Small Bodies in the Outer Solar System

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Abstract.
The dynamical and physical characteristics of asteroids, comets, Kuiper Belt objects and satellites give us insight on the processes operating in the Solar System and allow us to probe the planet formation epoch. The recent advent of sensitive, wide-field CCD detectors are allowing us to complete the inventory of our Solar System and obtain detailed knowledge about the small bodies it contains. I will discuss the recent results with a focus on the new bodies being discovered beyond Neptune with a particular emphasis on the very distant orbit of (90377) Sedna and 2003 UB313, which is larger than Pluto.

1. Introduction

The idea of a small body population beyond Neptune can not really be attributed to any one individual but a slow realization that the Solar System did not end at Neptune or Pluto (Leonard 1930; Edgeworth 1949; Kuiper 1951). Oort (1950) realized that the long period comets must come from a spherical cloud at a distance greater than 50000 AU. Whipple (1950) first described comets as weak conglomerates of volatile and solid material (the dirty snowball). Everhart (1972) found that long period comets (Periods > 200 years) could become short period comets (Periods < 20 years) through interactions with Jupiter. Joss (1973) argued that this wasn't efficient enough to provide a sufficient source of all the observed short period comets. The most informative work on the origin of short-period comets was from Fernandez (1980). He determined that a Kuiper disk of objects with low inclinations just beyond Neptune would be a good source for short period comets which had mostly low inclinations. These are unlike the long period comets which have an isotropic distribution of inclinations and are most likely to come from the proposed Oort cloud.

Observational work with photographic plates was slow and very inefficient. An extensive photographic survey of the ecliptic by Kowal (1978) found only one outer Solar System object. This object is the first known Centaur, 2060 Chiron, which has an orbit completely within the giant planet region. Kowal's lone discovery was nevertheless important because it showed that some small bodies do have orbits entirely outside of Jupiter's orbit. Soon afterwards a number of stars having IR excesses was observed by IRAS (Aumann et al. 1984). It was quickly discovered that one of these IR excess stars, β Pic, has a large

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observable disk of dust that extended out to about 1000 AU in radius (Smith & Terrile 1984). Weissman (1984) suggested that the IR excess could be from dust produced by collisions in a distant small body population such as an Oort cloud or Kuiper Belt.

With the development of Charge Coupled Devices (CCDs) in the 1980's surveys could go much deeper and computers allowed for efficient image analysis. In 1992 the first Kuiper Belt object (KBO) other than Pluto was discovered, 1992 QB_1 (Jewitt & Luu 1993). In the mid to late 1990's moving object detection software on high performance computers and large field-of-view CCD detectors opened up the flood gates for discovering small bodies in the outer Solar System.

Over 1000 trans-Neptunian Objects (TNOs) have been detected since the discovery of 1992 QB_1. The Kuiper Belt (or Edgeworth-Kuiper Belt) is thought to be a relic from the original protoplanetary disk. It is estimated to contain about 80,000 objects with radii greater than 50 km (Trujillo, Jewitt, & Luu 2001). This "belt" has been collisionally processed and gravitationally perturbed throughout the age of the Solar System in ways that are not yet fully understood (Farinella & Davis 1996).

The Kuiper Belt is the largest known relatively stable ensemble of small bodies in the planetary region, outnumbering the main-belt asteroids and Jovian Trojans by a factor of $\sim$300. The Kuiper Belt's vast distance from the Sun suggests the objects are chemically primitive, containing large amounts of volatiles. Thus we may be able to probe some aspects of the early history of the local solar nebula by studying the Kuiper Belt and related objects. The short-period comets and Centaurs are believed to originate from the Kuiper Belt (Fernandez 1980; Duncan, Quinn, & Tremaine 1988). Centaurs, which have semimajor axes and perihelia between Jupiter and Neptune, are currently in dynamically unstable orbits that will lead either to ejection from the Solar System, an impact with a planet or the Sun, or evolution into a short period comet (Dones et al. 1999; Tiscareno & Malhotra 2003). The long period comets likely come from the more distant and yet undetected Oort cloud.

2.   Kuiper Belt Dynamical Structure

The Kuiper Belt has been found to be dynamically structured (see Figure 1). This structuring was a big surprise to most astronomers as it was assumed any Kuiper disk would be dynamically cold (i.e., most objects would have low eccentricities and inclinations). The mean velocity dispersion ($\sim$1.2 km s^{-1}) found for KBOs is larger than the escape speed of most KBOs. Thus the current Kuiper Belt is in a state of erosion (Davis & Farinella 1997). Theoretical and modeling work has largely been devoted to explaining the current dynamical structure seen in the Kuiper Belt. Most invoke the migration of Neptune (Malhotra 1995; Hahn & Malhotra 1999; Levison & Morbidelli 2003), the passage of giant planetesimals through the disk (Morbidelli & Valsecchi 1997), or a passing star (Ida, Larwood, & Burkert 2000; Levison, Morbidelli, & Dones 2004; Morbidelli & Levison 2004; Kenyon & Bromley 2004). Recent modeling suggests that some minor planets which formed between Jupiter and Neptune may have been scattered into the Kuiper Belt region causing the belt to look much more excited than if they were not present (Gomes 2003).

There are five known dynamical classes of KBOs (Figures 1 and 2). Classical KBOs have semi-major axis $40 < a < 50$ AU with moderate eccentricities ($e \sim 0.1$ to 0.2) and inclinations. Resonant KBOs are in mean motion resonances with Neptune and generally have higher eccentricities and inclinations than Classical KBOs (Chiang et al. 2003; Elliot et al. 2005). The 3:2 resonance currently has the most known members, but this may be a selection effect since this resonance is located at the inner regions of the Kuiper Belt. The KBOs in the 3:2 resonance are called Plutinos since Pluto occupies this resonance. The Neptune Trojans are in a $1 : 1$ resonance with Neptune which means they have similar semi-major axes as Neptune but lead or trail the planet by about 60 degrees. Scattered disk objects have very large eccentricities with perihelia near the orbit of Neptune ($q \sim 30$ AU). The Scattered disk objects are believed to have been recently scattered out of the main Kuiper Belt through interactions with Neptune. Scattered disk objects are probably the progenitors of the Centaurs and short-period comets. A fifth class of KBO, the extended scattered disk (Figure 2), has only recently been recognized (Gladman et al. 2002; Morbidelli & Levison 2004) and to date only two members are known. These objects have large eccentricities but unlike the scattered disk objects the extended scattered disk objects have perihelia $q > 45$ AU which can not be directly caused by Neptune interactions alone. These objects may have obtained their orbits from a stellar passage near the Kuiper Belt (Morbidelli & Levison 2004). The bias corrected relative populations of classical : scattered : resonant are $1.0 : 0.8 : 0.1$ (Trujillo et al. 2001).

There is an edge to the classical population around 50 AU (Jewitt, Luu, & Trujillo 1998; Trujillo et al. 2001; Allen, Bernstein, & Malhotra 2002; Trujillo & Brown 2001). Only objects with very large eccentricities are known to have orbits which go beyond 50 AU. The only currently viable explanation known to date is that the disk was truncated by a passing star (Ida et al. 2000; Morbidelli & Levison 2004).

2.1. Sedna and the Extended Scattered Disk

How was the extended scattered disk and Sedna formed? Sedna's current large perihelion distance ($\sim$76 AU) along with its large eccentricity ($\sim$0.84) are hard to explain with what we currently know about the Solar System. If Sedna formed in its current location it must have initially been on a circular orbit otherwise accretion would not have been possible because the large relative velocities of colliding bodies would have been disruptive (Stern 2005). If Sedna obtained its large eccentricity through interactions with the currently known giant planets, somehow its perihelion must have been raised. Several theories on Sedna's history have been put forth (see Morbidelli & Levison 2004, for a review): 1) Sedna may have been scattered by an unseen planet in the outer Solar System. Neptune can only be invoked if an object has a perihelion distance of less than 50 AU (Gladman et al. 2002; Gomes 2003). 2) A single stellar encounter may have raised Sedna's perihelion (Brown, Trujillo, & Rabinowitz 2004; Morbidelli & Levison 2004). Galactic tides are too weak to raise the perihelion of an object that is so close to the Sun and only work for distant Oort cloud objects around 10,000 AU. The stellar encounter would have to have been very close, around 500 AU, in order for Sedna to be excited. This may hint that our Sun formed
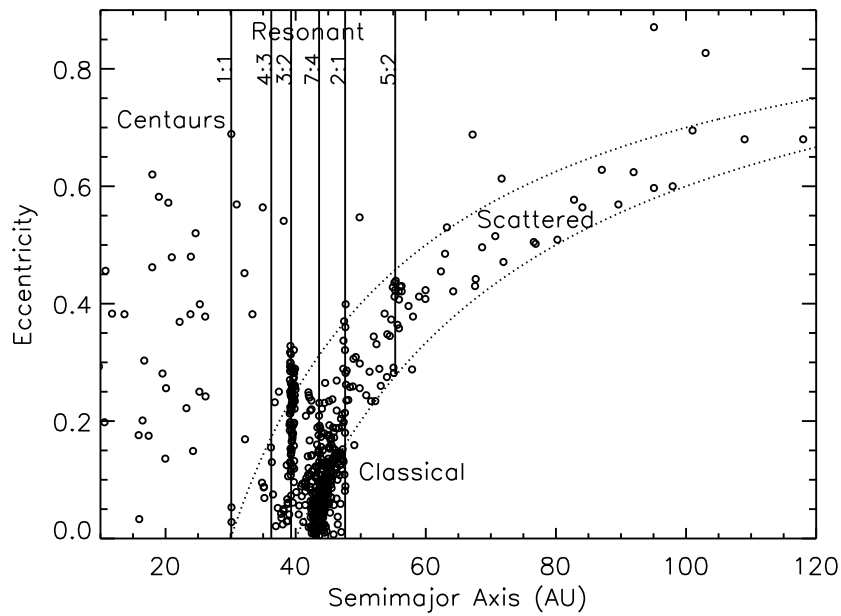
Figure 1.   Semimajor axis versus eccentricity of known trans-Neptunian objects which show four of the five distinct KBO populations as well as the Centaurs. Vertical solid lines show resonances with Neptune which includes the Neptune Trojans in the 1 : 1 resonance. Scattered disk objects reside between perihelia $30 < q < 40$ AU which are shown by dashed lines. Extended scattered disk objects have perihelia greater than 45 AU (see Figure 2). Classical objects are in the lower center portion of the figure. An edge around 50 AU can clearly be seen for low eccentricity objects.
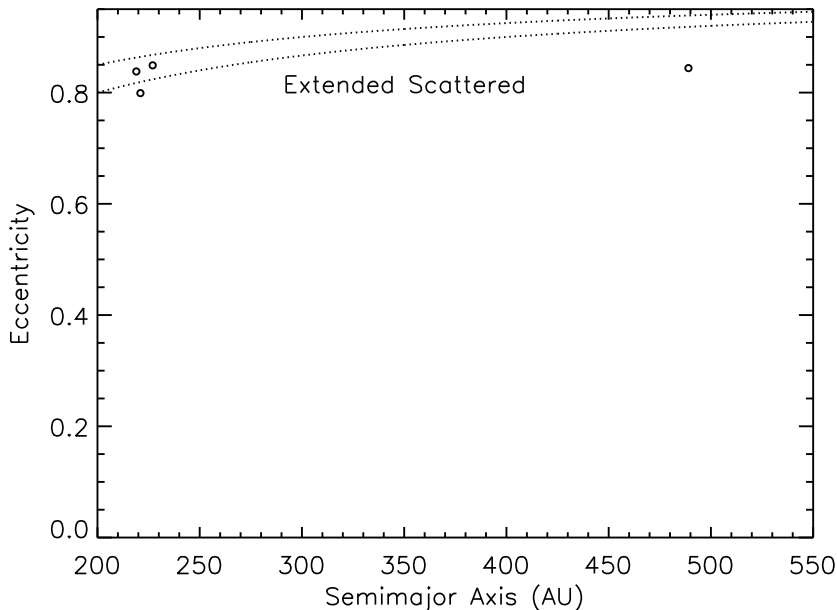
Figure 2.   Semimajor axis versus eccentricity of extended scattered disk objects which have perihelion greater than 45 AU (which fall below the dotted lines). Only two objects are known to be in the extended scattered disk; Sedna (seen in the upper right) and 2000 CR105. These objects with high semi-major axes and perihelion distances can not have obtained their current orbits with simple interactions with Neptune or any other known Solar System objects.

in a very dense stellar environment. In addition, this may have caused the edge we see today in the Kuiper Belt at 50 AU (Ida et al. 2000). A time constraint is required, that is, if the stellar encounter happened too soon Sedna would not have been formed but if it happened too late it would disrupt the Oort cloud. 3) A highly eccentric Neptune would have been able to produce Sedna. 4) If several massive planetary embryos were scattered into the outer Solar System during the planet formation epoch this may also produce Sedna's orbit as we see it today. 5) If the trans-Neptunian disk was thousands of times more massive it may have influenced Sedna's orbit. 6) Sedna may be a captured extrasolar planetesimal. To date, the stellar encounter scenario appears to work best.

2.2.   Neptune Trojans

As mentioned above, Trojans are objects which share a planet's semi-major axis but are ahead or behind the planet by about 60 degrees in orbital longitude, known as the leading (L4) and trailing (L5) Lagrangian regions. Recent dynamical studies show that Trojans are stable near the L4 and L5 points of Neptune for the age of the Solar System (Nesvorný & Dones 2002; Marzari, Tricarico, & Scholl 2003). The population mechanism and long-term stability of the Trojans is strongly linked to the physics and evolution of the Solar System. The Trojan's current dynamical properties constrain the formation, evolution and migration of the planets. It is still uncertain if the Trojans formed in their current locations or were captured at some point. In the present epoch there is no

known efficient mechanism to permanently capture Trojans but Trojan capture could have occurred more easily towards the end of the the planet formation epoch. Trojan asteroids may have a very similar history as the irregular satellites of the planets (Jewitt et al. 2004). The effects of nebular gas drag (Peale 1993), collisions (Chiang & Lithwick 2005), planetary migration (Gomes 1998; Kortenkamp, Malhotra, & Michtchenko 2004), overlapping resonances (Marzari & Scholl 2000; Morbidelli et al. 2005), and the mass growth of the planets (Fleming & Hamilton 2000) all potentially influence the formation, capture efficiency and stability of these bodies.

3.   The Kuiper Belt Size Distribution

The Cumulative Luminosity Function (CLF) describes the sky-plane surface density of objects brighter than a given magnitude. For the Centaurs and KBOs the CLF is well known for $m_R < 26$ mags. (Jewitt et al. 1998; Trujillo et al. 2001; Allen et al. 2002; Millis et al. 2002; Trujillo & Brown 2003). To determine the size distribution of the KBOs we assume they follow a differential power-law radius distribution of the form $n(r)dr = \Gamma r^{-q}dr$, where Γ and q are constants, r is the radius of the KBO, and $n(r)dr$ is the number of KBOs with radii in the range r to $r + dr$. For the KBOs $q \sim 4$ which means the belt should be dominated by the smallest objects. A similar result is found for the Centaurs (Sheppard et al. 2000). The recently discovered scattered disk object, 2003 UB313, is slightly bigger than Pluto. This object has an orbit which is typical of the other known scattered disk objects. Discovery of such a large object as 2003 UB313 ($r \sim 1500$ km) was not unexpected (Trujillo & Brown 2003).

   A recent deep survey using the Hubble Space Telescope reached a limiting magnitude of about 29th in the optical (Bernstein et al. 2004). Through extrapolation of the CLF to very small KBOs (radii ~ 10 km) the survey was expected to find hundreds of small KBOs. Only three new KBOs were detected in the survey. This strongly indicates that the Kuiper Belt does not follow the same power law size distribution found for larger objects ($r > 25$ km) at the smaller sizes. Thus, the Kuiper Belt may be very deficient in KBOs with small radii.

   The inferred mass of the current Kuiper Belt is about 0.1 Earth masses (Trujillo et al. 2001). This is about one hundred times lower than would be expected from the solar nebula when augmenting the masses of the planets. In addition, the current population size structure, binary population and angular momentum of the Kuiper Belt suggests a more massive disk existed in the primordial Kuiper Belt (Stern 1996; Jewitt & Sheppard 2002; Astakhov, Lee, & Farrelly 2005). A detailed accretion model of an earlier denser Kuiper Belt by Kenyon & Luu (1999) showed that several Pluto sized objects could form within the age of the Solar System. The mass may have been lost through Neptune interactions (Hahn & Malhotra 1999) and collisional grinding (Stern 1996; Kenyon & Luu 1999). Infrared excesses found around some main sequence stars appears to corroborate dust production produced through collisions between small bodies in possible Kuiper Belt analogs (Weissman 1984; Aumann et al. 1984). This dust is unstable to radiation pressure from the host star and the Poynting Robertson effect and thus the dust must be constantly replenished through collisions.

3.1.   Kuiper Belt Binaries

It appears that about $4\% \pm 2\%$ of KBOs have companions with separations $\geq 0.15\,''$ (Noll et al. 2002). To date most known KBO binaries have mass ratios near unity, though this may be an observational selection effect. These large nearly equal sized components probably did not form by simple direct collisions (Stern 2002). Formation of such binaries could occur through complex three-body interactions (Weidenschilling 2002; Funato et al. 2004; Astakhov et al. 2005) or when two bodies approach each other and energy is extracted either by dynamical friction from the surrounding sea of smaller KBOs or by a close third body (Goldreich, Lithwick, & Sari 2002). These processes mostly require that the density of KBOs was $\sim 10^2$ to 10^3 times greater than now.

4.   KBO Physical Properties

4.1.   Colors and Albedos

The surfaces of KBOs may have been altered over their lifetimes by collisions, cometary activity, and irradiation. The KBOs geometric albedos are still poorly sampled but the larger ones have been measured through detecting their thermal emission in the mid-infrared, submillimeter and millimeter wavelength regimes (Altenhoff, Bertoldi, & Menten 2004; Grundy, Noll, & Stephens 2005). It appears there is a large range of albedos with reflectivity being as dark as 4% and as bright as 60%. It is possible that the brighter surfaces are indicative of volatile ices while the darker surfaces may be more organic rich.

Colors of the KBOs have been found to be diverse, ranging from neutral to the reddest objects known in the Solar System ($V - R \sim 0.3$ to $V - R \sim 0.8$). The KBOs show signs of a possible correlation between colors and inclination at the ($\sim 3\sigma$) level (Trujillo & Brown 2002; Stern 2002; Tegler, Romanishin, & Consolmagno 2003; McBride et al. 2003; Peixinho et al. 2004; Fornasier et al. 2004; Barucci et al. 2005). This correlation has prompted the recent modeling work by Gomes (2003). In this scenario the current Kuiper Belt has two separate populations (Figure 3). The first are small bodies which formed near their current locations beyond Neptune and which have low to moderate inclinations. The second population are of bodies which formed in the giant planet region and were scattered into the Kuiper Belt. These objects would be on average larger, more neutral in color and have inclinations ranging from small to large. Objects which formed closer to the Sun could obtain larger sizes because the solar nebula was more dense there. Empirically, objects which formed closer to the Sun are more neutral in color, which is probably because they have less volatile material on their surfaces. This scenario is the result from the color observations mentioned above as well as that there appear to be two inclination distributions in the Kuiper Belt (Brown 2001) and that objects with higher inclinations appear larger (Levison & Stern 2001).

4.2.   Spectra

To date the spectra of many KBOs have been mostly featureless with some showing 2 μm water ice absorptions (de Bergh et al. 2005). Very recent spectra on some of the largest and thus brightest KBOs have shown significant ice features.
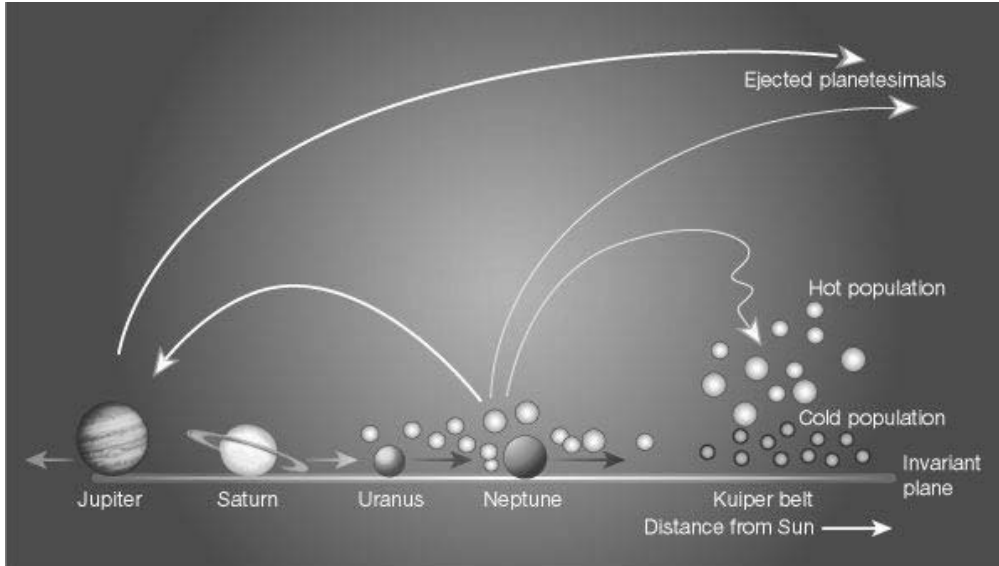
Figure 3.   There may be two populations in the Kuiper Belt. The "Cold" population formed near their present locations beyond Neptune and have low inclinations, are relatively small and red in color. The "Hot" population formed in the giant planet region and were scattered out to the Kuiper Belt. These objects range from small to large, are neutral to red in color and may have a wide range of inclinations (taken from Morbidelli & Levison 2003).

50000 Quaoar was found to have crystalline water ice on its surface (Jewitt & Luu 2004). This is surprising since crystalline water ice is not stable on the surface of these objects for long. Jewitt & Luu (2004) suggest that recent ice volcanism may have created the crystalline water ice. Spectra of 2003 UB313 make this object only the second, Pluto being the other, to have known methane ice on its surface (Brown, Trujillo, & Rabinowitz 2005). This may indicate that only the largest bodies can hold onto this volatile ice.

4.3.   Rotations and Phase Functions

Currently the most feasible way to determine KBO shapes and surface features is through their photometric light variations. The rotations and shapes of the KBOs may be a function of their size. Small KBOs (diameters $D < 100$ km) are thought to be collisionally produced (Farinella & Davis 1996). These objects retain no memory of the primordial angular momentum of their parent bodies. Instead, their spins are presumably set by the partitioning of kinetic energy delivered by the projectile responsible for break-up. Larger objects may be structurally damaged bodies held together by gravity (rubble piles). The spins of these objects should be much less influenced by recent impacts. A similar situation prevails in the main asteroid belt, where collisional modification of the rotations and shapes of the smaller objects is observationally well established (Catullo et al. 1984). The large objects in both the main-belt and the Kuiper Belt may provide a record of the primordial distribution of angular momenta

imbued by the growth process. A key attribute of the Kuiper Belt is that the population is very large compared to the main asteroid belt, allowing access to a substantial sample of objects that are too large to have been influenced by recent collisions.

Time-resolved observations of KBOs show that $\sim$32% vary by $\geq$0.15 magnitudes, 18% by $\geq$0.40 magnitudes and 12% by $\geq$0.60 magnitudes (Sheppard & Jewitt 2002; Ortiz et al. 2003; Sheppard & Jewitt 2003). Statistically, the trans-Neptunian objects are less spherical than their main-belt asteroid counterparts, indicating a higher specific angular momentum perhaps resulting from the formation epoch (Sheppard & Jewitt 2002). Most KBO photometric variations with rotation can be explained by nonuniform surfaces but two types of objects stand out in rotation period and photometric range space. The first type of objects are 20000 Varuna and 2003 EL61 which have large amplitudes and short periods which are indicative of rotationally distorted, low density rubble piles (Jewitt & Sheppard 2002). The second type, of which only 2001 QG$_{298}$ is a member of to date, shows an extremely large amplitude and slow rotation. Kuiper Belt object 2001 QG$_{298}$ is the first known Kuiper Belt object, and only the third minor planet, with a radius >25 km to display a light curve with a range in excess of 1 magnitude and is best described as a contact binary with similar sized components (Sheppard & Jewitt 2004). By correcting for the effects of projection, it is estimated that the fraction of nearly equal sized component contact binaries in the Kuiper Belt is at least $\sim$10% to 20% with the true fraction of contact binaries probably much higher. Two objects, 1996 TO$_{66}$ and 1995 SM$_{55}$ may have variable amplitude light curves which may result from complex rotation, a satellite or cometary effects (Hainaut et al. 2000; Sheppard & Jewitt 2003).

Phase darkening coefficients for KBOs in the 0 to 2 degree phase angle range show steep linear slopes (0.16 magnitudes per degree) indicating backscatter from low albedo porous surface materials (Sheppard & Jewitt 2003). The similarity of the slopes of the phase functions of all small KBOs suggests comparative uniformity of the surface compositions, physical states, and albedos. The measured phase slopes are all distinct from that of Pluto, which has a much higher albedo surface due to frosts deposited from its tenuous atmosphere.

Future observations on smaller KBOs ($r < 50$ km) would be beneficial to determine if their rotation periods and amplitudes are similar to the larger objects observed to date. A transition between gravitational to mechanical structural domination should be observed for objects with radii between 50 and 100 km. The smaller objects ($r < 50$ km) should show a significantly different distribution of rotation periods and amplitudes than the larger objects ($r > 100$ km). KBOs with radii smaller than about 50 km are probably just collisional shards with shapes and rotations presumably set by the partitioning of kinetic energy delivered by the projectile responsible for break-up. Unlike the larger KBOs their rotation states are much more influenced from recent collisional events. These smaller KBOs would be much fainter than the larger objects and thus would require a number of nights on large class telescopes (6-10 meters) to obtain the signal-to-noise needed to detect their light curves.

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