The Kuiper Belt As An Evolved Circumstellar Disk

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Abstract. In the past decade, more than 400 objects have been discovered in orbit about the sun beyond Neptune. They constitute a vast ring of bodies the larger of which are the surviving products of accretion in the outer circumsolar disk. This so-called Kuiper Belt is a repository of the solar system's most primitive (volatile-rich) matter, a supplier of comets to the inner solar system and a source of collisionally produced dust with similarities to extra-solar dust disks.

1 Introduction

Since 1992, more than 400 trans-Neptunian bodies (objects with orbital semi-major axes greater than Neptune's 30 AU) have been discovered. Widely known as Kuiper Belt (or sometimes Edgeworth-Kuiper) Objects (KBOs), they are of scientific significance on several levels. First, dynamical chaos and (possibly) gravitational scattering in the Kuiper Belt lead some objects into planet-crossing trajectories that are dynamically short-lived. Planet-crossing KBOs that are not scattered out of the planetary system may be passed inwards to the vicinity of the earth where sublimation of trapped volatiles leads to the production of measurable coma. In this way, the Kuiper Belt is the likely source of the short-period comets. Long-period comets, in contrast, originate in the larger and more distended Oort Cloud.

The Kuiper Belt is also important as a repository of primitive planetary matter. Blackbody equilibrium temperatures at Neptune's orbit are near 50 K. At such low temperatures, many volatiles are either frozen solid (e.g. H_2O) or physically trapped in the interstices of other ices (e.g. CO, CO_2). Thus, KBOs are thought to be carriers of volatile molecules. They may supply a significant fraction of the volatiles now found on the terrestrial planets. Indeed, a cometary source of Earth's ocean water is often discussed (Lauffer et al. 1999). The comets themselves should also be viewed as products of low temperature agglomeration in the sun's disk. It is probably not a coincidence that the size distribution of the debris released by sublimating comets is flat, like the distributions inferred in many circumstellar disks.

The main importance of the Kuiper Belt is that it provides a very local example of a highly evolved circumstellar disk. Processes that are probably general to the circumstellar disks of solar-mass stars can be discerned already in the size and orbital element distributions of the Kuiper Belt. For example, resonant structure in the Kuiper Belt is probably indicative of early ($< 10^7$ yrs) planetary migration. Collisions between KBOs and erosion of KBOs by interstellar dust lead to the production of dust, some of which has already been detected by spacecraft. Viewed externally, our solar system would sport a diaphanous ring, morphologically very similar to that around $HR4796A$, but fainter.

In this very brief overview, we draw attention to the main features of the Kuiper Belt and attempt to give an idea of where the research frontier currently lies. Recent, more detailed reviews may be found in Jewitt (1999), Farinella, Davis and Stern (2000), Jewitt and Luu (2000) and Malhotra, Duncan and Levison (2000), Luu and Jewitt (2002). Active and informative web sites about the Kuiper Belt include:
http://cfa-www.harvard.edu/cfa/ps/lists/TNOs.html
http://www.boulder.swri.edu/ekonews/
http://www.ifa.hawaii.edu/faculty/jewitt/kb.html

2 Physical Properties

The flux density scattered by a planetary body varies in proportion to $pr^2/(R\Delta)^2$, where p is the albedo, r is the body radius and R and Δ are the heliocentric and geocentric distances, respectively. At opposition, $\Delta = R - 1$. When $R >> 1$ the flux density varies roughly as pr^2/R^4; the strong distance dependence renders distant objects very faint. This simple fact delayed the discovery and recognition of the trans-Neptunian solar system until the very end of the 20th century. It also explains why measurements of the physical observations of KBOs remain challenging.

2.1 Sizes and Albedos

Optical observations provide a measure of the product of the geometric cross-section with the albedo, but cannot directly yield either quantity separately. Most estimates of the sizes of KBOs are based on optical measurements and an *assumed* geometric albedo $p = 0.04$. This is the albedo measured for objects believed to have escaped the Kuiper Belt, notably the Centaurs and the nuclei of certain short-period comets. Diameters derived in this way are generally larger than 100 km, as a result of bias against detecting smaller, fainter objects. The largest KBO discovered recently is (20000) Varuna, with a diameter near 900 km (Jewitt, Aussel and Evans 2001). Thermal radiation from this object has been detected at submillimeter wavelengths, allowing a determination of the albedo: (20000) Varuna has $p \approx 0.07$. By comparison, Kuiper Belt Object Pluto is 2300 km in diameter and has albedo $p = 0.6$ as a consequence of bright surface frosts deposited from a tenuous atmosphere. While Varuna appears mantled in dark, possibly carbon-rich material, the extent of frost coverage on other KBOs remains uncertain. Keck near-infrared spectroscopy shows evidence for water ice absorption at 2 μm on some but not all objects.

The geometric albedo is also a function of wavelength. KBOs range from neutral to considerably redder than the sun (e.g. $1.4 < (B-I) < 2.7$; the color of the sun is $(B-I) = 1.4$). This color dispersion indicates compositional diversity among the KBOs, the origin of which is unexplained (Luu and Jewitt 1996, Jewitt and Luu 2001).

The heat conduction time for a body of radius r is $\tau_C \approx r^2/\kappa$, where κ $[m^2 s^{-1}]$ is the thermal diffusivity of the constituent material. Slightly porous dielectric solids of the type expected to make up the KBOs have $\kappa \approx 10^{-7}$ $[m^2 s^{-1}]$. Objects with $r < 100$ km have $\tau_C >$ the age of the solar system, and therefore cannot cool by conduction. Objects with $r \approx 100$ km experience only modest (few K) internal heating by trapped long-lived radioactive nuclei (notably Th, K, U). Those with $r \approx 1000$ km experience heating sufficient to mobilize internal super-volatiles (notably CO and N_2). Therefore, we should not be surprised to find evidence of outgassing from at least the larger KBOs. The potent radioactive nucleus of ^{26}Al, with half-life $\approx 10^6$ yr, is unlikely to have been incorporated in $r > 1$ km KBOs because of the long growth times in the outer disk.

2.2 Size Distribution

The size distribution is inferred from the brightness distribution of the KBOs by assuming a constant albedo for all objects. The distribution is well represented by a differential power law of the form

$$n(r)dr = \Gamma r^{-q} dr$$

with $q = 4.0^{+0.6}_{-0.5}$ (Trujillo, Jewitt and Luu 2001). This distribution is such that the collisional cross-section of the KBOs is dominated by the smallest objects, while the mass is spread uniformly among equal (logarithmic) mass intervals. Models of agglomeration that include the effects of collisional shattering of growing KBOs are able to match the measured sized distribution (Kenyon and Luu 1998).

The distribution at sizes $<<$ 100 km is not well constrained. Models suggest that the smaller objects could be produced by collisional shattering of KBOs larger than 100 km. If so, we expect that the size distribution should flatten, somewhat, approaching the $q \approx 3.5$ value expected for a set of colliding bodies in collisional equilibrium cascade (Dohnanyi 1969). In this picture, the kilometer-scale nuclei of comets can be identified with fragments of larger KBOs. Collisional shattering of parent objects is one possible source of the dust in β Pic type systems (Dent et al. 2000).

2.3 Orbital Element Distributions

One of many surprising observational discoveries about the Kuiper Belt is that the orbital element distribution is highly structured, with evidence for division into several distinct groups (Figure 1).

- Roughly 10% of the known KBOs occupy mean motion resonances with Neptune. The 3 : 2 mean motion resonance at 39.4 AU is particularly densely occupied, and includes Pluto as a member. Pluto and some other "Plutinos" are stable even in Neptune-crossing orbits because of protection provided by the resonance. The leading theory for the population of resonances is the migration hypothesis in which the planets migrate in response to torques exerted by the scattering of nearby planetesimals. Capture into resonance is only efficient when the velocity dispersion is small and the planet drift velocity is small and steady (Malhotra, Duncan and Levison 2000). The implication is that capture occurred early, when the disk was still very thin. The maximum eccentricities of Plutinos (e $\approx$ 0.3) are well fit by outward migration of Neptune by $\Delta a \approx 7$ AU on timescales $\approx 10^7$ yr (Hahn and Malhotra 1999).

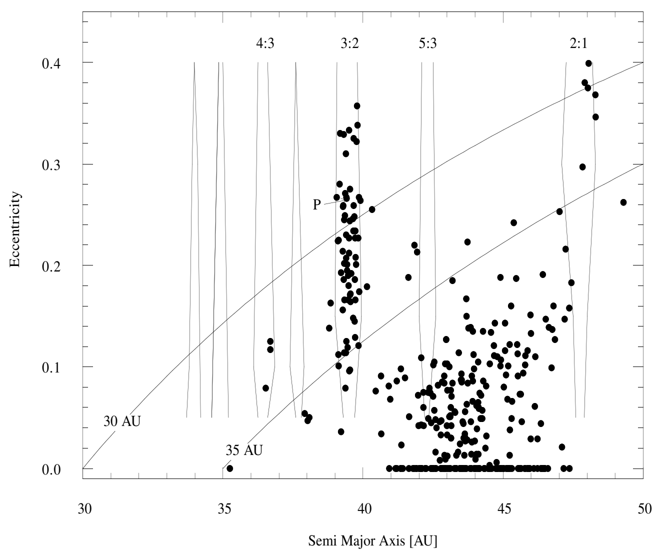

Fig. 1. Distribution of semi-major axis vs. orbital eccentricity for the Classical and Resonant Kuiper Belt Objects. The major mean-motion resonances are marked as vertical bands. Diagonal arcs show the loci of orbits having perihelia at 30 AU and 35 AU. Objects above the $q = 30$ AU line have Neptune-crossing orbits. Neptune is located at the lower left intersection of the axes ($a = 30$ AU, $e = 0$). Pluto is marked with a "P".

- A majority of the known KBOs occupy the "Classical Kuiper Belt". They have semi-major axes $42 < a < 50$ AU and modest inclinations and eccentricities. The number of $D > 100$ km Classical objects alone is $3.8^{+2.0}_{-1.5}$ x

10^4. These objects are dynamically stable on billion year timescales without resonance protection because they maintain a safe distance from Neptune.
The CKBOs show a distinctly excited velocity distribution, not at all consistent with the small relative velocities that must have prevailed when these bodies accreted. The source of the excitation is unknown, but several possibilities have been considered. Large planetesimals, with masses comparable to or greater than that of Mars, could have excited the velocity dispersion if these bodies were scattered through the Kuiper Belt by Neptune (Petit, Morbidelli and Valsecchi 1998). Such objects would also have disturbed and depleted the resonant objects. Perhaps the resonant KBOs are survivors from once much larger populations.
The Classical Belt has an outer edge near $R \approx 50$ AU (Figure 2: JLT98, Allen et al. 2001, TJL2001). There is no obvious reason why the sun's accretion disk should be truncated at this modest distance. On the other hand, the smallest of the proplyd disks have radii of comparable scale (McCaughrean and O'Dell 1996). Tidal truncation by a passing star has been proposed as an explanation by Ida et al. 2000. The current probability of a sufficiently close (150 - 200 AU) stellar encounter is negligible. However, early isotopic contamination of the solar system by a nearby supernova suggests that the sun may have formed in a cluster of $\approx$ 2000 stars (Adams and Laughlin 2001). Close encounters 4.6 Gyr ago might have been correspondingly more frequent.

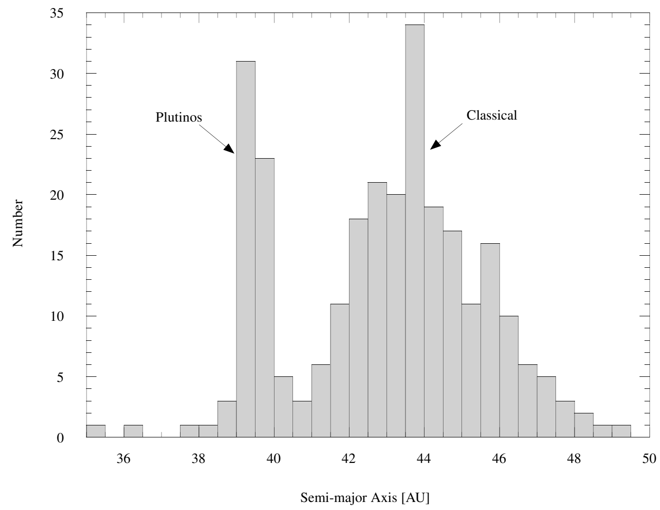

Fig. 2. Histogram of semi-major axes. Detailed consideration of the observational biasses inherent in ground-based surveys reveals that the deficiency of objects beyond 50 AU indicates a real edge to the Classical Belt.

- About two dozen KBOs belong to the Scattered Object (SKBO) group (Luu et al. 1997, Figure 3). These have large orbits with perihelia near 35 AU and eccentricities and inclinations larger than typical for the other dynamical groups in the Kuiper Belt. Such orbits are unstable on billion year timescales, as a result of continuing weak interactions with Neptune near perihelion. Recent identification of SKBOs with perihelia $q > 40AU$, however, render the perturbing role of Neptune uncertain. Other perturbers may be responsible. SKBOs are subject to particularly large observational selection effects. The number of SKBOs interacting with Neptune is at least $3.1^{+1.9}_{-1.3}$ x 10^4. If the SKBO perihelion distribution extends far beyond 40 AU, the total population of these objects could be much larger, possibly dwarfing the Classical and Resonant populations.

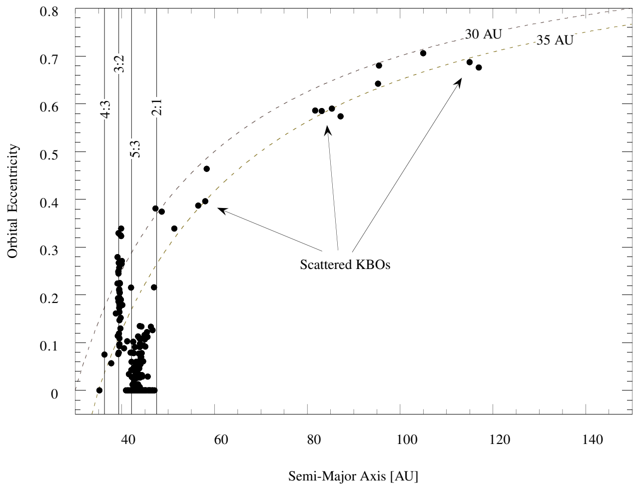

Fig. 3. Same as Figure 1 except that a wider parameter space is plotted to reveal the Scattered Kuiper Belt Objects. Note how these appear to cluster near a line of constant perihelion distance.

3 Numbers and Mass

The population of KBOs is estimated by extrapolation from surveys of limited areas of the ecliptic sky. The number of KBOs of diameter $D > 100$ km in the $30 < R < 50$AU region is $N(D > 100km) \approx 10^5$. Extrapolated down to $D = 1$ km with a $q = 4$ power law, the number of KBOs is $N(D > 100km) \approx 10^{11}$.

By mass, however, the present day Kuiper Belt is insubstantial. Published estimates from optical survey data give $0.05 < M < 0.2\ M_\oplus$ (Jewitt, Luu and

Trujillo 1998, Trujillo, Jewitt and Luu 2001). An upper limit, $M < 1M_\oplus$, is set by dynamics (specifically by the absence of perturbations on the orbit of comet P/Halley). We note below that the original mass in the Kuiper Belt may have been much larger, perhaps near $30M_\oplus$.

Short-period comets enter the inner solar system at a rate near $10^{-2}yr^{-1}$. The Kuiper Belt appears easily able to supply this rate for the full age of the solar system. However, it is not clear from where in the Kuiper Belt the short-period comets originate. Source regions of chaotic instability near resonances are likely sources. Decay of SKBOs could also provide a source of planet-crossing bodies.

4 Collisions and Dust

The $\Delta V = 1.3$ km s^{-1} velocity dispersion among KBOs is larger than the gravitational escape velocity from all but the largest objects. Therefore, collisions between KBOs tend to be destructive, leading to the production of dust. Collisions with interstellar dust grains also erode KBOs and produce dust. This dust has apparently already been detected by the Voyager spacecraft when leaving the planetary region after their encounters with the gas giants. The mean optical depth normal to the plane of the ecliptic is about 10^{-7}, three to four orders of magnitude less than the corresponding optical depth of the β Pic disk. From the distance of another star, the Kuiper Belt would be invisible with current coronagraphic technology. However, it may not always have been so. If the mass of KBOs was originally much larger than now, enhanced collision rates might have maintained much larger mean optical depths. Dust produced in the Kuiper Belt drifts inwards under the action of Poynting-Robertson drag (Figure 4). Particles of micron size have 10^6 yr lifetimes to collisional descruction that are shorter than the 10^7 yr transport timescale, so most do not survive the journey to the vicinity of Earth.

5 Formation

A disk of planetesimals each of radius, r [m], will develop, through mutual gravitational scattering, an internal velocity dispersion comparable to the escape velocities of the constitutent planetesimals. The escape velocity from a spherical ice body of unit density is $V_e \approx 0.001r$ $[ms^{-1}]$. The circular Keplerian velocity is just $V_K = (GM_\odot/a)^{1/2}$, where G = 6.67 x $10^{-11} Nkg^{-2}m^2$ is the gravitational constant, $M_\odot$ = 2 x 10^{30} kg is the solar mass and a is the semi-major axis expressed in meters. The orbital inclination resulting from the velocity dispersion is simply $\tan(i) = \Delta V/V_K$. Substituting $\Delta V = V_e$ and assuming $\Delta V << V_K$, we see

$$i[rad] \approx 0.001r(a/GM_\odot)^{1/2}.$$

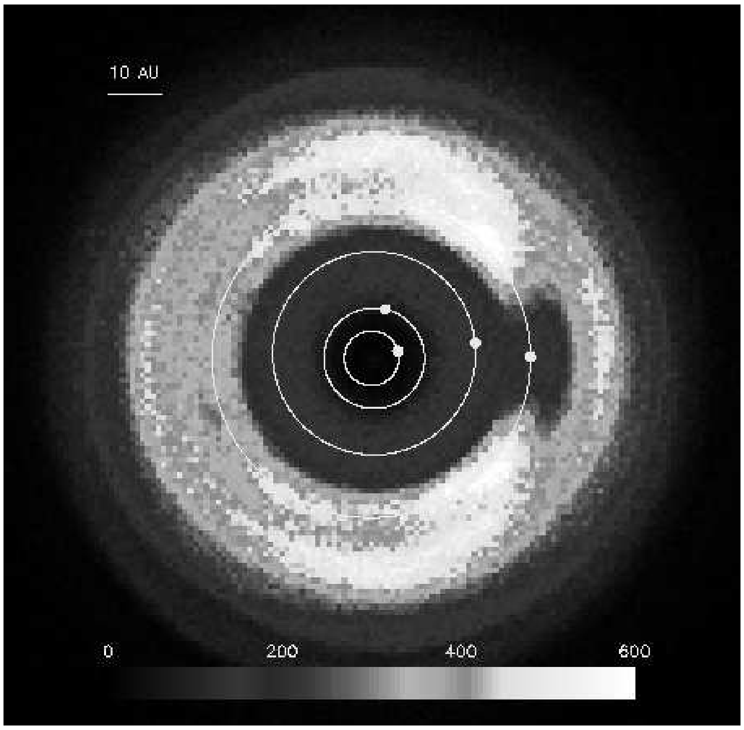

Fig. 4. Distribution of dust particles released from the Kuiper Belt and moving under the action of solar and planetary gravity, and radiation forces. This figure is intensity coded for the column density of 23 μm sized grains and includes neither the dust size distribution nor the radial variation of the impressed radiation field. Orbits and locations of the gas giant planets are marked. Figure from Liou and Zook 1998.

At a = 40 AU, a disk of r = 1 km bodies would inflate to an average inclination near 2 x 10^{-4} [rad] = 0.01 [deg]. With r = 100 km the equilibrium mean inclination is still only 1 [deg]. For comparison, the measured, de-biassed width of the KBO inclination distribution is nearer 20 [deg] (Trujillo, Jewitt and Luu 2001).

How was the inclination distribution excited to its observed, high value? The emergence of nearby Neptune presumably had a profound influence on the structure of the Kuiper Belt. The dynamically cool accretion disk would be heated by Neptune- perturbed objects, effectively truncating the growth of the KBOs. The timescale for the accretion of Neptune is uncertain. Its high molecular weight suggests that growth was not complete until after depletion of the sun's gas nebula at 10^7 (Bryden, Lin and Ida 2000) but much longer times, 10^8 yrs, are possible (Lissauer et al. 1995). For this reason, it is widely believed that the KBOs, up to and including 1000 km scale Pluto, grew in the first 10^7 to 10^8 yrs of the solar system and that subsequent accumulation of KBOs in the inner regions was terminated by the runaway growth of Neptune. The planet would introduce less disturbance in the outer Belt, but low disk surface densities at large radii would seriously retard the growth of large objects.

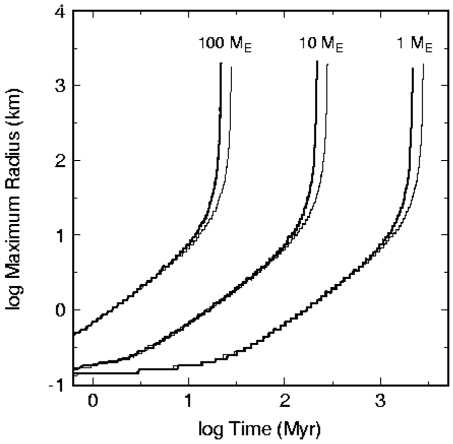

Fig. 5. Maximum radius of growth vs. elapsed time for Kuiper Belt disk masses 1, 10 and 100 $M_{\oplus}$, as marked. Thin and thick lines show, respectively, calculations without and with velocity evolution. The models assume an initial eccentricity 0.001, corresponding to velocity dispersion $\Delta V \approx 10$ m s^{-1}. Figure from Kenyon and Luu 1998.

The outstanding problem with this scenario is that the mass of material in the belt is too small for growth to have produced the observed KBOs even in 10^8 yrs (Stern and Colwell 1997, Kenyon and Luu 1998). The latter authors find growth times for 1000 km scale objects $\tau[Myr] \approx 200(M/10M_{\oplus})^{-1}$. To obtain the observed objects by agglomeration on 10^8 (10^7) yr timescales requires masses $M \approx 20M_{\oplus}$ ($200M_{\oplus}$), roughly 2 x 10^2 (2 x 10^3) times higher than now present (Figure 5). The inference is that the present day Kuiper Belt is a remnant of a once much more massive structure (Stern and Colwell 1997, Kenyon and Luu 1998). If so, the early solar system might have looked much more like such dusty stars as ϵ Eri and HR 4796A, with an encircling disk of high optical depth.

How was the Kuiper Belt cleared? Dynamical clearing certainly played a role, particularly in the inner ($R < 40$ AU) regions. The disk beyond 50 AU might have been ejected by a passing star (Ida *etal.* 2000). In between, collisional grinding of KBOs into dust has been proposed as a mechanism of reducing the total mass in the Belt (Farinella, Davis and Stern 2000). Collisional grinding presumably pulverizes KBOs until the fragments are so small that radiation drag or other weak forces are able to clear the dust from the system. This scenario, still not worked out in convincingly quantitative detail, is attractive not least because it encourages us to think of the Kuiper Belt in a younger phase as a very dusty and prominent ring, perhaps similar to that around HR4796A.

Planetesimals closer to the sun were either accumulated into the growing giant planets or gravitationally scattered away. A majority of those ejected left the planetary region at greater than the local solar escape velocity. These objects, perhaps 10^{13} in number from our sun alone, perpetually roam interstellar space. If all stars ejected a similar number of planetesimals, we should expect to find interstellar comets re-entering the inner solar system once every 10 - 100 yrs or so. None has yet been seen but future survey telescopes (e.g. VISTA, VST and LSST) might find them. Many planetesimals ejected close to the local escape velocity were subsequently perturbed, by galactic tides and by gravitational impulses from passing stars into weakly bound, highly eccentric orbits (the capture efficiency would be higher if the sun were in a dense cluster; see Fernandez 1997). The 10^{12} objects now in the Oort Cloud are thought to have been captured in this way. Thus we see that, ironically, the remote, cold Oort Cloud (long period) comets in fact formed closer to the sun and therefore at higher temperatures than the comets in the Kuiper Belt.

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