KUIPER BELT OBJECTS

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KEY WORDS: outer solar system, comets, planet formation

Shortened Title: KUIPER BELT OBJECTS
Dec 24 1998

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Invited review for Annual Reviews of Earth and Planetary Science.

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ABSTRACT

The region of the solar system immediately beyond Neptune's orbit is densely populated with small bodies. This region, known as the Kuiper Belt, consists of objects that may pre-date Neptune, the orbits of which provide a fossil record of processes operating in the young solar system. The Kuiper Belt contains some of the solar system's most primitive, least thermally processed matter. It is probably the source of the short-period comets and Centaurs, and may also supply collisionally generated interplanetary dust. We discuss the properties of the Kuiper Belt and provide an overview of the outstanding scientific issues.

HISTORY OF THE KUIPER BELT

Edgeworth (1943) was the first to speculate on the existence of planetary material beyond the orbit of Pluto. Referring to the solar nebula, he wrote "It is not to be supposed that the cloud of scattered material which ultimately condensed to form the solar system was bounded by the present orbit of the planet Pluto; it is evident that it must have extended to much greater distances". He also suggested that the trans-Plutonian region was the repository of the comets: "From time to time a member of this swarm of potential comets wanders from its own sphere and appears as an occasional visitor to the inner regions of the solar system". These qualitative ideas were later repeated by Edgeworth (1949) and echoed by Kuiper (1951), who gave no indication that he was aware of Edgeworth's papers. Rather, his motivation was in part to correct Oort's (1950) assertion that the comets formed near, and were ejected by, Jupiter and had a composition like that of the main-belt asteroids. Edgeworth's and Kuiper's remarks were speculative conjectures rather than predictions in the accepted, scientific sense. Perhaps for this reason, the notion of a trans-Neptunian belt had less immediate impact on the subsequent development of cometary science than did the contemporaneous but more quantitative work by Oort (1950), and Whipple (1951). Nevertheless, the possibility of a trans-Plutonian ring was clearly recognized before the middle of the 20th century. This concept was sustained by Whipple (1964) and others while, much later, Fernandez (1980) explicitly re-proposed a trans-Neptunian ring as a source of the short-period comets.

Baum and Martin (1985) suggested (but apparently did not attempt) an early observational test of the "comet belt" hypothesis. Luu and Jewitt (1988) made a concerted but ultimately unsuccessful observational effort in which both photographic plates and an early charge-coupled device (CCD) were used to examine the ecliptic. In the same year, Duncan, Quinn and Tremaine (1988) provided additional motivation for searches by showing that a flattened, disk-like source was required to fit the restricted range of inclinations of the short-period comets. Further ecliptic surveys by Kowal (1989), Levison and Duncan (1990), Cochran, Cochran and Torbett (1991) and Tyson et al. (1992) proved negative. Observational success was achieved first with the discovery of 1992 QB1 (Jewitt and Luu 1993) and followed up with the rapid discovery of a growing number of trans-Neptunian bodies (Jewitt and Luu 1995; Irwin *et al*. 1995; Williams *et al*. 1995; Jewitt, Luu and Chen 1996 - hereafter JLC96; Luu *et al*. 1997; Jewitt, Luu and Trujillo 1998 - hereafter JLT98; Gladman et al. 1998). These discoveries have powered a veritable explosion of research on the Kuiper Belt in the past half decade. Indeed, Pluto itself is now considered to be the largest of the known Kuiper Belt Objects.

The purpose of this review is to summarize the current observational constraints on the Kuiper Belt, and to discuss extant models and theories of its formation and evolution, all in a style suited to the diverse readership of Annual Reviews. The known population of the Kuiper Belt, as well as the important literature on this subject, changes on timescales short compared to the interval between reviews such as this. For the most recent information, the reader is referred to a list of orbital parameters maintained by Brian Marsden and Gareth Williams (http://cfa-www.harvard.edu/cfa/ps/lists/TNOs.html) and to a general site on the Kuiper Belt maintained by the author (http://www.ifa.hawaii.edu/faculty/jewitt/kb.html).

OBSERVING THE KUIPER BELT

Kuiper Belt objects (KBOs) are best identified by their slow, retrograde (westward) motions when observed in the anti-solar direction. Then, the angular velocity, $d\theta/dt$ [arcsec. hr^{-1}] is determined largely by parallax. Slow speeds indicate large distances, according to

$$d\theta / dt \approx \frac{148}{R + R^{1/2}} \quad (1)$$

where R [AU] is the heliocentric distance, and the geocentric distance is taken as $\Delta = R - 1$. The apparent red magnitude m_R, of an object observed in reflected light is

$$p_R r^2 \phi(\alpha) = 2.25x10^{16} R^2 \Delta^2 10^{0.4(m_O - m_R)} \quad (2)$$

in which p_R is the geometric albedo, r [km] is the object radius, $\phi(\alpha)$ is the phase function and m_o is the apparent magnitude of the sun (Russell 1916). At opposition we may take $\phi(0) = 1$. Equations (1) and (2) are plotted in Figure 1, assuming $p_R = 0.04$ (c.f § 2-vii). The figure shows that 100 km sized objects beyond Neptune should exhibit apparent red magnitudes > 20 and characteristic slow retrograde motions (a few arcsec per hour). Successful Kuiper Belt surveys have therefore been designed to reveal faint objects moving slowly with respect to the background stars. Increasingly, these surveys are automated (Trujillo and Jewitt 1998) so as to accommodate large data rates.

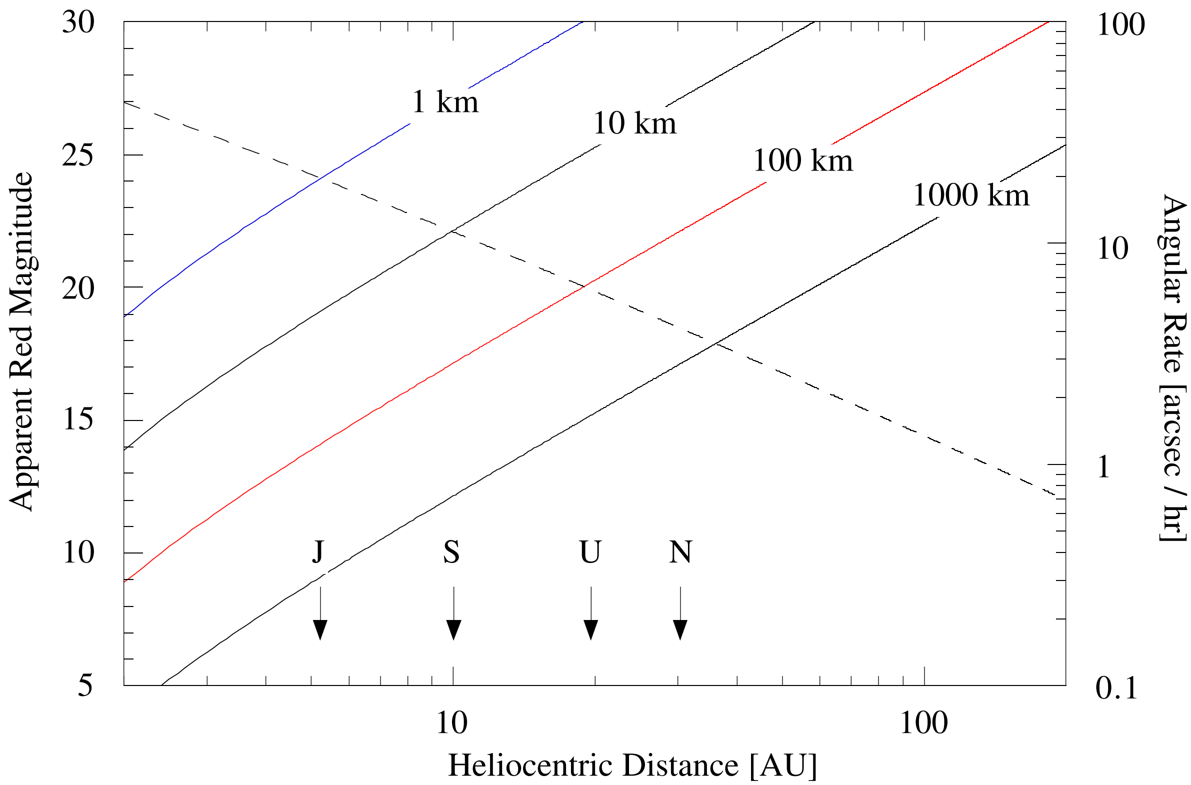

Figure 1 Apparent red magnitude (left) and retrograde opposition angular rate (right) of KBOs as a function of distance from the sun. Magnitudes were computed from Eq. (2) assuming geometric albedo 0.04, radii as marked on the figure and assume observation at opposition (phase function = 1 and $\Delta = R$ - 1). The angular rate is computed from Eq. (1) and shown by a dashed curve. The locations of the major planets are indicated.

CONTENTS OF THE KUIPER BELT

At the time of writing (December 1998), ground-based surveys have revealed 85 KBOs, of which 44 possess relatively reliable multi-opposition orbits.

The orbits of known KBOs naturally divide into 3 distinct categories, as follows:

Classical Objects

About two thirds of the observed KBOs have semi-major axes $42 \leq a \leq 47$ AU, and seem unassociated with resonances (Figures 2 and 3). These objects define the "Classical" Kuiper Belt. Classical KBOs have small eccentricities (median e = 0.07) that maintain a large separation (mostly > 10 AU) from Neptune even when at perihelion. The inclinations occupy a wide range ($0 \leq i \leq 32^{\circ}$).

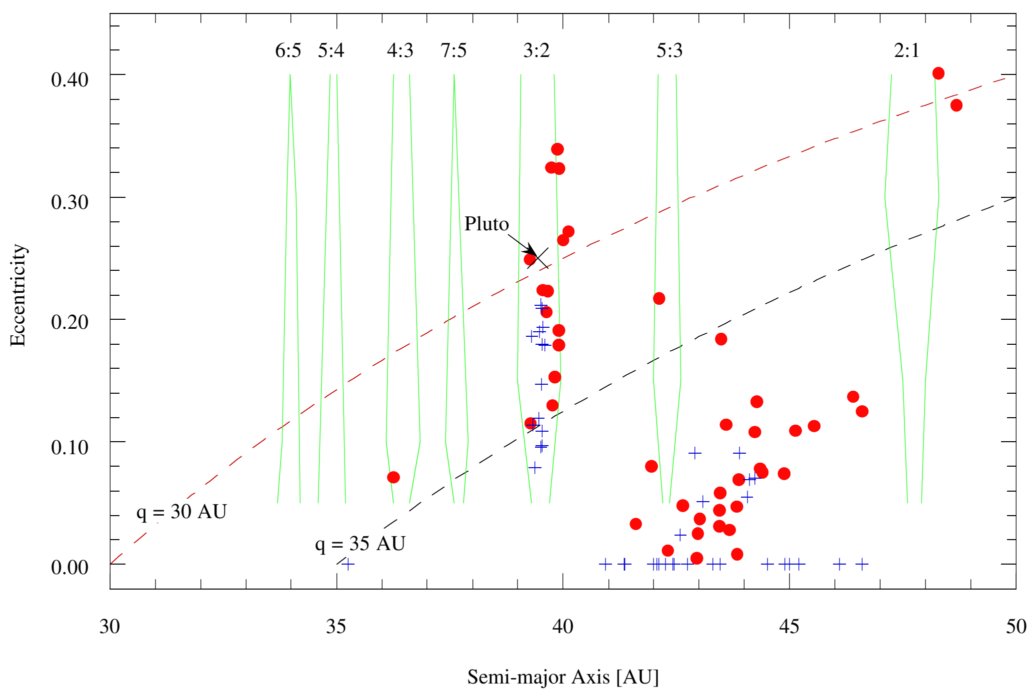

Figure 2 Semi-major axis vs. orbital eccentricity for the known KBOs. Multi-opposition objects (solid circles) are distinguished from single opposition objects (pluses) and Pluto (cross). The distribution is highly non-random, and shows a clear correlation with mean-motion resonances (approximate boundaries of these resonances are shown as vertical bands, taken from Malhotra 1995). The diagonal dashed lines mark the loci of orbits having constant perihelion distances 30 and 35 AU. Scattered KBO 1996 TL66 falls outside and is omitted from the plot.

Resonant Objects (Plutinos)

About one third (15 of 44) of the well-observed objects reside in the 3:2 mean motion resonance with Neptune at a = 39.4 AU (Figures 2 and 3). These bodies are collectively known as Plutinos ("little Plutos") to highlight the dynamical similarity with Pluto, which also resides in this resonance (Malhotra and Williams 1998). The apparent abundance of the Plutinos is affected by observational bias. Corrected for their smaller mean heliocentric distance (relative to Classical KBOs), they probably constitute 10 to 15% of the population inside 50 AU (JLT98). The eccentricities ($0.1 \le e \le 0.34$) and inclinations ($0 \le i \le 20^{\circ}$) of the Plutinos bracket the values of Pluto (e = 0.25, i = 17°). Presumably, the resonance provides immunity to destabilizing perturbations from Neptune. Indeed, some of the Plutinos have perihelia inside Neptune's orbit (as does Pluto) and would be immediately ejected if not for the protection offered by the resonance. Other resonances (notably the 4:3 and the 5:3) may also be populated, although at a lower level than the 3:2. Two objects (1996 TR66 and 1997 SZ10) fall in or near the 2:1 resonance.

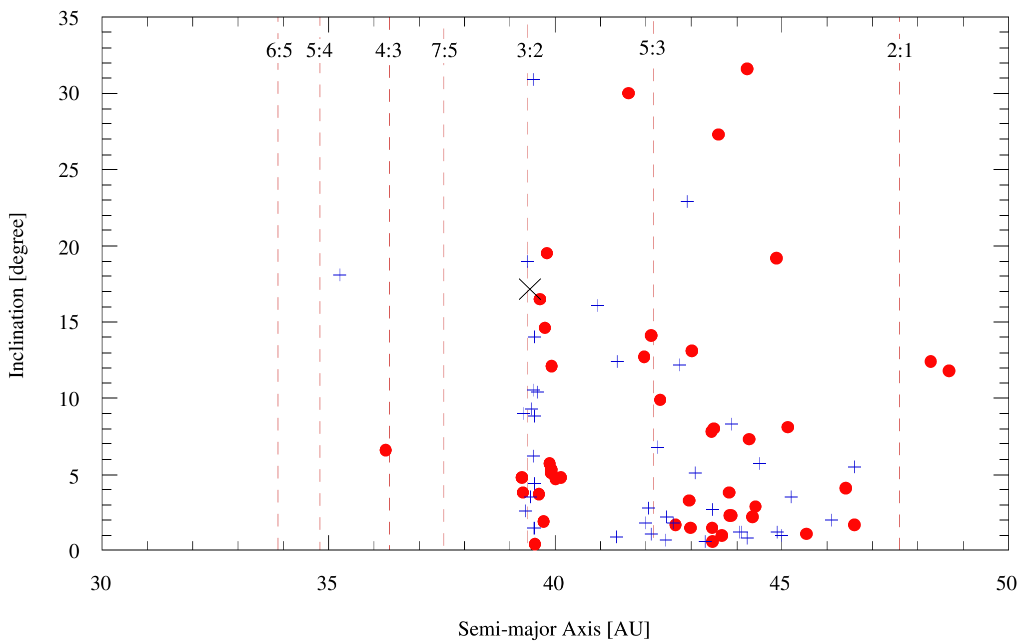

Figure 3 Distribution of semi-major axis vs. orbital inclination for the known KBOs. Multi-opposition objects (solid circles) are distinguished from single opposition objects (pluses) and Pluto (cross). Scattered KBO 1996 TL66 is omitted from the plot. Locations of mean-motion resonances are shown by vertical dashed lines.

Scattered Objects

The observational sample includes one clearly deviant object, 1996 TL66 (a,e,i = 85 AU, 0.59, 24°; Luu et al. 1997). The proximity of the perihelion (q = 35 AU) to Neptune (at 30 AU) suggests a weak dynamical involvement with that planet. It is likely that 1996 TL66 is the first detected member of a population of bodies scattered by Neptune (Fernandez and Ip 1983) and having dynamical lifetimes measured in billions of years (Duncan and Levison 1997). Such scattered KBOs may occasionally enter the planetary system, constituting a source of short-period comets separate from that of chaotic zones.

MODELS

Models of the Kuiper Belt have evolved in a somewhat piece-meal fashion. Most published dynamical models neglect mutual gravitational interactions and collisions among KBOs. This is reasonable in the present day, low density Kuiper Belt (but see Ip and Fernandez 1997). However, several lines of evidence now point to the existence of a once more massive Kuiper Belt, in which mutual interactions may have excited a collective (wave) response to perturbations (Ward and Hahn 1998) and in which collisions played an important role. Accordingly, models describing collisions have recently appeared (Farinella and Davis 1996, Stern and Colwell 1997), but have not yet been integrated with the dynamics. It seems likely that key features of the Kuiper Belt were imprinted at a time when collective effects dominated the transport of energy and angular momentum. Therefore, it is important to heed Ward and Hahn's (1998) warning that published simulations of Kuiper Belt dynamics, by omitting important physics, may be in serious error.

The division of the orbital parameters of the KBOs into 3 main groups was unexpected, and has become the focus of recent theoretical attention. Observed properties worthy of explanation include

1. *The general absence of KBOs with a ≤ 42 AU, other than those trapped in mean motion resonances.*

Long-term numerical integrations show that clearing of the inner belt is a result of strong perturbations by Neptune (Holman and Wisdom 1993; Duncan, Levison and Budd 1995). This is seen in Figure 4, where most non-resonant orbits inside 42 AU have lifetimes << 4 Gyr. Objects originally in this region were quickly scattered away or absorbed by Neptune. A clear discrepancy exists between numerical simulations and the real Kuiper Belt. Low *e*, low *i* orbits in the 36 to

39 AU range are stable (Figure 4, Duncan, Levison and Budd 1995) and yet no KBOs have been found in this region (Figure 2). Objects in this region might have been removed by resonance sweeping (Malhotra 1995) due to planet migration, or by outward movement of the ν_8 secular resonance due to planet - disk interactions in an early, massive phase. A second empty zone, between 40 and 42 AU, is unstable due to overlapping secular resonances which induce chaotic motion (Knezevic et al. 1991, Holman and Wisdom 1993). At larger distances, the influence of Neptune is greatly diminished and non-resonant orbits are stable provided their perihelia remain ≥ 40 AU.

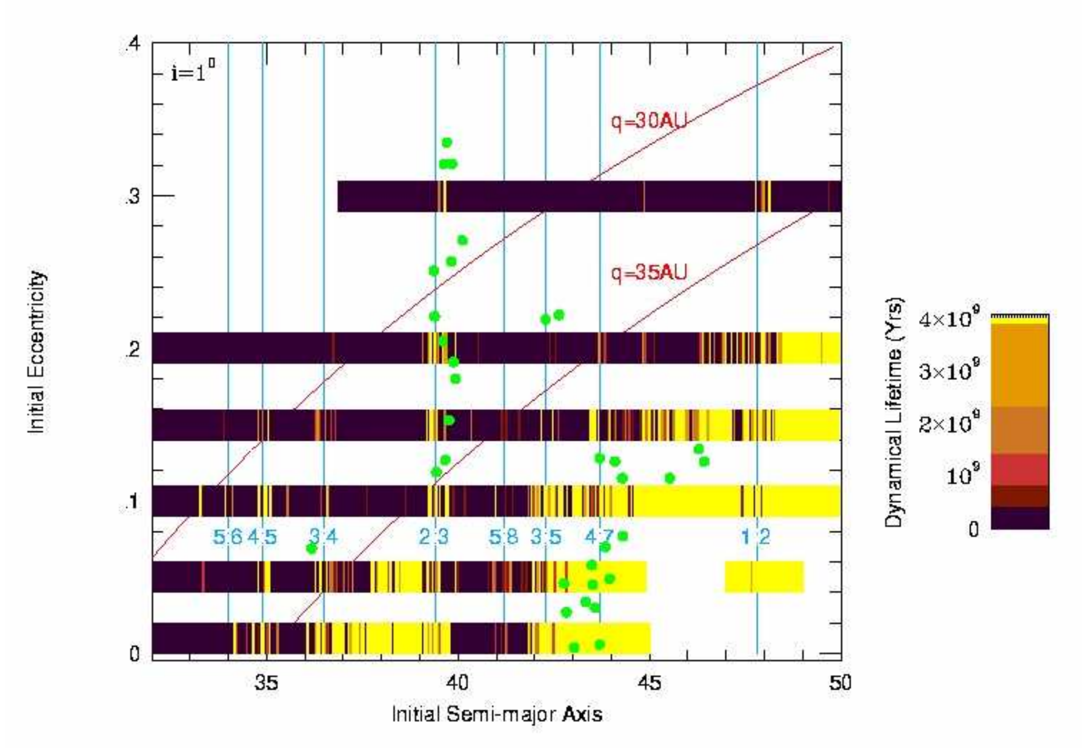

Figure 4. Dynamical simulations of test particle longevity compared with locations of real KBOs (solid circles: see Fig. 2) in the semi-major axis vs. eccentricity plane. Note that the simulations are for assumed inclinations of 1° while the real KBOs exhibit inclinations up to 32°. Figure from Duncan, Levison and Budd (1995).

2. *The large number of objects trapped in the 3:2 resonance.*

The numerical integrations of Holman and Wisdom (1993) show that initially circular, coplanar orbits near the 3:2 resonance can develop moderate eccentricities and inclinations simply through the long-term action of planetary perturbations. This was explored further by Levison and Stern (1995) as a way to explain the orbital properties of Pluto. They found that orbits excited in this way are unstable to unrealistically high libration amplitudes and suggested that a dissipative process (possibly a collision) might have stabilized Pluto in the 3:2 resonance. Presumably, corresponding collisions would be needed to stabilise the many other Plutinos now known to be in the resonance. However, the distribution of orbital eccentricities predicted by this model is inconsistent with the orbits of Plutinos as determined from recent data (Figure 2). Whereas the majority of their simulated resonant objects have e < 0.1, precisely these eccentricities are missing from the observed Plutino population.

A second possible explanation is the "resonance sweeping hypothesis" (Malhotra 1995). As originally envisaged, proto-Neptune scattered nearby planetesimals in the surrounding disk, exchanged angular momentum with them and, as a consequence, underwent a radial excursion (Fernandez and Ip 1984). Planetesimals that were scattered inwards fell under the control of Uranus, while those scattered outwards were either ejected from the planetary system, entered the Oort Cloud, or fell back to the region of the planets to be scattered again. This asymmetry in the fates of scattered objects caused the orbits of Saturn, Uranus and Neptune to expand (Fernandez and Ip 1984) while Jupiter, the innermost massive scatterer, migrated inwards to provide the ultimate source of the angular momentum carried away by scattered planetesimals.

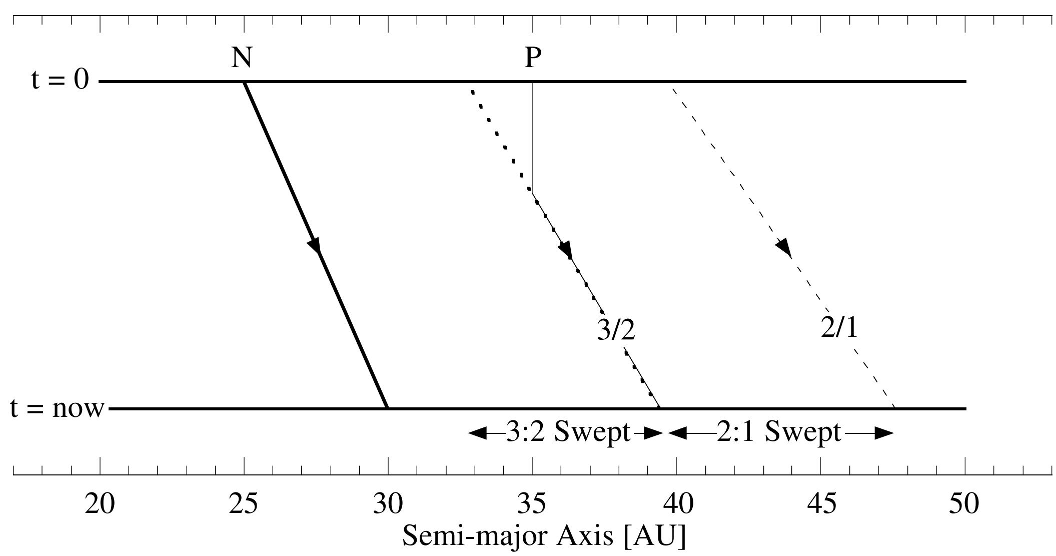

Figure 5 Radial migration of Neptune (N) and its 3:2 and 2: 1 mean motion resonances. Trapping of Pluto (P) into the 3:2 resonance is symbolically illustrated. The zones swept by the 3:2 and 2:1 resonances are marked. Figure slightly modified from Malhotra (1995).

As Neptune migrated, its mean-motion resonances swept through the planetesimal disk, trapping objects (Figure 5). Malhotra (1995) found that the maximum eccentricity reached by resonantly trapped particles is related to the distance of Neptune's migration. For a first order (j+1:j) resonance (where j is a positive integer),

$$e_{final}^2 \approx e_{initial}^2 + \left(\frac{1}{j+1}\right)\ln\left(\frac{a_{N,final}}{a_{N,initial}}\right) \qquad (3)$$

where $e_{initial}$ and e_{final} are the starting and ending eccentricities of the planetesimal and $a_{N,initial}$, $a_{N,final}$ are the starting and ending semi-major axes of Neptune. For the 3:2 resonance (j = 2), with $e_{final} >> e_{initial}$, the Plutinos (median eccentricity e_{final} = 0.24), give $a_{N,initial}$ ~ 25 AU, or a total migration of about 5 AU. The 3:2 resonance would have swept from 33 AU to its present location at 39 AU and the more distant 2:1 resonance from 40 AU to its present location at 47.6 AU (Figure 5).

Numerical simulations of the sweeping process give partial agreement with the data (Figure 6). The ranges of eccentricity (and perhaps, inclination) of KBOs trapped in the 3:2 resonance are well matched by the model without the need for stabilizing collisions. The high population of 3:2 objects is also faithfully reproduced, because resonance trapping is efficient. Resonance sweeping also explains why apparently stable objects in the 36 to 39 AU region are not found: these bodies would have been swept by the outwardly moving 3:2 resonance. Simulations presented by Malhotra (1995) predict a substantial population of KBOs in the 2:1 resonance. Only two of the known KBOs fall in or near this resonance (Figure 2), but this number is compatible with Malhotra’s prediction once the effects of observational bias are taken into account (JLT98). The trapping efficiency is a function of the speed and character of Neptune's migration, of the initial eccentricity and inclination of the planetesimals, and of proto-Neptune’s mass (the trapping occurs during the late phases of the growth of the planet). Recently, Ida et al. (1998) explored simulations of resonance trapping using extremely rapid Neptune migration timescales ($\leq 10^6$ yr) and sub-Neptune masses. This is too fast to be consistent with torques due to planetesimal scattering but might be appropriate for torques exerted by a massive gas disk. The physical significance of this result is not clear. Hydrogen and helium in Neptune (and Uranus) are depleted relative to their solar proportions. This is widely taken as evidence that Neptune grew slowly, reaching its final mass after the escape of the bulk of the gas disk (e.g. Lissauer et al. 1995; Pollack et al. 1996). In this case, insufficient mass would be present in the gas disk to torque Neptune on 10^6 yr timescales.

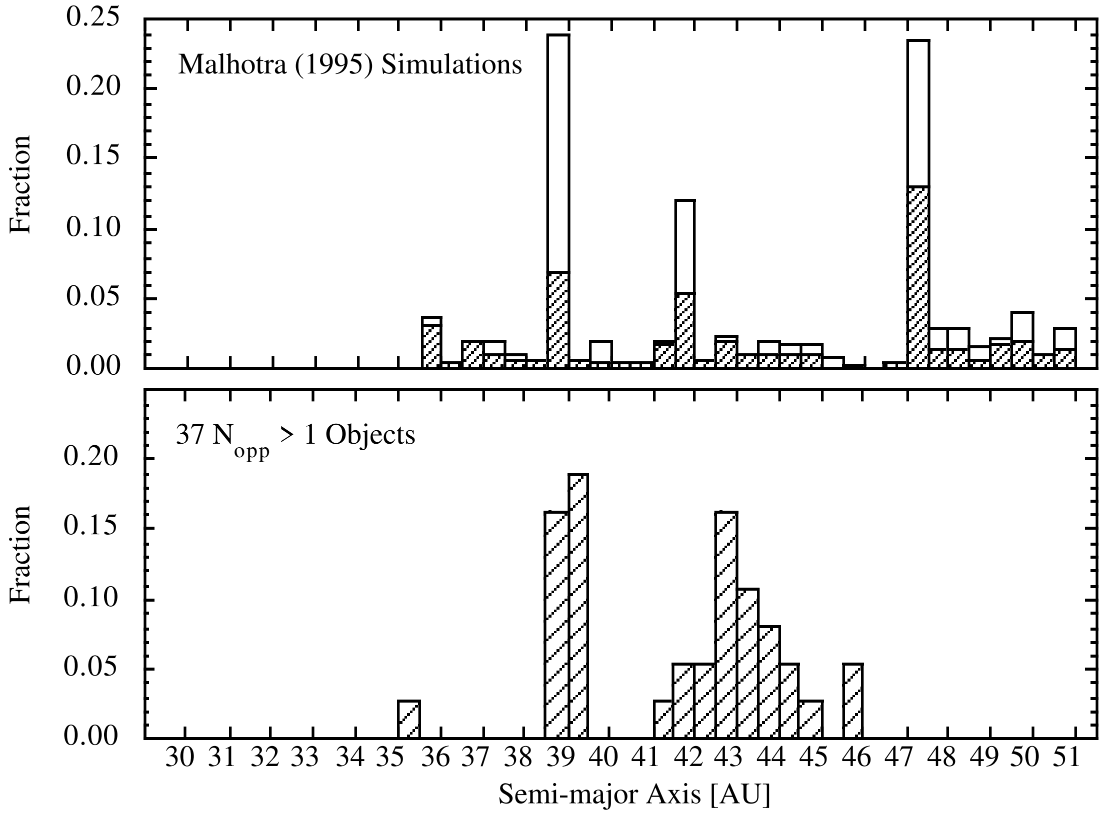

Figure 6 Distribution of semi-major axes of KBOs according to simulations of resonance sweeping due to planetary migration (top panel, adapted from Malhotra 1995) compared to the apparent distribution (bottom panel). The differently shaded histograms in the top panel indicate results from different sets of initial conditions. A Neptune migration timescale of 2 x 10^6 yr was adopted.

Whether or not resonance-sweeping is responsible for the Plutinos is unclear. There is little doubt that planetary migration occurred. The gas giant planets must have exchanged angular momentum with the surrounding protoplanetary disk; only the amount and the timescale of the exchange are uncertain.

3. *The very wide range of inclinations of both classical and resonant KBOs.*

As noted above, excited inclinations (and eccentricities) are natural consequences of resonance trapping (Holman and Wisdom 1993; Duncan, Levison and Budd 1995; Malhotra 1996). It is more surprising to observe very high inclinations in the classical Kuiper Belt (Figure 3). These inclinations and eccentricities correspond to relative collision velocities near $\Delta V = 1$ km s^{-1}. With a critical specific fragmentation energy near 10^3 J kg^{-1} (Fujiwara et al. 1989), the velocity dispersion is large enough to ensure that collisions with objects having only 10^{-3} of the target mass (e.g. a 10 km projectile striking a 100 km target) cause fragmentation. Therefore, impacts in the present day Kuiper belt are primarily erosive rather than agglomerative, and the KBOs cannot have grown in the present high velocity regime (Stern 1996; Farinella and Davis 1996). The inescapable conclusion is that the velocity distribution among the KBOs has been amplified since the epoch of formation. The source of this amplification is a leading puzzle.

The disturbing influence of Neptune is largely restricted to the inner part of the Belt ($a \le 42$ AU), and cannot explain the high mean e and i of the more distant Classical KBOs (e.g. Figs. 3 and 4 of Holman and Wisdom 1993 give median $e \sim 0.02$ and $i \sim 1^\circ$ for objects in initially circular, coplanar orbits between $42 \le R \le 50$ AU). Mutual gravitational interactions among KBOs may have pumped the velocity dispersion, especially if the early Kuiper Belt were very massive and contained large objects. There is good evidence for the temporary existence of short-lived, Earth-mass objects in the early outer solar system: large-body impacts are thought to account for the basic characteristics of planetary spin (Dones and Tremaine 1993) including the large obliquity of Uranus (Slattery, Benz and Cameron 1992). Morbidelli and Valsecchi (1997) found that a handful of Earth-sized projectiles could excite the velocity dispersion of the KBOs and lead to extensive depopulation. In their model, the degree of damage inflicted on the Kuiper Belt is a sensitive function of the assumed masses and trajectories of the scattered objects. While the choice of these parameters is necessarily arbitrary, it appears that a few well-aimed Earth mass bodies can disrupt the Belt and leave a dynamically excited remnant with traits similar to those observed (Petit et al. 1998). It is not clear how to reconcile the massive planetesimals hypothesis with the resonance sweeping hypothesis for the population of the mean motion resonances. Massive scatterers capable of stirring up the velocity dispersion to 1 km s^{-1} would also dislodge most objects from resonance with Neptune. To argue that resonance sweeping occurred after the epoch of the massive scatterers is also problematic, since the efficiency of trapping into resonance decreases as the initial eccentricity and inclination increase (Malhotra 1995): capture from nearly circular ecliptic orbits is much preferred. This dilemma presently evades resolution.

4. *The Source of the Short-Period Comets*

The short-period comets have dynamical lifetimes among the inner planets of order 10^5 to 10^6 yr (Levison and Duncan 1994) and must be continually replenished if they are to maintain a steady-state population over the age of the solar system. There is a consensus that the Kuiper Belt is the source of the short-period comets, but the precise location of the source remains unidentified. Chaotic zones at the edges of resonances represent one plausible source (Morbidelli 1997). The chaotic zones may be populated and depopulated by mutual scattering as well as by dynamical chaos (Ip and Fernandez 1997). Randomly deflected Scattered KBOs may also contribute to the short-period comet supply (Duncan and Levison 1997), as might the semi-stable 1:1 Lagrangian resonances with the major planets and the narrow, stable ring at 26 AU identified by Holman (1997). Potentially, all of these sources contribute to the flux of short-period comets.

CUMULATIVE LUMINOSITY FUNCTION, SIZE DISTRIBUTION

The cumulative luminosity function (CLF) is the number of KBOs per unit area of sky brighter than a given limiting magnitude, measured as a function of the magnitude. The CLF provides a measure of the size distribution and total number of KBOs and is therefore a quantity of particular observational interest. The CLF is well defined in the magnitude 20 to 26 range (Figure 7). At brighter magnitudes, the available constraints are based mainly on photographic data, and are difficult to calibrate and interpret. At fainter magnitudes, a measurement using the Hubble Space Telescope (HST: Cochran et al. 1995) has proved controversial. Brown, Kulkarni and Liggett (1997) found that the reported number of KBOs is, implausibly, 2 orders of magnitude beneath the sensitivity limits of the HST, a result which Cochran et al. (1998) dispute. Independent confirmation of the measurement is desirable.

The CLF is described by

$$\log\left[\Sigma\left(m_R\right)\right] = \alpha\left(m_R - m_0\right) \qquad (4)$$

where $\Sigma(m_R)$ is the number of objects per square degree brighter than red magnitude m_R, and α and m_o are constants. Least squares fits to the CLF give α = 0.58 ± 0.05, m_o = 23.27 ±

0.11 ($20 \le m_R \le 25$; JLT98) and $\alpha = 0.54 \pm 0.04$, $m_o = 23.20 \pm 0.10$ ($20 \le m_R \le 26.6$; LJ98b). Gladman et al. (1998). used a different sub-set of the data (including some of the photographic constraints and the uncertain Space Telescope measurement) and a different (maximum likelihood) fitting method to find $\alpha = 0.76\ ^{+0.10}/_{-0.11}$, $m_o = 23.40\ ^{+0.20}/_{-0.18}$ ($20 \le m_R \le 26$). Within the uncertainties, the various fits are consistent. In fact, the true uncertainties are likely to be larger than indicated because of hitherto ignored systematic errors. For example, it is probable that the surface density is a function of ecliptic longitude, owing to the nature of the Neptune-avoiding resonant objects, and yet no allowance for longitudinal effects has been attempted by the observers.

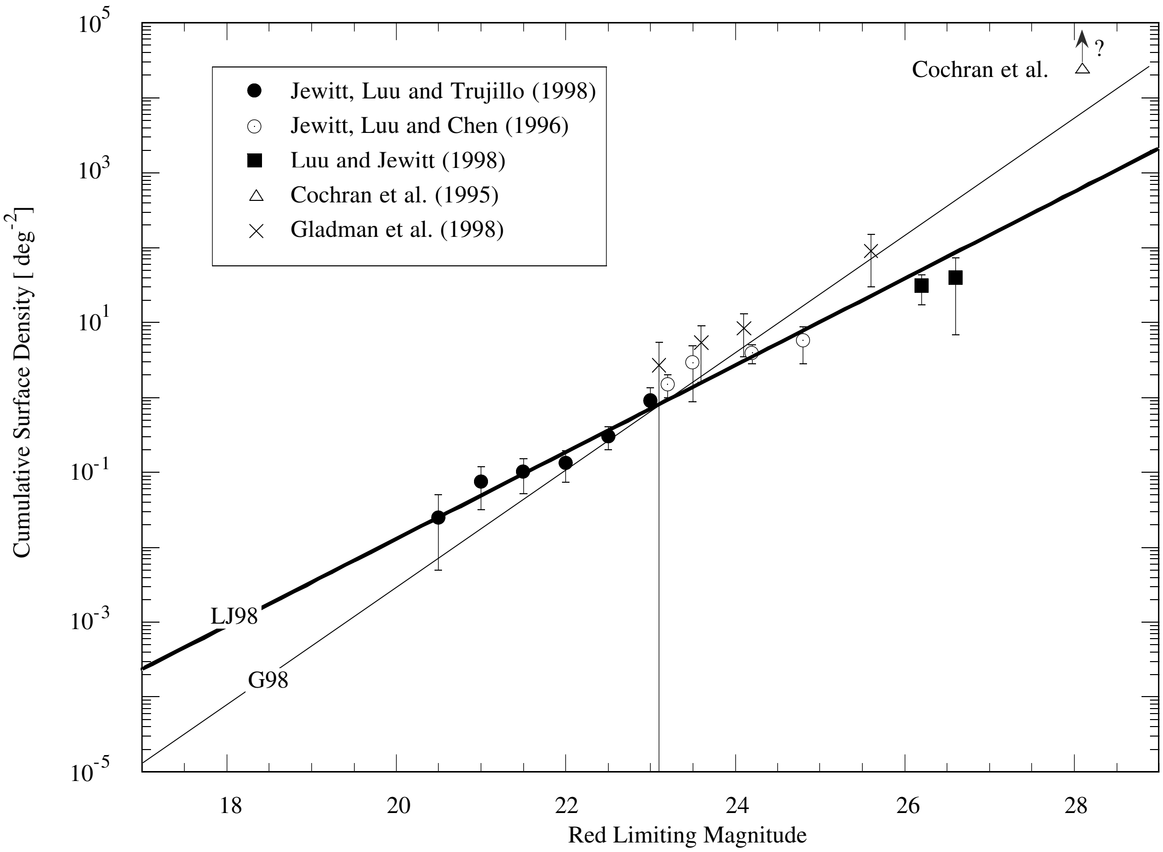

Figure 7. Cumulative luminosity function of the Kuiper Belt. The lines through the data mark fits by Luu and Jewitt 1998b (thick line) and Gladman et al. 1998 (thin line).

The gradient of the CLF is determined by the size and spatial distributions of the KBOs, and by the distribution of albedo among these objects. Simple models in which the size distribution is taken to be a power law with index -β, the spatial distribution is another power law with index -2, and the albedo is constant give $\beta \approx 4.0 \pm 0.5$ (JLT98, LJ98b) to $\beta \approx 4.8$ (Gladman et al. 1998). Also, the albedo might be a systematic function of object size (gravity), adding another unmodeled effect to the CLF. In any event, the size distribution of KBOs (diameter ≥ 100 km) is probably steeper than the canonical $\beta = 3.5$ as produced by shattering collisions (Dohnanyi 1969). It is not yet known whether the size distributions of the different dynamical classes in the Kuiper Belt are the same, but it is easy to think of reasons why they should not be. For example, impulses larger than a few 10's of m s^{-1} (from collisions and mutual gravitational scattering) are capable of dislodging objects from resonance. Since small KBOs suffer larger average impulse velocities than their massive counterparts, resonant objects may have a steeper size distribution than the Classical Belt.

The total numbers of KBOs must be estimated by extrapolation from surveys of limited areas of the ecliptic. The extrapolations hinge on knowledge of the spatial extent of the Kuiper Belt, both radially and perpendicular to the ecliptic. Regions beyond $R \sim 50$ AU are poorly sampled by the available data, so that the number of objects is known only in the range $30 \leq R \leq 50$ AU. Furthermore, highly inclined KBOs spend a smaller fraction of each orbit near the ecliptic than KBOs of small inclination, and are thus subject to an observational bias. For this reason, the data provide only a lower limit to the intrinsic thickness of the Belt. The apparent thickness is 10° ± 1° FWHM (Jewitt, Luu and Chen 1996) but, corrected for bias, the intrinsic thickness may be 30° or more, with no statistically significant difference between the classical and resonant populations.

The number of KBOs larger than 100 km in diameter (assuming 0.04 geometric albedo) in the 30 to 50 AU distance range is ~ 10^5 (JLT98). By extrapolation, assuming size index $\beta = 4$, the number of KBOs larger than 5 km diameter in the 30 to 50 AU region is 8 x 10^8, but with an uncertainty approaching an order of magnitude. Meaningful comparison with the number of comets required to replenish the short-period population for the age of the solar system is difficult, since the sizes of the comets are not well known. The numbers seem of the right order, however (Duncan, Quinn and Tremaine 1988; Duncan, Levison and Budd 1995). The total mass in observable (diameter ≥ 100 km) objects is of order 0.1 M_{Earth} (1 M_{Earth} = 6 x 10^{24} kg; Jewitt, Luu and Chen 1996; Jewitt, Luu and Trujillo 1998; Luu and Jewitt 1998), based on an assumed bulk density 1000 kg m^{-3} and a power law differential size distribution with index q = 4. The mass is uncertain primarily because the KBO diameters are computed on the untested assumption of dark surfaces (albedo 0.04). The derived mass is consistent with the dynamical limit to the mass, ~ 1 M_{Earth} (Hamid et al. 1969).

PHYSICAL OBSERVATIONS

Optical (Luu and Jewitt 1996; Green et al. 1997) and near-infrared colors (Jewitt and Luu 1998) of KBOs exhibit a wide diversity that suggests a range of surface types among KBOs. The best spectral discriminant is the V - J color index, which measures the ratio of the surface reflectances at V (~0.55 μm) and J (~1.2 μm) wavelengths. Figure 8 shows that V-J varies from 0.7 (1996 TO66) to 2.2 (1996 TP66) in the Kuiper Belt (and up to 2.6 in the Centaur 5145 Pholus). V-J can be measured to a 1σ accuracy of about 0.1 mag., so that the color differences are highly significant (~20σ). Tegler and Romanishin (1998) further claim that the KBOs are divided by *optical* color into two distinct classes with no intermediate examples, but the color separation of the groups exceeds the formal uncertainty of measurement by only a few times the 1σ accuracy of the colors. This intriguing result awaits independent confirmation.

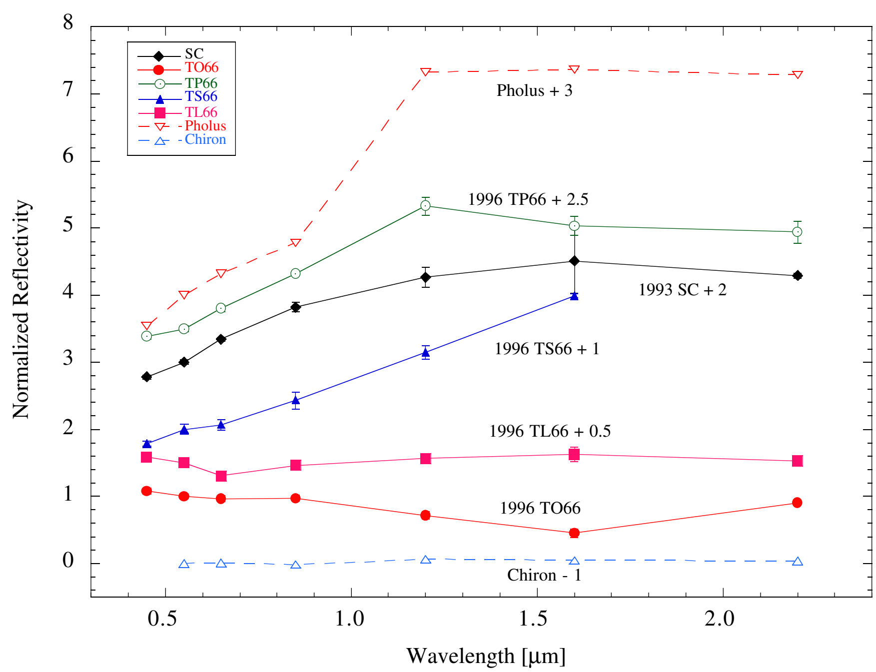

Figure 8 Normalized reflectivity versus wavelength for 5 KBOs. The KBOs are vertically offset for clarity, but preserve a fixed scale. Reflectivities of Centaur objects 2060 Chiron and 5145 Pholus are shown for comparison. Figure from Jewitt and Luu (1998).

Bombardment of simple ice mixtures (H_2O, CO_2, CO, NH_3) by energetic particles (photons or atomic nuclei) is known to cause surface darkening and modification of the chemical structure of the surface to a column density of ~100 g cm^{-2} (Johnson et al. 1987, Moroz et al. 1998). Incident particle energy is dissipated by breaking chemical bonds which then recombine to make new, structurally complex compounds. Hydrogen atoms liberated in this process are sufficiently small that they can escape from the irradiated material even at the low temperatures prevailing in the Kuiper Belt (~ 50 K). The resulting "radiation mantle" is a hydrogen-poor, carbon-rich (and therefore dark), high-molecular-weight compound having low volatility (Figure 9). The timescale for saturation damage of the surface layer by cosmic rays is of order $10^{8\pm1}$ yrs (Shul'man 1972), but measurable surface darkening may occur much more rapidly. The surfaces of cometary nuclei are believed to be coated by such material, and it is natural to expect the same of KBOs. Within this context, it is difficult to see why the KBOs would vary in optical color from neutral to very red, or why the V-J index should be so variable from object to object.

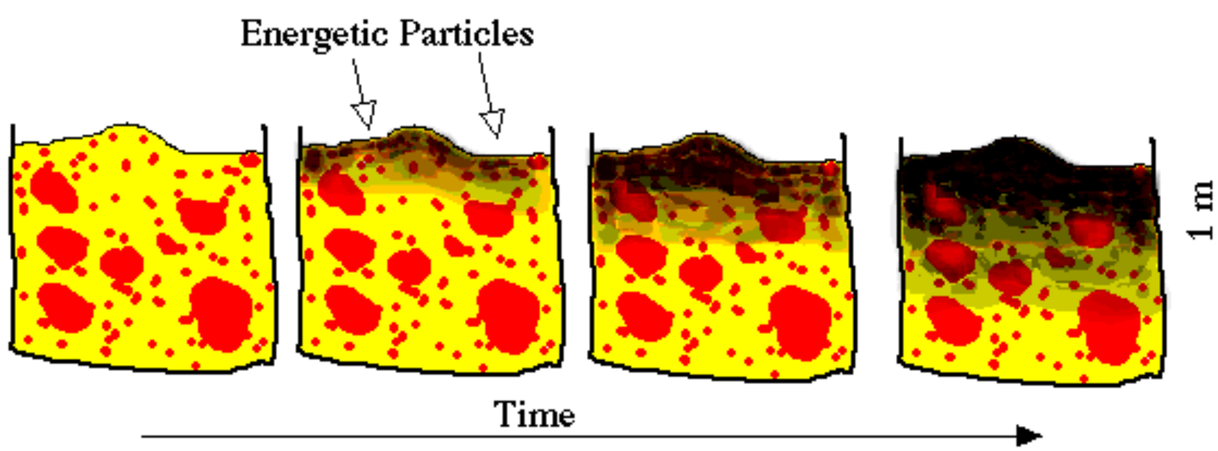

Figure 9. Development of an irradiation mantle. A KBO consisting of a mixture of refractory particles and common ices is bombarded by high energy cosmic rays. Over time, a hydrogen-depleted crust of high molecular weight and of column density ~ 100 g cm^{-2} develops. Carbon compounds in the mantle are responsible for the low albedo.

A consensus regarding the origin of spectral diversity has yet to emerge. One possibility is that KBOs are occasionally resurfaced by collisionally generated debris (Luu and Jewitt 1996). The surface color would change because material excavated from depths > few meters would be unaffected by cosmic ray irradiation. The instantaneous surface color would be determined primarily by the time since resurfacing. This remains a plausible hypothesis for color diversity only so long as the timescales for irradiation and resurfacing are of the same order. Unfortunately, neither timescale is well known. Should the color distributions really be bimodal, the resurfacing hypothesis would be immediately ruled out, because partial resurfacing always produces intermediate colors.

A second possibility is that different KBOs have intrinsically different surface compositions, either because they formed differently, or because of long-term evolutionary effects. For example, large KBOs might be more thoroughly outgassed than small KBOs as a result of greater radioactive heating, and would be better at retaining surface frost deposits. However, at present, there is no compelling evidence for a color-size relation among the KBOs.

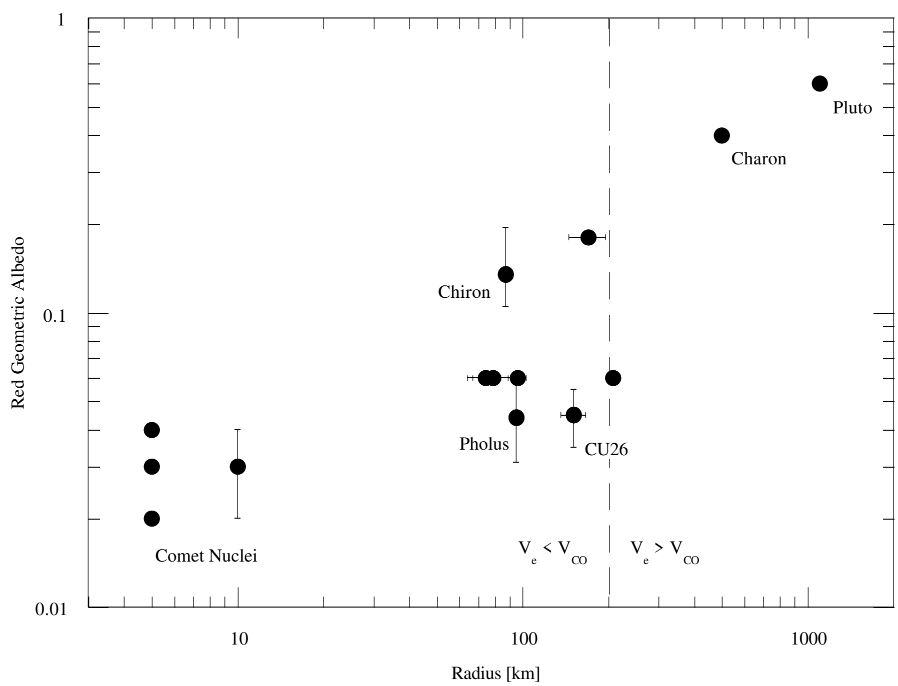

Figure 10 Red geometric albedo vs. radius for a variety of outer solar system objects. The dashed vertical line marks $V_e = V_{CO}$, where V_e is the escape velocity (at assumed density ρ = 1000 kg m^{-3}) and V_{CO} is the thermal velocity of a CO molecule at T = 40 K. There is a trend for albedo to increase with object size. However, this trend is dominated by Pluto and Charon, objects both large enough to retain weak atmospheres.

Energetic irradiation should produce a spectrally bland material corresponding to the destruction of all hydrogen bonds and the loss of hydrogen to space. Spectral evidence is limited to near infrared spectra of KBOs 1993 SC and 1996 TL66. The heavily smoothed spectrum of 1993 SC is reported to show absorption bands reminiscent of (but not specifically identified with) complex hydrocarbon compounds (Brown et al. 1997). The spectrum of 1996 TL66 is featureless and flat (Luu and Jewitt 1998). More spectra are urgently needed.

The albedos of KBOs have yet to be measured. The standard technique applied to main-belt asteroids is the simultaneous measurement of optical (reflected sunlight) and thermal (absorbed and re-radiated sunlight) radiation, from which both the cross-section and the albedo can be measured. The Planck maximum for objects at 40 AU (temperature ~ 50 K) falls near 60 µm wavelength, which is inaccessible from the ground. Measurements using the ISO orbiting telescope yielded marginal detections of 1993 SC and 1996 TL66, from which low (few percent) albedoes may be inferred (Nick Thomas, private communication). Stellar occultations may soon be available from the TAOS project and others (Brown and Webster 1997), from which diameters and albedos might be directly inferred. At the present, however, all KBO diameters are computed on the *assumption* of a uniform red albedo p_R = 0.04. This value is adopted from measurements of the albedos of cometary nuclei and Centaurs (bodies in transition from the Kuiper Belt to the short-period comets), most of which tend to be very dark. For example, if the albedo should be higher by a factor of 10, the derived KBO diameters would decrease by a factor $10^{1/2}$, and the masses by a factor $10^{3/2}$. The diversity of surface types indicated by Figure 8, for example, certainly suggests that the albedos of KBOs may not all be the same. There is some evidence that the albedo is a function of object diameter (Figure 10). The largest objects have sufficient gravitational attraction to retain weak atmospheres from which albedo-enhancing surface frosts may be deposited. Our conclusions about sizes and masses of KBOs are thus rendered uncertain.

DUST

Collisions between KBOs and the impacts of interstellar grains should provide a continuous source of dust. Liou, Zook and Dermott (1996) presented numerical integrations of the equation of motion for dust particles released in the Kuiper Belt. They included radiation pressure, plasma drag, and Poynting-Robertson drag forces, as well as gravitational forces due to the planets (excepting Mercury and Pluto). Kuiper Belt dust particles that survive to cross the orbit of Earth do so with small eccentricities and inclinations, and would be difficult to distinguish from asteroidal dust grains on the basis of their orbital parameters alone. Liou, Zook and Dermott found that ~20% of the modelled 1 to 9 µm diameter particles survive to reach the sun (the majority are ejected from the solar system by the gas giant planets). However, timescales for the collisional destruction of Kuiper Belt grains by interstellar dust particles (Figure 11) are less than the dynamical transport times (which cluster near 10^7 yr) for many of the small particles modelled by

Liou et al. (1996). Therefore, the survival probability of Kuiper Belt dust entering the inner solar system must be considerably smaller than 20%, and the size distribution of the surviving grains will be modified by shattering collisions with interstellar grains. Such particles might one day be identified in terrestrial stratospheric collections (Brownlee 1985) by their high solar wind track densities (due to long transport times from the Kuiper Belt).

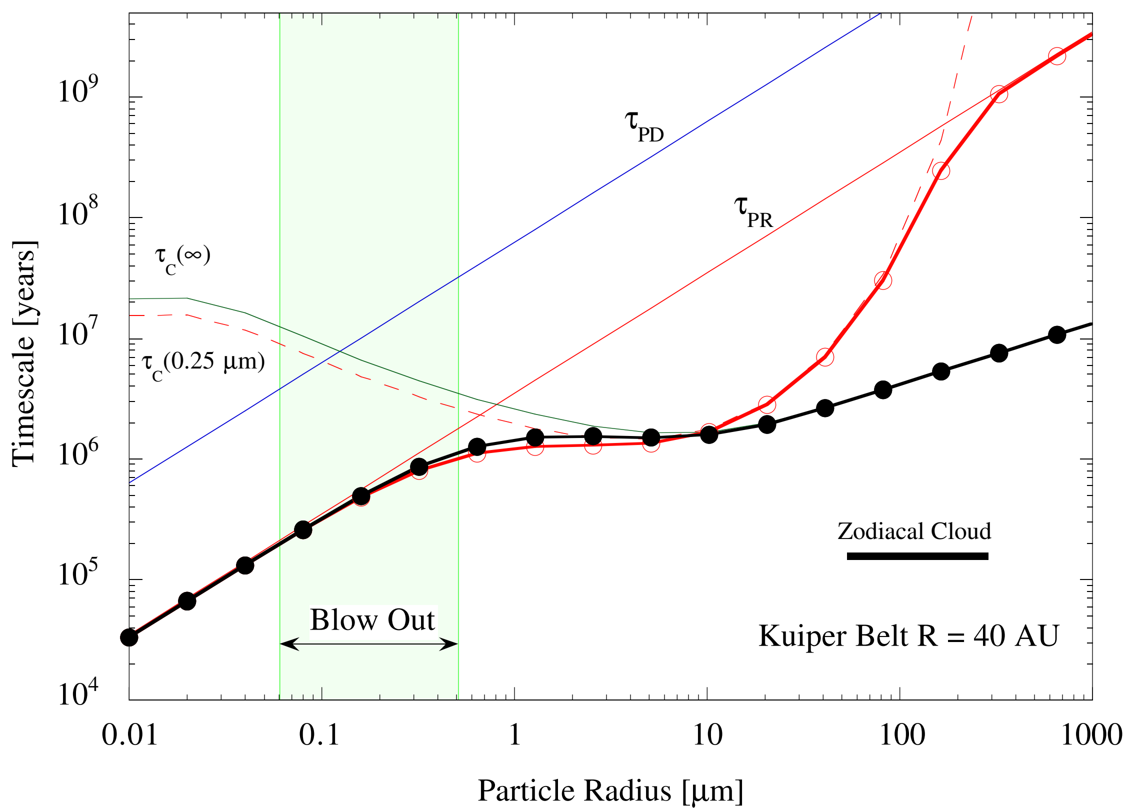

Figure 11. Timescales for Poynting-Robertson decay (t_{pr}), plasma drag (t_{pd}) and collision with interstellar dust (t_c) all plotted as a function of radius for particles at 40 AU in the Kuiper Belt. The shaded region marks particles likely to be ejected from the solar system by radiation pressure. The lines with circles show the lifetimes to all three processes combined. The interstellar dust particles were assumed to follow a power law size distribution with differential index -3.5 and with maximum particle radius a_0. The line with filled circles corresponds to $a_0 = \infty$, and that with empty circles $a_0 = 0.25$ µm. Figure from Jewitt and Luu (1997).

We bracket the current dust production rate in the belt as follows. A lower limit is given by the rate of erosion due to interstellar dust impacts, $dM_d/dt \geq 4 \times 10^2$ kg s^{-1} (Yamamoto and Mukai 1998). An upper limit may be estimated by dividing the Kuiper Belt mass ($\leq 0.1\ M_{Earth}$: JLT98) by the age of the solar system (4.6 Gyr), giving $dM_d/dt \leq 10^7$ kg s^{-1}. Thus, we have

$$4 \times 10^{2} \text{ kg s}^{-1} \leq dM_d/dt \leq 10^{7} \text{ kg s}^{-1} \qquad (5)$$

for the current rate of dust production. For comparison, the production rate needed to sustain the Zodiacal Cloud is ~ 10^4 kg s^{-1} (Leinert et al. 1983, Grün et al. 1994).

With both foreground (Zodiacal Cloud) and background (galactic) confusion, it is perhaps not surprising that attempts to measure thermal emission from Kuiper Belt dust have failed (Backman, Dasgupta and Stencel 1995). However, there is one reported in-situ detection of dust in the Kuiper Belt. Gurnett et al. (1997) counted dust impacts using plasma wave analyzers on the Voyager 1 and 2 spacecraft. They determined an average number density of micron-sized grains $N_1 = 2 \times 10^{-8}$ m^{-3} along the two Voyager trajectories, beyond 30 AU. The plasma wave analyzers are sensitive to only a narrow range of particle sizes: impacts below the threshold mass 1.2 x 10^{-14} kg (corresponding to particle radius 1.4 µm at unit density) do not excite measurable plasma waves (Gurnett *et al*. 1997) while larger impacts are, presumably, rare. The average mass of a grain is taken as m_d ~ 2 x 10^{-14} kg (c.f. Gurnett et al. 1997) and the volume of the Kuiper Belt (represented as an annular slab with inner and outer radii 30 AU and 50 AU, respectively, and a thickness of 10 AU) as V ~ 2 x 10^{38} m^3. The total mass of dust in micron sized particles is then $M \sim m_d N_1 V \sim 8 \times 10^{16}$ kg. With a $\tau_c \sim 10^6$ yr dust lifetime, the implied production rate in micron-sized particles is of order $M/\tau_c \sim 3 \times 10^3$ kg s^{-1}, which is near the lower limit in Eq. (5).

If the dust size distribution extends far above the micron size range, then the Voyager impact measurements provide only a lower limit to the total rate of production of debris. In a Dohnanyi (1969) type power law distribution with index -3.5, micron-sized particles contain only ~1/16th of the mass, when measured to maximum radius 1mm (~1/500th when measured to 1 m). The non-detection of centimeter-sized particles from Pioneer 10 (Anderson et al. 1998) unfortunately does not provide a strong constraint on the dust size distribution.

CONSTRAINTS ON THE ORIGIN OF THE KUIPER BELT

Factors relating to the origin and evolution of the Kuiper Belt may be summarized in this manner:

1. The surface density of the condensible part of the planetary mass obtained by smearing the masses of the giant planets is given roughly by $\sigma(R) \approx 10\ (10/R)^{3/2}$ [kg m^{-2}], where R is heliocentric distance measured in AU (Weidenschilling 1977, c.f. Pollack et al. 1996). The mass obtained by integrating this surface density over the $30 \leq R \leq 50$ AU annulus is ~ 25 M_{Earth}, or about 10^2 times the estimated mass of the present Kuiper Belt. Either the extrapolation of $\sigma(R)$ beyond Neptune is invalid (i.e. the protoplanetary disk had an edge) or a large part of the mass initially present in the $30 \leq R \leq 50$ AU zone has been removed.

2. Given only the present mass in the 30 to 50 AU region, the timescales for growth of the KBOs by binary accretion to 100 km and 1000 km scales are much longer than the age of the solar system (Stern 1995, Kenyon and Luu 1998). Such growth is therefore impossible, with the implication that either the KBOs formed elsewhere and were transported to their present locations by processes unknown or that the Kuiper Belt surface density was originally larger than at present.

3. Perturbations from Neptune exert a major disturbing influence on the adjacent Kuiper Belt (Holman and Wisdom 1993; Levison and Duncan 1993; Duncan, Levison and Budd 1995), raising the velocity dispersion and decreasing the accretion rate. Therefore, it is probable that the KBOs (in the inner part of the belt) were formed before Neptune (Stern 1996). However, assuming 35 M_{Earth} between 35 and 50 AU, Stern (1996) obtained Pluto growth times near 10^9 yr, which is longer than the 10^8 yr. timescale for formation of Neptune (Lissauer et al. 1995, Pollack et al. 1996). Only recently have more compatible Pluto growth times have been obtained. Kenyon and Luu (1998) assert that the 10^9 yr timescales obtained by Stern were incorrect due to an error in the numerical solution of the coagulation equation. Their numerical experiments show that 1000 km sized objects could form in < 10^8 yr provided the initial Kuiper Belt mass is 10 - 30 M_{Earth} (Kenyon and Luu 1998). Again, the implication is that a substantial mass of material has been lost from the Kuiper Belt.

Several possibilities have been suggested to explain the depletion of mass from the Kuiper Belt. Long-term numerical integrations (e.g. Holman and Wisdom 1993; Duncan, Levison and Budd

1995) show that the decline in the number of KBOs is approximately logarithmic with time and therefore too slow to be the main cause of the depletion. The resonance sweeping mechanism also appears incapable of losing 99% of the mass. Numerical experiments show that > 50% of initially non-resonant objects are captured into mean-motion resonances (Malhotra 1995). Admittedly, these experiments are simplistic, and the capture probability has not been assessed over a full range of initial orbital eccentricities. As noted by Fernandez and Ip (1984) and Malhotra (1995), the motion of Neptune is taken to be smooth and continuous. In reality, scattering of massive planetesimals would lend a stochastic character to Neptune's radial excursion, resulting in a decreased trapping efficiency. Stern and Colwell (1997) suggest that collisional grinding could have eroded the 30 AU - 50 AU region from 10 to 35 M_{Earth} down to the observed ~ 0.1 M_{Earth} in 10^9 yr. However, their model neglects velocity evolution and dynamics and is therefore of uncertain significance. Crucially, they note that sufficient erosion is obtained only if the mean eccentricity is somehow sustained above $e \geq 0.1$. In any case, the larger KBOs (namely, those detected in current ground-based surveys) cannot be destroyed by collisional grinding (Farinella and Davis 1996). For collisions to have removed 99% of the initial mass, one would have to postulate a steep initial size distribution (q ~ 5) in which objects large enough to escape comminution carry only 1% of the mass.

4. The existence of the Pluto-Charon binary sets additional constraints on the Kuiper Belt. First, it is widely supposed (based on the large specific angular momentum of the planet-satellite pair) that Charon was formed by a giant impact into Pluto (McKinnon 1989; Dobrovolskis, Peale and Harris 1997). If so, this impact must have occurred prior to the capture of Pluto into the 3:2 resonance, for otherwise the recoil would have knocked the planet out of resonance (Hahn and Ward 1995). Second, the rate of impacts into Pluto large enough to eject Charon is presently vanishingly small. Accordingly, the existence of an impact-formed Charon suggests a much higher density Kuiper Belt, perhaps containing many Pluto sized bodies (Stern 1991). Third, the eccentricity of the orbit of Charon should be tidally damped to a very low level ($e << 10^{-3}$) on timescales that are short compared to the age of the solar system. Surprisingly, Tholen and Buie (1997) have measured $e = (7.6 \pm 0.5) \times 10^{-3}$. If confirmed, this eccentricity will set important constraints on the impact rate in the modern-day Kuiper Belt.

SUMMARY

About 10^5 objects with diameters in excess of 100 km orbit the sun between 30 AU (the orbit of Neptune) and 50 AU (the practical limit of existing surveys). These objects obey a differential power law size distribution with index $q \sim -4$. The distribution seems to extend smoothly to Pluto (diameter ~ 2300 km) and allows the possibility that other Pluto-sized objects await discovery. The combined mass of these objects is about 0.1 M_{Earth}. When extrapolated to small sizes, the $q = -4$ distribution predicts that the total number of trans-Neptunian objects larger than 1 km diameter is 10^{11}. However, the size distribution of bodies smaller than 100 km in diameter is obtained by extrapolation and has not been confirmed by direct observation.

The orbits of the KBOs are divided into three main groups. So-called Classical KBOs orbit the sun with semi-major axes $42 \le a \le 50$ AU, possess small eccentricities and maintain a large separation from Neptune even at perihelion. Their orbits appear stable on timescales longer than the age of the solar system. About two thirds of the KBOs belong to the Classical group. Most of the remaining objects reside in mean-motion resonances with Neptune. The 3:2 resonance at a = 39.4 AU is particularly densely populated. Pluto is the largest of the 10's of thousands of objects trapped in this resonance. The Scattered KBOs follow large, eccentric orbits with perihelia near 35 AU, close enough to Neptune to permit weak dynamical control by that planet on billion year timescales. One example, 1996 TL66, is presently known. The inferred population is large, and may even dominate the total mass of trans-Neptunian objects.

The abundance of resonant objects (about 35% in the raw data and about 10 to 15% when corrected for the effects of observational bias) may provide important clues about the formation and early evolution of the Kuiper Belt. The resonance sweeping hypothesis (in which Neptune's orbit expanded during planet growth) makes verifiable predictions of the inclination and eccentricity distributions and of the resonance population ratios. In its present guise, this hypothesis suggests a total Neptune excursion from 25 AU to the present 30 AU, on a timescale that was evidently short.

The velocity dispersion among KBOs is near 1 km s^{-1}, suggesting that collisions are largely erosive and that the velocity dispersion has been amplified since the formation epoch. Excitation of the orbits of the resonant KBOs is an expected consequence of trapping into the resonance.

However, the non-resonant orbits of Classical KBOs are equally excited, suggesting the action of a more general disturbing agent. One suggested possibility is that massive scattered objects were projected through the Kuiper Belt during the late stages of Neptune accretion, stirring up the velocity distribution of the KBOs as they repeatedly passed through.

The combined mass of KBOs in the 30 to 50 AU region is too small for these objects to have grown by accretion in the 10^8 yrs prior to the emergence of Neptune. Roughly 10 M_{Earth} of material are needed to ensure growth of Pluto sized objects on this timescale. By implication, the present Kuiper Belt is a mere shadow of its former self, with about 99% of the initial mass now lost. The loss mechanism remains unidentified.

In short, our understanding of the formation and evolution of the Kuiper Belt is presently incomplete, even confused. This is to be expected in a field which is still very young. As more and better observations of KBOs are obtained, existing models will become more tightly constrained and new and unexpected ones will suggest themselves.

ACKNOWLEDGEMENTS

I thank the National Aeronautics and Space Administration for support.

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