller bodies in a state of arrested development. The outer regions were also very cold, allowing water and other volatiles to be trapped as ice. This is the Kuiper belt.

I will briefly summarize the main areas in which our work holds the greatest significance.

Structure: The most important direct result from the Kuiper belt, other than the establishment of its existence, is the observation that the orbits of KBOs are divided into several distinct groups or types, and that the existence of these groups can be traced to evolutionary effects in the Solar system (Figure 1).

> **Classical Objects:** The first two KBOs, 1992 QB1 and 1993 FW, are prototypes of the Classical population. These objects have modest eccentricities and inclinations and do not closely approach Neptune. The latter avoidance gives them relative dynamical stability, even on timescales comparable to the age of the Solar system. The thickness of the Classical belt (which is best imagined as a fat doughnut with a radius of about 43 AU) indicates that the objects have been stirred up by the action of some past disturbing force.

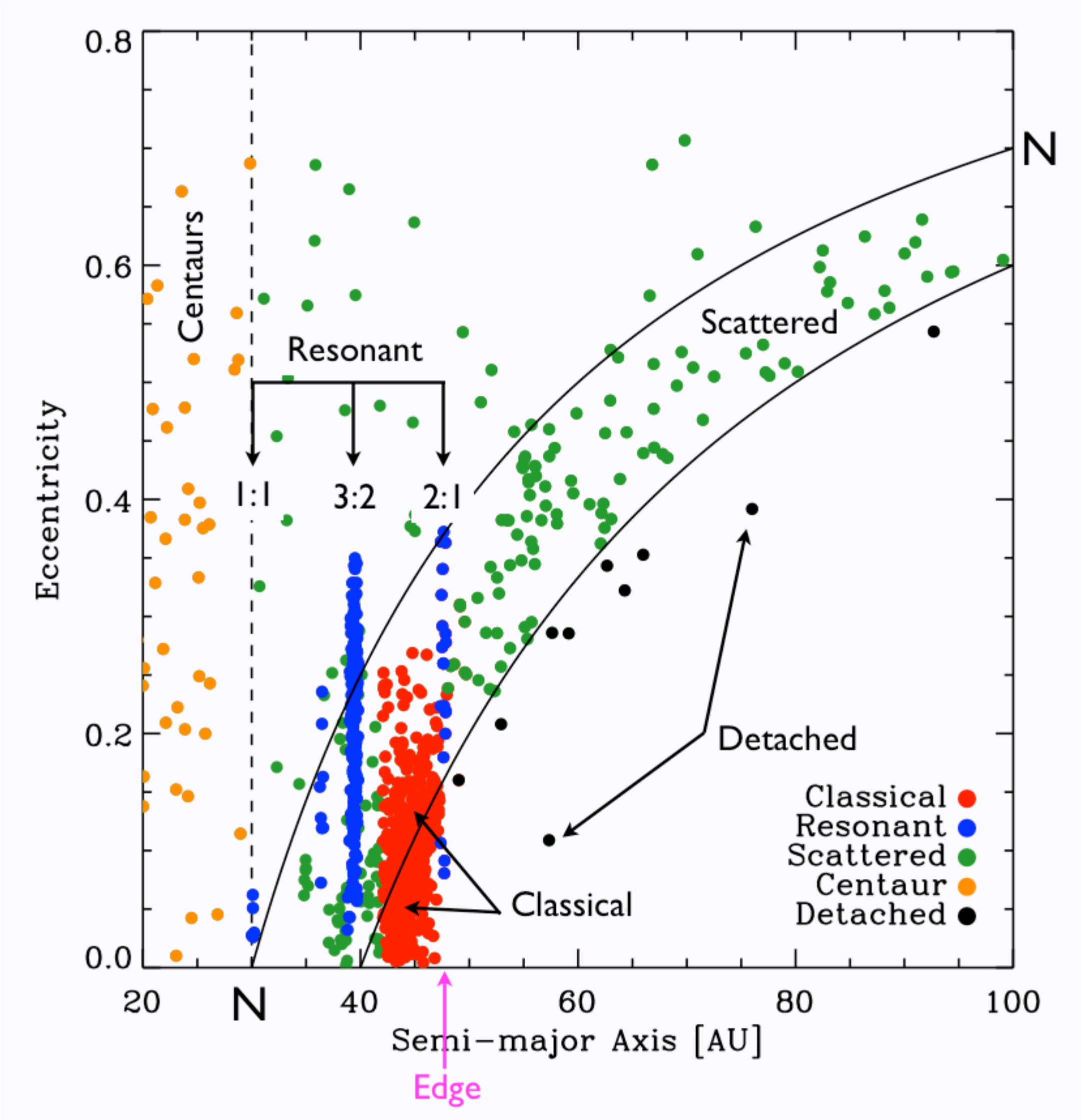

Figure 1: It is convenient to show the orbits of KBOs on a plot of semimajor axis vs. orbital eccentricity, as here. Plotted are some of the KBOs identified in the last 20 years, color-coded to show their division into distinct dynamical groups. Classical KBOs are shown in red. The Classical objects show an unexpected edge near the 2:1 mean-motion resonance at 47 AU, still not well explained. Detached objects (black) can have more eccentric orbits, but their large orbits also prevent them from closely approaching Neptune. Black arcs show lines of constant perihelion distance. Objects above the line labeled NN cross Neptune's orbit. Objects between the black arcs approach Neptune closely enough to be scattered by it - these are the Scattered KBOs (or "Scattered Disk" objects). The Resonant KBOs are shown in blue. Pluto is one of the blue dots in the 3:2 resonance (can you tell which one?). Centaurs (orange) are escaped, short-lived KBOs.

Resonant Objects: Many KBOs occupy orbits having periods that are in simple integer ratios to that of Neptune. The prototype is Pluto, which takes 250 years to orbit the Sun while Neptune takes 165. The ratio 250:165 = 3:2 and these bodies are said to be "in 3:2 mean-motion resonance". Our observations show that many resonances are occupied (e.g. 2:1, 5:3, 4:3, 1:1) and there are many different types of resonance in the Kuiper belt. The importance of resonances to dynamics is that they permit the cumulative action of gravitational forces. Like pushing a child on a swing in phase with the natural period of the swing, resonances allow small forces to have a big effect on the orbits of KBOs over long times.

Many more KBOs are trapped in resonances than would be expected by chance: why? The probable answer is that migration of Neptune caused the resonant trapping, described below.

Scattered Objects: Many KBOs occupy inclined eccentric orbits with closest approach to the Sun in the 30 to 40 AU range. This is close enough to Neptune (30 AU) that they are susceptible to perturbations that, with time, cause their eccentricities to grow, raising their aphelia to large distances: 2007 TG422 is the current record holder (aphelion 1100 AU). These Scattered KBOs (also called Scattered Disk objects) are dynamically unstable on billion year timescales. Many will be lost from the Solar system while others experience deflection inwards, to feed the "inward armada" (explained below).

Detached Objects: A few KBOs have perihelia beyond 40 AU, so that interactions with Neptune are unlikely to have played a role in shaping their orbits, at least given the current configuration of the Solar system. Sedna holds the current record (perihelion at 76 AU) but there are surely many more at larger distances. As they are gravitationally decoupled from Neptune, it is not clear how these objects were emplaced. Scattering by a passing star or an extant planet has been suggested.

Centaurs: Although not formally part of the Kuiper belt, the Centaurs are a dynamically short-lived (~10 Myr) population of escaped KBOs being scattered by the giant planets.

Mass: Added together, the masses of the objects currently in the Kuiper belt add up to about one tenth of the mass of Earth. Although this is roughly 1000 times the mass of the asteroids, the mass is still far too small for the KBOs to have formed in-place on any reasonable timescale. This is because KBOs are spread over an enormous volume, so vast that KBOs rarely collide. But without collisions, KBOs cannot grow. Worse, the high relative speeds when collisions do occur in the modern belt would cause shattering and destruction, not growth. To solve the latter problem, it is widely agreed that the KBOs formed in a dynamical environment that was very quiet compared to the present-day environment. The belt has been dynamically excited, somehow. Two possible solutions to the collision rate problem have been suggested. If the Kuiper belt were once confined to a much smaller volume than now, then the rate of collisions might have been higher and the timescales for growth shorter. No convincing schemes for making the young Kuiper belt very tiny compared to its modern-day self have been identified. Instead, the second and broadly accepted solution to this conundrum is that the present-day belt is a remnant of its formerly much more massive self. Initially, the Kuiper belt could have been several hundred to 1000 times its present mass, so that the collisions between KBOs would have been much more common than now. Most models of the formation of the KBOs are predicated on the assumption that the Kuiper belt was much more massive than it is now (e.g. 30 Earth masses, or about 300 times the present mass). This raises the obvious question: where did all this initial mass go?

One suggestion is that the depletion of the Kuiper belt could have been caused by extensive collisional grinding of the objects into dust. The dust would have temporarily given the Solar system a ring-like appearance as observed in the debris disks of nearby stars (Moro-Martin et al. 2007, Wyatt 2008, see also Figure 8) but, over time, the dust would have been swept away by radiation forces. Alternatively, some suppose that the Kuiper belt was dynamically depleted, presumably by interactions with Neptune.

Migration: Probably the most important consequence of the discovery of the Kuiper belt is the identification of evidence for the past radial migration of planets (meaning that the orbits of the planets have changed in size with time). This evidence is provided by the resonant KBOs. As explained by University of Arizona dynamicist Renu Malhotra (1995), KBOs can be efficiently trapped in mean-motion resonances with Neptune if the planet's orbit expanded sufficiently slowly and sufficiently smoothly over time. Why would Neptune's orbit expand? The answer lies in angular momentum exchange between the planet and the KBOs, a process described for the general planet-disk case by Goldreich and Tremaine (1980) (see also Fernandez and Ip 1984). In a one-planet system, scattering of KBOs would result in shrinkage of the orbit as ejected bodies carry away angular momentum. In our multi-planet Solar system, the net effect is for Saturn, Uranus and Neptune to migrate outwards while Jupiter, the most massive planet and the ultimate source of the energy needed to eject KBOs, moves inwards. Initial models suggested that Neptune formed near 20 AU from the Sun then moved outwards to 30 AU by exchanging energy and angular momentum with the KBO disk. Jupiter moved inwards by less than 1AU. The first exoplanets were discovered close to their parent stars at about the same time that migration was established in the Solar system. These "hot Jupiters" are thought to have migrated to their near-star locations from initially much larger orbits, a neat example of planetary migration popping up in two areas almost simultaneously.

Planetary Rearrangements: The realization that past planetary migration is important has opened a Pandora's box of numerical models for the evolution of the Solar system. For example, the Nice model (Tsiganis et al. 2005) considers the consequences for Solar system architecture of two major planets, Jupiter and Saturn, drifting into a mean-motion resonance. If this happened (and there is as yet no compelling independent evidence that it did), then the small-body populations of the Solar system might have been substantially rearranged. For example, by picking appropriate parameters for their model, some have argued that the irregular satellites of the planets (e.g. Figure 2) might have been captured from the Kuiper belt (Nesvorny et al. 2007). Recent modifications give Jupiter a much more complicated migration path (inward to the Sun then outwards to the present orbit) than in the original model, in order to try to better match the known Solar system. These and other N-body models are exciting because they have a flexibility that allows them to match a remarkable number of known properties of the Solar system. However, the flexibility results from the considerable number of input parameters on which they depend. This leaves the models open to the accusation that they are contrived, and renders them largely incapable of making observationally testable predictions, at least so far. It is probably too early to judge whether the models describe the evolution of the real Solar system, especially since ever more elaborate variations continue to be produced. The main significance of the new work is that it opens our minds to a much more complicated and chaotic set of formation and evolution models for the Solar system than was previously considered.

Figure 2: Saturn's irregular satellite Phoebe is about 200 km in diameter ("irregular" means that the orbit around the planet is large and eccentric and, in this case, the orbital motion is opposite to the direction of Saturn's spin). Phoebe was captured from elsewhere in the Solar system but the source region and the mechanism of capture remain unknown. One possible source is the Kuiper belt. NASA/ESA/JPL/SSI.

Inward Armada: Over very long timescales, weak disturbances by Neptune send some KBOs towards the Sun while others are ejected to travel endlessly amongst the stars, after close encounters with other planets (principally Jupiter and Saturn). The inward moving objects constitute an "inward armada" that is progressively depleted by collisions, ejection and disintegration (Figures 3 and 4) as the orbits of its members diffuse closer and closer to the Sun. Some parts of the armada were discovered long before their source in the Kuiper belt was identified. For example, objects with orbits crossing the orbits of the giant planets were known as Centaurs and regarded, initially, as wayward asteroids. We now clearly see the Centaurs as KBOs that have escaped the Kuiper belt. They rattle amongst the giant planets for about 10 Myr, on average, before either being ejected from the Solar system, impacting into a planet or the Sun, or being trapped by Jupiter in small orbits. There, high temperatures sublimate the ices, producing the short period (more exactly, the "Jupiter family") comets, debris streams that cause meteor showers, and dust that populates the Zodiacal cloud. From dust, to meteors, to debris trails, Jupiter family comets and Centaurs, the Kuiper belt provides the unifying and previously unknown source. It makes no more sense to study these sub-populations in isolation, any more than it would make sense to study the four legs, head, body, trunk and tail of an elephant as though they are unconnected to a single animal. But that's what we used to do; the Kuiper belt imbues us with a perspective on the armada that was previously beyond our reach.

Figure 3: The Zodiacal Light, a cone-shaped diffuse region visible to the unaided eye under dark skies long before and long after sunrise and sunset, respectively. The axis of the cone marks the mid-plane of the Solar system. The light is reflected from numerous dust particles released principally from outgassing short-period comets from the trans-Neptunian region. The dust particles collide and spiral into the Sun - requiring replenishment at about 50 tonnes per second to sustain the cloud in steady state. The Zodiacal particles are thus tiny fragments of disintegrated Kuiper belt objects. They bathe the inner Solar system, including the Earth, out to about the orbit of Mars. Known to the ancients, like the comets themselves, we now understand that this structure has its origin in material delivered from the Kuiper belt. Courtesy ESO/Y.Beletsky.

Beyond making the general statement that the Kuiper belt is the source of the inward armada, it has proved remarkably difficult to identify precisely from where in the belt the armada originates. The Classical Kuiper belt was the first proposed source region (Levison and Duncan

1997). However, this is unlikely because Classical objects are generally dynamically stable over multi-billion year timescales. The resonant populations are a possible source, since the edges of resonances exhibit dynamical chaos, and are capable of randomly launching objects towards Neptune and the inner Solar system (Tiscareno and Malhotra 2009). But the resonant populations are perhaps not large enough (Gladman et al. 2012). The orbits of Scattered objects are intrinsically unstable on billion year timescales because of their interactions with Neptune at perihelion. Again, surveys do not show enough of them to easily explain the flux of Jupiter family comets (Volk and Malhotra 2008). The resolution of this problem might involve uncertainties in existing surveys, or in the assumed size distribution of small KBOs, and perhaps other sources exist. The 1:1 resonant "Trojan" populations could, for example, be significant (Horner and Lykawka 2010).

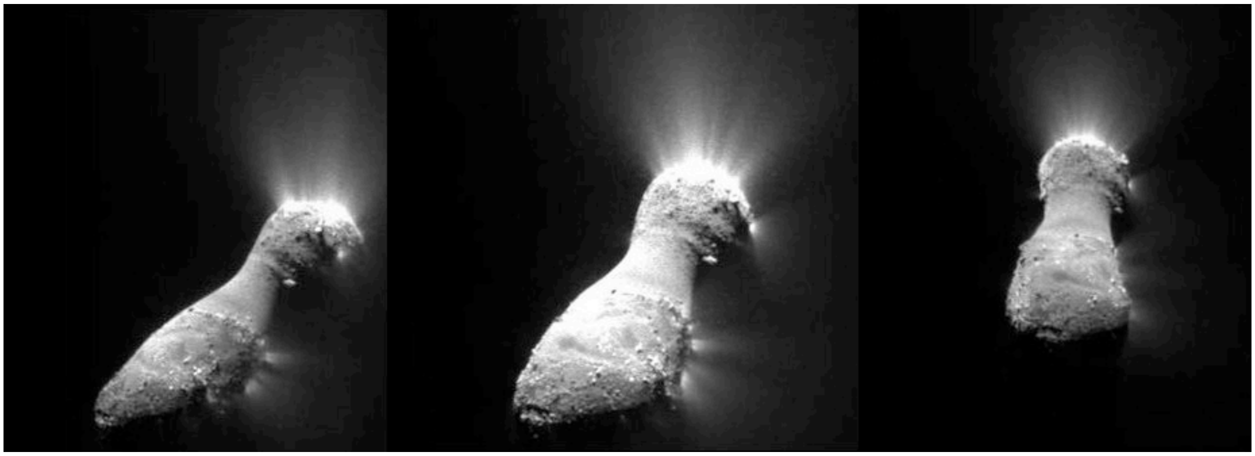

Figure 4: Elongated nucleus of Jupiter-family comet (escaped Kuiper belt object) P/Hartley 2, from three perspectives offered by the EPOXI mission. The nucleus is about 2 km long and may consist of two original bodies in a contact binary, with the contact region buried in a waist of smooth-appearing debris. Any trace of the original surface has been lost by extensive outgassing in the heat of the Sun. Indeed, the precursor KBO was probably much larger than the remnant seen here. Courtesy NASA.

The situation is even less clear in the past, when planetary migration might have changed the layout of the Solar system, leading to radically different regimes for radial transport. In an earlier configuration, other populations that are not now dynamically coupled to the Kuiper belt, could have originated in this trans-Neptunian source. This origin has been suggested for the Jovian Trojans (Morbidelli et al. 2005), the irregular satellites of the planets (Nesvorny et al. 2007) and for the outer regions of the asteroid belt (Levison et al. 2009). Whether this is true is far from clear. Occam's Razor suggests that the outer belt asteroids formed near to where they now orbit. The irregular satellites can be captured from nearby, heliocentric orbits more efficiently than from distant orbits in the Kuiper belt, as can the Jovian Trojans. What we most need are observational tests of the various origin scenarios, but the models have enough free parameters and uncertain initial conditions that they do not lend themselves to observational testing.

Compositions: With temperatures of -230 C, the Kuiper belt is the Solar system's ice box, in which even volatile products of accretion have been preserved for 4.6 billion years. The outgassing of volatile materials (like carbon monoxide) from Jupiter family comets proves this - required accretion temperatures are near -230 to -240 C, just as we measure in the Kuiper belt. Despite the uniformly low temperatures and expected absence of chemistry, KBOs show a wide range of surface compositions. Water and methane are spectroscopically easy to detect, and both are found in the Kuiper belt. Nitrogen ice, which dominates the surface of Pluto and Triton (Figure 5), for example, is difficult to detect on smaller or more distant objects, but may be present. In the larger objects, the compositional variations are clearly related to the object size and distance from the Sun (temperature), and are readily explained by atmospheric escape (Schaller and Brown 2007).

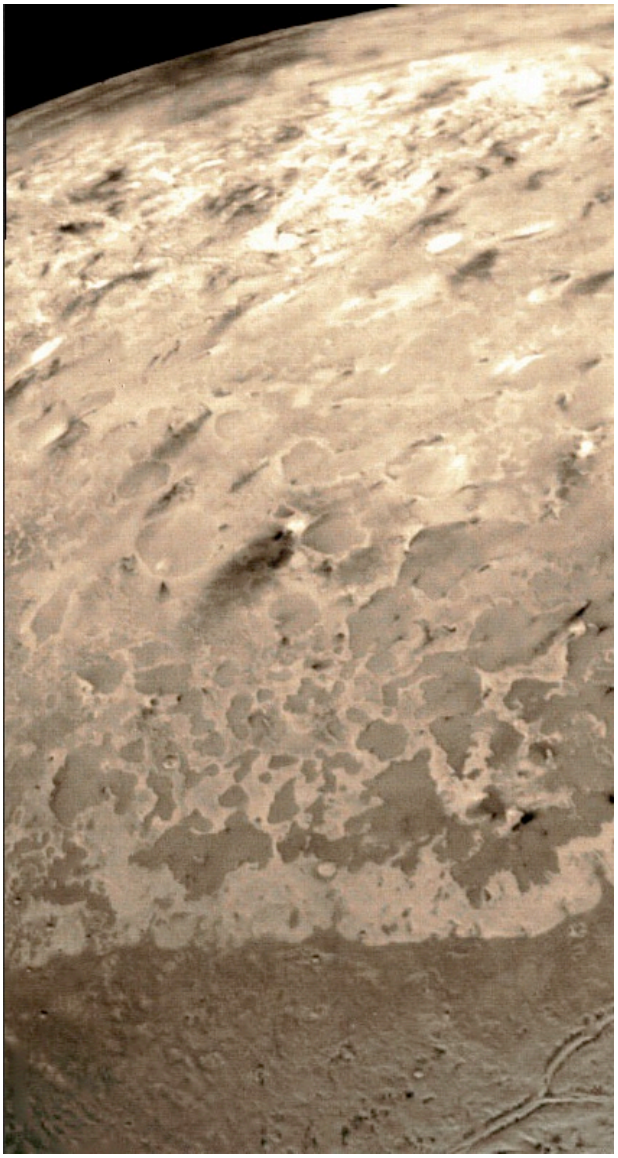

Figure 5: Icy surface of Triton, a large moon of Neptune captured from the Kuiper belt and imaged by the Voyager spacecraft. Pending data from NASA's New Horizons mission to Pluto, Triton offers our best indication as to the surface nature of a large KBO. The surface consists of solid nitrogen, mixed with methane and other trace species. Black smudges near the center and top of the image show places where dust is launched above the surface and carried by winds in the thin atmosphere (pressure ~ 1/100,000 bars). The terrain in the middle suggests local removal of surface ices, presumably driven by Solar heating. At the bottom are seeming tectonic features. Very few impact craters are present, indicating that this portion of the surface is geologically young. Triton is large enough (diameter 2700 km) that its interior should be significantly heated by embedded radioactive nuclei and water at depth could be liquid. NASA Voyager II image.

Small KBOs show a wider range of colors than any other populations in the Solar system (Luu and Jewitt 1996). The "ultra-red matter", thought by some to reflect irradiated organic compounds, is found only in the Kuiper belt and in some Centaurs, recently escaped from the belt (Jewitt 2002). Its absence in the inner Solar system may reflect thermal or physical instability: its origin and nature remain poorly understood but these are excellent subjects for laboratory astrophysicists. The distribution of colors of KBOs is peculiar, with smaller objects, at least, being probably bimodal (Peixinho et al. 2012). There is essentially no physical understanding of the color distribution of KBOs, although ad-hoc explanations abound.

Binary and Multiple Objects: Binary KBOs (e.g. Figure 6) have been identified in abundance and even objects with more than one satellite are known (Noll et al. 2008). Many observational biases exist against the detection of binaries in which the ratio of diameters of the primary and secondary bodies is large (because the smaller object is then lost in the glare of the larger, brighter one) and against the detection of binaries having a small angular separation. Therefore, the detection of even a few binary objects implies that a much larger fraction would be seen to be binary if observed with higher sensitivity and resolution. The estimated binary fraction in the Classical belt is 20% but this is surely a lower limit (Noll et al. 2008).

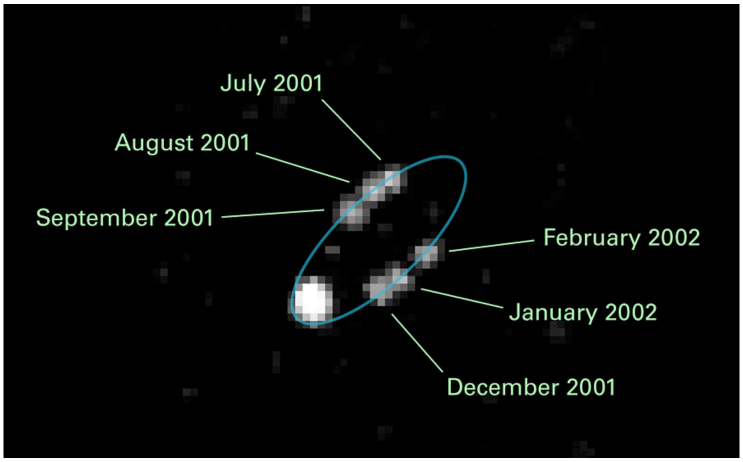

Figure 6: Binary KBO 1998 WW31, observed on a range of dates in 2001 and 2002. The period is about 1.5 years, the orbit semi-major axis about 22,000 km and the orbit eccentricity is near 0.8. The larger component is ~130 km diameter, the smaller ~100km. Veillet et al. 2002.

Many of the observed binaries are wide, meaning that they are held together loosely by mutual gravity. The two most important questions are 1) how did these binaries form? and 2) how did they survive against destabilizing effects including collisions and, in some cases, close interactions with Neptune? It is still too early to reach definitive conclusions, but the likely formation scenarios involve capture in a dense initial disk having a small velocity dispersion. Dynamical friction and/or three-body reactions, both unimportant in today's Solar system, were probably important at formation. The survival of wide binaries sets limits to the degree of collisional processing over the lifetime of the Solar system. While close binaries cannot be resolved (the resolution of the best telescopes at the distance of the Kuiper belt corresponds to ~1500 km), the distinctive lightcurves of some objects indicate their binary nature. The incidence of close- or contact-binaries may approach 10% or 20% (Sheppard and Jewitt 2004, Lacerda 2011).

Pluto: The oddness of Pluto as a planet was always known, even at its discovery in 1930. Its orbit is unlike that of any other planet in being both highly eccentric (0.25) and highly inclined (17 degrees) relative to the orbit plane of the Earth. And, although early astronomers (perhaps wishfully) believed otherwise, Pluto is very small, with a mass 500 times less than the mass of Earth. These peculiarities made sense as soon as we had identified a few dozen other Kuiper belt objects in the same 3:2 resonance as Pluto. Called "Plutinos" to emphasize the similarity with the former planet, these KBOs resemble Pluto in having orbits that are both highly eccentric and inclined. Also like Pluto, the orbits of many Plutinos cross inside Neptune's orbit (the latter is nearly circular at 30 AU), while maintaining a respectful distance from the larger body. All of these properties, for Pluto as for the Plutinos, result from repetitive gravitational perturbations from much-more-massive (about 17 Earth masses) Neptune (Malhotra 1995). And while at first objectors claimed that Pluto was different from other KBOs in having satellites, we now know that many other KBOs have satellites too, in some cases more than one. Even the claim that Pluto is distinguished from other objects by its size (2300 km diameter) is spurious: Eris is, within the uncertainties of measurement, the same size as Pluto while captured KBO Triton is bigger (2700 km).

The realization that Pluto is better understood as a large KBO than as the Solar system's most peculiar planet fired the imaginations of young children about 5 years ago. Scientifically this a non-issue. There is absolutely no doubt that Pluto is a big KBO and that it can only be understood in the context provided by the Kuiper belt. This has been known by astronomers since 1992. The public debate has been centered more around the realization that the term "planet" is vaguely defined. But, just as not having a rigorous definition of "continent" or "ocean" did little to interfere with our species' exploration of the Earth, the "what is a planet?" debate has nothing to do with understanding or exploring the Solar system (Jewitt and Luu 2007).

Dust and Debris Disks: The average speed between colliding Classical KBOs is about 1.1 km/s (Trujillo et al. 2001) while collisions in other components of the belt are faster. At these speeds, colliding objects splinter and fragment, producing rubble and dust. We have both indirect and direct evidence for collisions in the Kuiper belt. For example, KBOs larger than about 50 km follow a size distribution slightly steeper than smaller KBOs (discussed by Schlichting and Sari

2011). This is suspected to be because large objects retain their primordial sizes while smaller ones are fragments produced collisionally from large objects. Some of the nuclei of Jupiter family comets, typcally 1 to 10 km in size, may be products of Kuiper belt collisions (Davis and Farinella 1997). Direct evidence comes from dust detectors on various distant spacecraft (Figure 7). These show a steady rate of impact with micron-sized and larger dust grains, indicating a global dust production rate of about two tonnes per second (Vitense et al. 2012). Because the outer Solar system is so cold, ice sublimation and cometary activity cannot create the dust. Collisional grinding of KBOs is responsible.

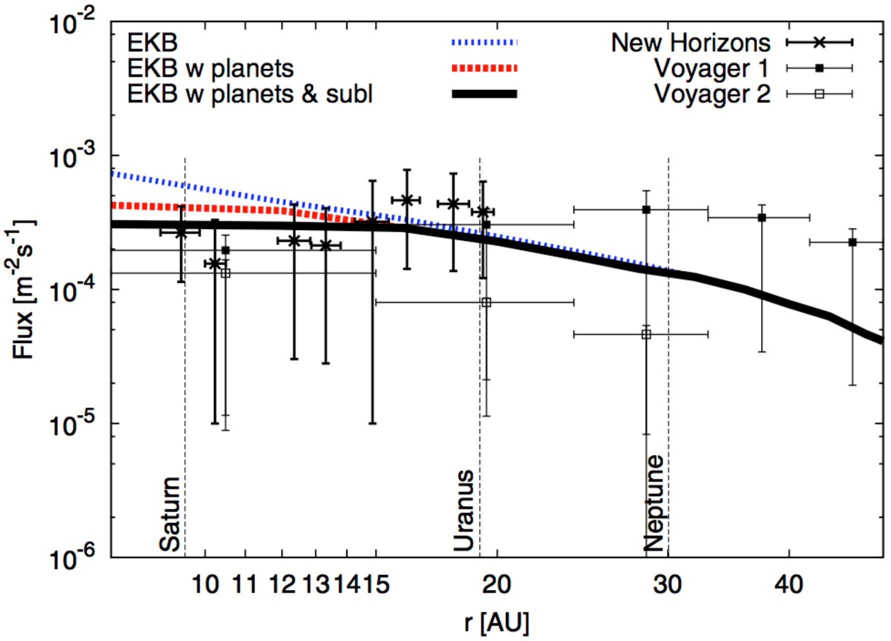

Figure 7: The flux of dust grains impacting spacecraft in the outer Solar system. The impact flux corresponds to dust production rate of two tonnes per second, due to self-grinding Kuiper belt collisions. Note that the impact rate barely drops out to 40 AU. From Vitense et al. 2012.

We therefore expect that the Kuiper belt is a source of dust for the outer Solar system and that, if we could view this dust from an external perspective, it would appear concentrated in a diffuse and thick ring with a radius of order 40 AU, qualitatively like the Fomalhaut ring (Figure 8). Fomalhaut, however, is a much younger (~200 Myr) and more massive (2 Solar mass) star, and its inferred Kuiper belt mass (~100 Earth mass) is enormous compared to the Kuiper belt's current 0.1 Earth mass. Perhaps we are observing Fomalhaut at a time corresponding to the early clearing phase in the Solar system.

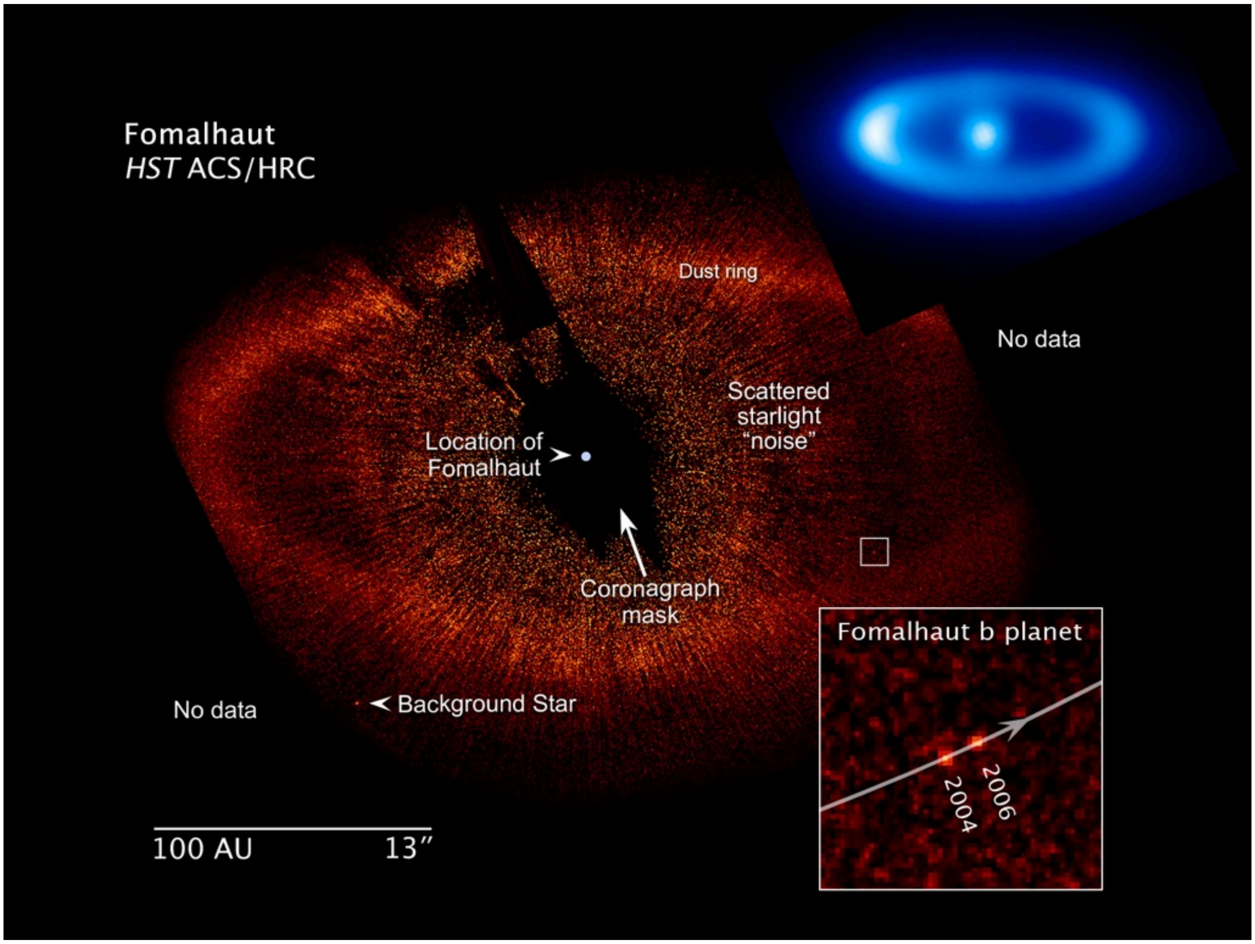

Figure 8: The dusty debris disk of nearby main-sequence star Fomalhaut. The star itself has been occulted to reduce strong scattered starlight. Removal of residual scattered light is responsible for the streaked appearance of the disk. The shape of the disk indicates an inclination of about 66 degrees to the line of sight. A scale bar at the lower left shows 100 AU - roughly the diameter of the Classical part of the Kuiper belt. The upper right inset, in blue, shows heat from the disk (wavelength 70 μm) in a Herschel spacecraft image (Ake et al. 2012), courtesy ESA. The lower right inset shows an object co-moving with the star and presumed to be in orbit about it. Figure by Kalas et al. 2008.

Thanks: Science advances in large part by proving that the conventional wisdom is incomplete, or inconsistent or simply wrong. So, it's normal for one's work to be picked-apart and criticized all the time by other scientists. That's the strength of science. Sometimes the criticism becomes personal, or politicized and sometimes it is relentless. I am used to that but, given this background, to receive a big award for my work was quite unexpected. The Shaw prize does the opposite of criticizing by showing that some other people do recognize the importance of what I have done. So, I say thank you very much to Mr Run Run Shaw, to his Foundation and to the members of the Astronomy selection committee this year and I hope to see you all one day in the Kuiper belt (Figure 9)!

Figure 9: Artist's rendition of the icy surface of a KBO illuminated by the distant Sun. ESO/L. Calçada

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