PHYSICAL NATURE OF THE KUIPER BELT

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Recent ground-based observations have unveiled a large number of bodies in orbit beyond Neptune, in a region now widely known as the Kuiper (or, less commonly, Edgeworth-Kuiper) Belt. About 10^5 Kuiper Belt Objects (KBOs) with diameters larger than 100 km exist in the 30 AU to 50 AU trans-Neptunian region. Their combined mass is about 10% of that of Earth. The orbits of KBOs fall into at least three distinct dynamical classes (the "Classical" objects, the Plutinos and the "Scattered" objects). Each throws light on physical processes operating in the solar system prior to and during the formation of the planets. The Kuiper Belt is significant both as the likely source of the short-period comets (and the dynamically intermediate Centaurs), and as a repository of the solar system's most primitive (least thermally processed) material. KBOs show an unexpected and presently unexplained diversity of surface colors, possibly reflecting intrinsic compositional variations and transient resurfacing by impacts. The present-day Kuiper Belt is probably the surviving remnant of a once much more massive $(10 M_\oplus?)$ preplanetary disk. It is very likely that collisions and disk-planet interactions played a major role in shaping this early precursor. While the collisional production of dust is presently modest ($\sim 10^3$ kg s^{-1}), and the optical depth small ($\sim 10^{-7}$), the early Belt was probably very dusty and may have sustained a disk analogous to those reported around some nearby main-sequence stars.

I. History

The Kuiper Belt has a long and mostly speculative history, dating back at least to papers by Edgeworth (1943, 1949) and Kuiper (1951). These authors noticed that prevailing theories of planetary accretion provided no reason to expect that the planetary system should end at the orbit of Neptune (or of Pluto, then believed to be a massive and bona fide planet in its own right). Edgeworth believed that the comets

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might be derived from the trans-Plutonian region (MacFarland 1996), an idea that is now widely accepted. Kuiper argued that kilometer-sized comets would grow in the trans-Neptunian region on timescales of 10^9 yrs, and that Pluto was responsible for scattering these objects to the Oort Cloud. Subsequently, these comets would be sent back to the planetary region by stellar perturbations to appear as long-period comets (those having periods > 200 yrs), according to Oort's (1950) prescription. These ideas were further developed by other researchers, including Whipple (1964), who used anomalies in the motion of Neptune to infer the mass of trans-Neptunian objects (the anomalies are now known to be due to systematic astrometric errors). Later workers realised that the observed flux of short-period comets was too large to be derived from planetary perturbations of long-period comets falling from the Oort Cloud (Joss 1973), raising the possibility of separate sources for the long-period and short-period comets. The Kuiper Belt was explicitly advanced as the source of short-period comets by Fernandez (1980). Numerical work by Duncan et al. (1988) confirmed that the short-period comets could not be captured from the spherical Oort Cloud, providing indirect support for the existence of a belt-like cometary source.

Observationally, the search for objects in the outer solar system was impeded by their expected faintness. The flux of sunlight scattered from a solid body varies approximately as $p_R r^2 R^{-4}$, where p_R is the geometric albedo, r is the radius and R is the heliocentric distance. Objects of a given size and albedo are 10^4 times fainter when beyond Neptune ($R = 30$ AU) than when in the main asteroid belt ($R = 3$ AU). This simple fact provided a daunting and, for many years, insurmountable obstacle to the direct observation of small bodies in the outer solar system. Kowal (1989), for example, used the Palomar Schmidt to conduct a 6000 square degree photographic survey of the ecliptic to red magnitude 19.5 but found nothing beyond the planetary region. The turning point came with the application of large-format, high quantum efficiency charge-coupled device (CCD) detectors in the late 1980's. Although the first CCD survey was also negative (Luu and Jewitt 1988) the new technology spurred increasing observational effort (Levison and Duncan 1990; Cochran et al. 1991; Tyson et al. 1992), culminating with the detection of the first Kuiper Belt object (1992 QB1) on 1992 August 30, using a 2048 × 2048 pixel

CCD on the University of Hawaii 2.2-m telescope (Jewitt and Luu 1993). Intensive surveys since 1992 have increased the observational sample to about 160 objects at the time of writing (Jewitt and Luu 1995, Irwin, Tremaine and Zytkow 1995, Williams et al. 1995, Jewitt, Luu and Chen 1996, Jewitt, Luu and Trujillo 1998, Luu and Jewitt 1998, Gladman et al. 1998, Chiang and Brown 1999). Our knowledge of the Kuiper Belt is based primarily on these 160 objects, most particularly on the 54 whose orbital elements are known with confidence from astrometry at more than one opposition. An updated list of these orbits is maintained by the Minor Planet Center at the web site http://cfa-www.harvard.edu/cfa/ps/lists/TNOs.html, while updated information on Kuiper Belt research is maintained at http://www.ifa.hawaii.edu/faculty/jewitt/kb.html.

The present chapter aims to present the observational status of the Kuiper Belt, and is organized as follows. In Section II, we discuss the optical surveys, in Section III we consider dust production in the Kuiper Belt, and in Section IV we remark on the dynamically related Centaur class. Physical properties are the subject of Section V. We end with a list of topical questions in Section VI.

II. Results from the Optical Surveys

Figure 1 shows a plan view of the Kuiper Belt based on survey observations up to mid-1999. Evidence for dynamical sub-structure in the Kuiper Belt is provided in Figure 2, which shows orbital semi-major axis a vs. eccentricity e for the known KBOs. The KBOs display a highly non-uniform distribution of orbital elements in $a - e$ space, leading to the definition of three distinct dynamical groups within the Kuiper Belt.

A. Classical Objects

About 2/3rd of the well-observed KBOs have semi-major axes $a \geq 42$ AU and perihelia $q > 35$ AU and together these characteristics define the "classical" Kuiper Belt. Numerical simulations suggest that the orbits are stable over periods comparable to the age of the planetary system (Holman and Wisdom 1993; Duncan, Levison and Budd 1995; Morbidelli, Thomas and Moons 1995), essentially because the perihelia are well separated from Neptune. The classical KBOs possess modest eccentricities but can have inclinations as large as 32°

(Table 1). Both the inclination and eccentricity distributions are wider than expected on the basis of long-term simulations that account only for planetary perturbations (e.g., Figs. 3 and 4 of Holman and Wisdom 1993 show typical eccentricities and inclinations of only 0.02 and 1 degree, respectively), implying excitation by another mechanism.

B. Resonant Objects (Plutinos)

Approximately 1/3rd of KBOs appear clustered near the 3:2 mean-motion resonance with Neptune at $a = 39.4$ AU (Fig. 2). These objects have large eccentricities ($0.1 \leq e \leq 0.34$) and inclinations up to $\sim 20deg$ (Table 1). Many of them cross the orbit of Neptune (the critical eccentricity for crossing is $e = 0.24$), and would be subject to strong Neptune perturbations were they not dynamically protected by the resonance. In this regard, the 3:2 objects resemble Pluto, which is located within the resonance (plotted in Fig. 2 with an X) and which is also Neptune-crossing. Like Pluto, the "Plutinos" (a name chosen to symbolise this remarkable dynamical similarity) are aphelion librators, which reach perihelion when near ± 90 deg. from Neptune. Pluto itself occupies several other resonances, notably the "argument of perihelion libration", which maintains its perihelion at high ecliptic latitude and therefore further minimizes Neptune perturbations (e.g., Malhotra and Williams 1998). It is not yet known what fraction of the Plutinos might occupy these other resonances because the sky-plane coverage of published surveys remains very small. The upper limit to the eccentricity of the Plutinos (the most eccentric is 1996 TP_{66}, with $e = 0.34$, $q = 26.4$ AU) is presumably set by destabilizing perturbations from Uranus. There is a deficiency of Plutinos with $e \leq 0.1$.

The apparent fraction of Plutinos is over-estimated as a result of observational bias (the Plutinos have smaller orbits than classical KBOs and so appear brighter, and are easier to detect, at a given size). Bias-corrected statistics suggest that the "true Plutino fraction" is closer to 10% to 15% (JLT98). Thus, the Plutinos appear to be a significant but distinct minority component of the Kuiper Belt. Other mean-motion resonances are also populated (Fig. 2), notably the 2:1 resonance at 47.6 AU (1996 TR_{66} and 1997 SZ10), the 4:3 at 36.4 AU (1995 DA_2), and the second order 5:3 resonance at 42.3 AU (1994 JS).

The mechanism by which the resonances were populated has not yet been firmly established. The leading hypothesis invokes radial migration of the planets due to the exchange of angular momentum with

planetesimals scattered from the protoplanetary disk. Simulations suggest that planetesimals scattered among the planets lead to an asymmetry that drives Saturn, Uranus and Neptune away from the sun. Jupiter provides the ultimate source of the angular momentum and, accordingly, its orbit contracts (Fernandez and Ip 1984, Malhotra 1995, Hahn and Malhotra 1999). As Neptune migrated outward, its mean-motion resonances would have swept through the Kuiper Belt collecting objects. Malhotra (1995) finds especially efficient trapping of KBOs in the 3:2 and 2:1 resonances. The trapping efficiency is high (of order unity) for initial orbits of low-eccentricity and inclination, and for slow and smooth planetary migration. The relative populations of the resonances depend partly, in this resonance sweeping model, on the rate of migration. This raises the intriguing possibility that measurements of the population ratios may allow an estimate of the rate at which Neptune's orbit expanded. One problem for the resonance sweeping hypothesis, at least in its simplest form, is that most known KBOs are not trapped in mean-motion resonances. For example, the classical KBOs lie in a region that should have been swept clean by the outwardly migrating 2:1 resonance. It is likely that effects such as the stochastic migration of Neptune in response to the ejection of massive planetesimals would decrease the trapping efficiency, possibly to levels consistent with the data.

C. Scattered Objects

Four KBOs in the known sample possess large, eccentric, inclined orbits with perihelia near 35 AU (Fig 3). The prototype "Scattered Kuiper Belt Object" is 1996 TL$_{66}$ (Luu et $al.$ 1997), with $a = 85$ AU, $e = 0.59$, $i = 24deg$. These objects may represent a chaotic swarm of bodies scattered outwards by Neptune in the early stages of the solar system (Torbett 1989; Ip and Fernandez 1991; Duncan and Levison 1997). With perihelia near 35 AU, Neptune is able to exert weak dynamical control. The number of Scattered KBOs is highly uncertain. A population of order 6×10^3 (500-km diameter or larger) is suggested by the discovery of 1996 TL$_{66}$ (Luu et al. 1997), but this estimate is good at best to order of magnitude. The SKBOs appear rare in flux-limited surveys because their large, eccentric orbits render them invisible except when near perihelion. In absolute numbers the SKBOs may dominate the trans-Neptunian region.

D. Cumulative Luminosity Function

The cumulative luminosity function (CLF) of the Kuiper Belt is shown in Figure 4. In the Figure we have omitted measurements based on photographic plates (principally the survey by Kowal 1989 and the photographic portion of Luu and Jewitt 1988). Photographic surveys are difficult to calibrate and require long integrations that permit excessive trailing loss even on slow moving objects. The Hubble Space Telescope (HST) measurement (Cochran et al. 1995) at red magnitude 28.1 is controversial and deserves special mention. The central issue is that the HST images are under-sampled, so that astronomical objects and cosmic rays cannot be readily distinguished by their morphology alone. Consequently, the KBOs must be sought against a large background due to cosmic rays. The measurement has been criticized by Brown et al. (1997) on the basis that noise in the data would prevent the detection of objects at the claimed limiting magnitude (but see Cochran et al. 1998). Furthermore, the authors searched the HST data only for Plutino-type orbits. Inclusion of other dynamical classes would, by analogy with the ground-based surveys, increase the derived surface density by a factor of order 3. For these reasons the usefulness of the HST measurement is presently not clear.

The CLF is well described by a power law relation of the form

$$log[\Sigma(m_R)] = \alpha(m_R - m_0) \tag{1}$$

where $\Sigma(m_R)$ is the cumulative surface density measured to limiting magnitude m_R, and a and m_0 are constants. Fits to the CLF give $\alpha = 0.58 \pm 0.05$, $m_0 = 23.27 \pm 0.11$ ($20 \leq m_R \leq 25$; JLT98), $\alpha = 0.54 \pm 0.04$, $m_0 = 23.20 \pm 0.10$ ($20 \leq m_R \leq 26.6$; LJ98), $\alpha = 0.76^{+0.10}_{-0.11}$, $m_0 = 23.40^{+0.20}_{-0.18}$ ($20 \leq m_R \leq 26$; Gladman et al. 1998) and $\alpha = 0.52 \pm 0.02$, $m_0 = 23.50 \pm 0.06$ ($20 \leq m_R \leq 27$; Chiang and Brown 1999). Gladman et al. (1998) observed that least-squares fits are not appropriate when the data are cumulative and the uncertainties are Poissonian, as opposed to Gaussian. The slope they derived using a maximum likelihood method differs from those found by other investigators using least-squares, but Chiang and Brown (1999) showed that this difference is due to their selective use of only a sub-set of the available data, and not to the fitting method. In any case, differences among the fitted parameters are at the 2σ level for α and m_0, and are therefore statistically insignificant. Furthermore, the assumption that

the uncertainties are Poissonian in distribution is probably not correct. We already know, for example, that the azimuthal distribution of Plutinos is non-uniform (Malhotra 1995, JLT98), meaning that systematic sky-plane surface density variations are folded into the survey data, but have not been taken into account. More survey observations, especially at $m_R \leq 20$ and $m_R \geq 26$, will soon resolve these ambiguities.

E. Inclination distribution

The apparent Full Width at Half Maximum (FWHM) of the belt is $\sim$ 10° (JLC96, c.f. Fig. 5), the most extreme inclination being 39.1° for 1999 CZ_{118} (not plotted in Fig. 5 because it is still a single opposition object). However, this must be considered as a lower limit to the width of the intrinsic inclination distribution, because of the effects of observational bias. Objects of high orbital inclination spend a larger fraction of each orbit far from the ecliptic than do objects of small inclination. Existing surveys, which have mainly been focused on the ecliptic, are therefore biassed against finding objects of high inclination.

Models which attempt to correct for the inclination bias so far do not yield unique values of the intrinsic inclination distribution because of the limited sample size. The most secure result from these models is that the intrinsic inclination distribution must be very broad, perhaps 2 to 3 times the apparent FWHM (JLC96), in order to give rise to the apparent distribution. An immediate implication of the broad inclination distribution is that the velocity dispersion among KBOs is $\Delta V \approx 1 - 1.5$ km s^{-1}. Collisions occur with specific energies that are high enough to guarantee erosion of all but the largest objects (Stern 1995). Indeed, it has been suggested that the nuclei of short-period comets are collisionally produced fragments of large KBOs (Farinella and Davis 1996).

Numerical simulations show that the inclinations of resonant objects can be pumped to maximal values near 20° (Malhotra 1996). This is in good agreement with the maximum inclination among the known Plutinos, namely 19.5° (1995 QZ9). What is more surprising is that the classical KBOs have a mean inclination formally consistent with the Plutinos, and that the most highly inclined KBOs are found outside of mean motion resonances (Fig. 5). The origins of the high inclinations of classical KBOs are not understood. One possibility is that the classical Belt might have been stirred by a small number of bodies of

Earth- and sub-Earth mass, scattered outwards by Neptune and now
lost from the planetary system (Morbidelli and Valsecchi 1997; Petit
et al. 1998). While interesting in its own right (and possibly even cor-
rect!) it has not been shown how the massive scatterers could excite
the classical Belt without simultaneously depopulating the mean mo-
tion resonances. Some KBOs could be scattered into resonances (the
fractional volume of phase space occupied by resonances is $\approx 7\%$) albeit
with low probability of long term capture (Levison and Stern 1995).

F. Size distribution and Statistics

The optical surveys are flux-limited rather than volume-limited, lead-
ing to a bias towards large (bright) objects near the inner edge of the
belt and against small (faint) objects far away. As a result, the size
distribution of KBOs cannot be measured directly, but must be in-
ferred from the CLF using a model of the spatial distribution. We
consider the size distribution of KBOs as represented by a differential
power law, $n(r)dr = \Gamma r^{-q}dr$, where r [km] is radius and Γ and q are
constants. Assuming a fixed albedo 0.04 for all objects and an inverse
square radial distance distribution, Monte Carlo simulations give best-
fit values $\Gamma = 3.8 \times 10^{10}$ and $q \sim 4$ (JLT98; Luu and Jewitt 1998).
In a $q = 4$ distribution, the cumulative number of objects with radius
$> r$ is $N(r) = \Gamma/(3r^3)$. The objects discovered in ground-based sur-
veys number $N(50\ \mathrm{km}) \sim 10^5$. The distribution allows $N(1000\ \mathrm{km}) \approx$
10, i.e., ten Pluto-scale objects, all but one as yet undiscovered. At the
other end of the size distribution, the effective radius of the well-studied
short-period comets is in the range 1 km to 5 km. The fitted distribu-
tion allows $N(5\ \mathrm{km}) = 1 \times 10^8$, while $N(1\ \mathrm{km}) \sim 10^{10}$. Clearly, the
Kuiper Belt is likely to hold large numbers of undetected small bodies.
Models of the growth of KBOs (Kenyon and Luu 1999) give $q = 3.5$
($r < 0.3 - 3$ km) and $q = 4$ ($r > 1 - 3$ km), in excellent agreement with
inferences from the gradient of the CLF.

   The total mass of a $q = 4$ distribution is

$$M = \frac{4 \times 10^9 \pi \rho \Gamma}{3} \left(\frac{0.04}{p_R}\right)^{3/2} \ln\left(\frac{r_{max}}{r_{min}}\right) \tag{2}$$

where ρ [kg m^{-3}] is the bulk density and p_R is the red geometric albedo.
The bulk density is uncertain to within a factor of a few. Cometary
nuclei may provide useful analogs of small KBOs. They have bulk
density $\rho \approx 500$ to 1000 kg m^{-3}. Conversely, Pluto and Charon are

examples of large KBOs: they have $\rho \sim 2000$ kg m^{-3} (Foust et al. 1997). Taking $\rho = 1000$ kg m^{-3} as a plausible average effective density, and with $p_R = 0.04$, we find that the observable KBOs, with $r_{min} = 50$ km and $r_{max} = 1150$ km (the radius of Pluto), have mass $M \sim 5 \times 10^{23}$ kg (0.1 $M_{\oplus}$). A comparable mass is contained in bodies smaller than 50 km radius in this distribution; however the size distribution of the smaller bodies is observationally unconstrained, and their combined mass could potentially be larger if the distribution is steeper than $q = 4$. Higher geometric albedos would decrease the mass estimate. With $p_R = 0.4$, for example, the mass given by Eq. (2) is reduced by a factor 30. The optical survey data thus suggest a mass within the 30 AU – 50 AU zone that is a few tenths of an Earth mass, but which is quite uncertain. The optical mass is smaller than the dynamical limit (~ 1 $M_{\oplus}$) set by Hamid et al. (1968), and far smaller than the mass expected by Kuiper (1951) based on an extrapolation of the surface mass density of the solar system. Significantly, the modern Kuiper Belt contains too little mass for KBOs to have grown in the $\sim 10^8$ yrs available prior to the disruptive emergence of Neptune (Stern and Colwell 1997; Kenyon and Luu 1998, 1999). If the observed KBOs formed *in situ*, then the original mass must have been 100 times the present mass. Scattering by Neptune (Holman and Wisdom 1993) appears incapable of clearing the Kuiper Belt, except in the region close to the planet. Self-destruction by collisional grinding has been suggested (Stern 1996) and partially modelled (Kenyon and Luu 1999). KBOs larger than ~ 100 km are largely immune to collisional disruption (Farinella and Davis 1996). The ground-based KBOs are thus likely to be true survivors from the earliest days of the solar system.

G.   Radial Extent of the Belt

Depletion of the Kuiper Belt by Neptune perturbations is largely restricted to the $30 \leq R \leq 42$ AU range (Holman and Wisdom 1993; Duncan et al. 1995), suggesting that the more distant parts of the Belt might be more densely populated than the region so far observed. Using an R^{-2} extrapolation of the surface mass density of the solar nebula, Stern (1996) has estimated that the density of the Kuiper Belt beyond 50 AU might be 100 times higher than in the $30 \leq R \leq 50$ AU annulus. On the other hand, it is not obvious that the Kuiper Belt necessarily extends to very large radii. An R^{-2} disk with a finite mass must be truncated at some definite outer radius, and several physical

processes are known which could provide an edge. Empirically, two of six protoplanetary disks seen in silhouette against the Orion Nebula have diameters $\leq$ 100 AU (McCaughrean and O'Dell 1996), and are thus comparable in scale to the known Kuiper Belt. These disks are thought to have been tidally truncated during close stellar encounters in an early, dense stellar environment.

The semimajor axes of the orbits of known KBOs span the range 35 AU to about 115 AU, while the heliocentric distances at which KBOs have been discovered are restricted to the more limited range 26 AU to about 50 AU. Clearly, observational selection discriminates against the discovery of distant objects because they are faint. However, detailed Monte Carlo simulations (Fig. 6) show that, with the parameters of our own Mauna Kea CCD surveys, we should expect to have discovered substantial numbers of classical KBOs beyond 50 AU, whereas none has yet been found (Dones 1997; JLT98). This result may be explained in several ways. First, the maximum object size (r_{max}) might be a decreasing function of semimajor axis. This would seem physically plausible as a consequence of lower surface density at larger distances, resulting in longer timescales for growth in the protoplanetary disk. However, the surface density in a R^{-2} disk at 45 AU (where we see many objects) is only 50% larger than at 55 AU (where we see none), and it is hard to imagine that r_{max} could be so sensitive to the local surface density. Second, the size distribution might be steeper than $q = 4$, so reducing the number of large objects visible beyond 50 AU (Gladman et al. 1998). Third, the Kuiper Belt surface density might decline faster than R^{-2} beyond the observed region. In fact, our data are consistent with a discrete outer edge to the classical belt at $a \sim 50$ AU, although we remain uncomfortable with this interpretation. Only the scattered KBOs occupy a volume that is clearly more extended than the known classical belt.

III.   Dust and the Relation to Circumstellar Disks

Collisions among KBOs generate dust. Unfortunately, in a $q = 4$ distribution the collisional cross-section is dominated by the smallest (optically invisible) KBOs, and the dust production rate is therefore difficult to assess with confidence. A crude upper limit, $\dot{M}_+ \sim 10^7$ kg s^{-1}, may be obtained by dividing the current mass of the Belt (~ 0.1 $M_\oplus$) by the 4.5 Gyr age of the solar system. A model-dependent lower limit

is set by erosion of KBOs by interstellar dust grains, with potential production rates estimated at $\dot{M}_- \sim 10^2$ to 10^4 kg s^{-1} (Yamamoto and Mukai 1998).

Surprisingly, Kuiper Belt dust may already have been detected. The Voyager 1 and 2 spacecraft recorded significant dust impact rates when beyond Neptune's orbit (Gurnett et al. 1997). The Voyager experimenters did not themselves cite the Kuiper Belt as the source of dust. However, in the absence of other identifiable sources in the trans-Neptunian region, this seems to us a plausible hypothesis.

The reported average number density of μm-sized grains is $N_1 = 2 \times 10^{-8}$ m^{-3} (Gurnett et al. 1997). The normal optical depth due to these grains is of order $\tau \sim N_1 Q_s \pi a^2 H$, where a is the grain radius, Q_s is the dimensionless scattering efficiency, and H is the vertical thickness of the Kuiper Belt. We take $Q_s \sim 1$, $a \sim 1\mu$m, and $H \sim 10$ AU to find $\tau \sim 10^{-7}$. This is much smaller than the optical depths of dust disks around other nearby main-sequence stars. For example, the β Pic and α Lyr dust disks have normal optical depths $\tau \sim 10^{-3}$ and $\tau \sim 10^{-5}$, respectively (Backman and Paresce 1993).

We take the average mass of a grain as $m_d \sim 2 \times 10^{-14}$ 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 $V \sim 2 \times 10^{38}$ m^3. The total mass of dust in micron-sized particles is then $M_d \sim m_d N_1 V \sim 8 \times 10^{16}$ kg (10^{-8} $M_\oplus$). With a $\tau_c \sim 10^6$ yr lifetime against collisional destruction (Jewitt and Luu 1997), the implied production rate in micron-sized particles is of order $M_d/\tau_c \sim 3 \times 10^3$ kg s^{-1}. This constitutes a realistic estimate provided the dust size distribution extends to particles no larger than those measured by the plasma wave analyzers, as would be the case for dust grains produced by the small interstellar dust impacts. It is intriguing to observe that the empirical dust production rate is within the range of estimates for interstellar erosion (Yamamoto and Mukai 1998).

On the other hand, if the dust is produced by collisional grinding among KBOs, the size distribution must extend to sizes much larger than those measured by Voyager, and the mass production rate should be corrected for the presence of larger but less abundant particles. The plasma wave analyser is sensitive to only a narrow range of particle sizes: impacts below the threshold mass 1.2×10^{-14} kg (corresponding

to particle radius 1.4 μm at unit density) do not excite measurable plasma waves (Gurnett et al. 1997) while substantially larger particles are too rare to be counted. We assume that the Voyager spacecraft detected particles in the radius range $1.4 \leq a \leq 10$ μm, and adopt a differential power law size distribution with index -3.5 (Dohnanyi 1969) in order to estimate the mass in larger particles. The mass and mass production rates must then be augmented by a factor

$$f = \frac{\int_{1.4}^{a_{max}} a^{-1/2}\mathrm{d}a}{\int_{1.4}^{10} a^{-1/2}\mathrm{d}a} \approx \frac{\sqrt{a_{max}}}{2} \qquad (3)$$

where $a_{max} >> 1.4$ μm is the maximum particle size expressed in μm. From Eq. (3) we find $f \sim 16$ for $a_{max} = 1$ mm, $f \sim 500$ for $a_{max} = 1$ m and $f \sim 1.6 \times 10^4$ for $a_{max} = 1$ km. The debris production rates therefore approach 5×10^4 kg s^{-1} for millimeter-sized particles, 1.5×10^5 kg s^{-1} for meter-sized particles and 5×10^7 kg s^{-1} for km-sized particles. Clearly, these values involve huge extrapolations from the Voyager dust detections and are highly uncertain. Nevertheless, they seem broadly compatible with our crude upper limit to the dust production rate, and with at least the lower estimates (10^6 kg s^{-1}) of Stern (1996).

Perhaps the principal unexplained feature of the Voyager data is that no impacts were detected beyond 51 AU for Voyager 1 and 33 AU for Voyager 2. If future detailed models of dust dynamics cannot explain this cut-off, then it is possible that the detected dust grains have another source. In this case, the above mass and mass production rates must be regarded as upper limits to the collisionally produced Kuiper Belt dust content.

The survival of a 42 cm-diameter fuel tank on the spacecraft Pioneer 10 during its 10-year flight through the Kuiper Belt (at relative velocity 12 km s^{-1}) sets an independent but less tightly constraining limit to the dust content of the Kuiper Belt (Anderson et al. 1998).

Three other opportunities exist for the detection of Kuiper Belt dust.

First, one might search for diffuse thermal emission from Kuiper Belt dust. From an observational point of view, the detection of diffuse Kuiper Belt dust is complicated by the foreground Zodiacal Cloud, as well as by the background due to galactic dust. Backman et al. (1995) used COBE observations at 140 μm and 240 μm wavelength to set an upper limit to the mass of Kuiper Belt dust $M_d < 10^{-5}M_{\oplus}$.

This limit, which is itself quite model-dependent, is compatible with $10^{-8} M_{\oplus}$ estimated above from the Voyager dust impacts.

Second, recent impacts in the Kuiper Belt should produce observable optical (Alcock and Hut 1993) and infrared (Stern 1996) dust signatures. Consider a body of initial radius a_0 that is pulverized by impact into particles of mean radius a. The resulting dust cloud will contain $(a_0/a)^3$ particles of combined geometric cross-section $C \sim a^2(a_0/a)^3$. The cloud will expand and brighten in reflected light until it reaches the critical radius $a_C = a \, (a_0/a)^{3/2}$, at which the optical depth is unity. This expansion takes a time $t = a_C/v$, where v is the mean speed of ejection of the dust. For example, with $a_0 = 1$ km, $a = 1$ μm and $v \sim 1$ km s^{-1} we find $C = 10^{15}$ m^2, $a_C = 3 \times 10^7$ m (corresponding to angular radius 1" at 40 AU distance) and $t \sim 1$ day. Such a debris cloud would reach peak apparent red magnitude ~ 7 on a timescale of 1 day and thereafter expand into a diffuse cloud of steadily decreasing surface brightness. After 100 days, the cloud would have angular diameter ~ 100", a mean surface brightness of order 17 mag. arcsec^{-2}, and would still be an easy observational target with 50 to 100 times the surface brightness of the moonless night sky. The timescale for radiation pressure to deflect particles in the expanding cloud is $t_{rp} \sim v/(\beta g)$, where $\beta \sim 1$ for micron-sized grains and $g = 4 \times 10^{-6}$ m s^{-2} is the solar gravity at 40 AU. We find $t_{rp} \sim 10$ yr, meaning that no perceptible radiation pressure swept tail would grow. The number of such spherical, expanding debris clouds visible at one time is highly uncertain. Estimates range from a few to many thousands (Alcock and Hut 1993; Stern 1996). No convincing examples have yet been reported.

Third, the Poynting-Robertson and plasma-drag forces may carry Kuiper Belt dust particles into the inner solar system, where direct samples might be found in existing interplanetary dust particle collections (Flynn 1996). The dust lifetime against collisional destruction by interstellar impacts ($\sim 10^6$ yr; Jewitt and Luu 1996) is short compared to the $\sim 10^7$ yr transport time (Liou et al. 1996) for particle sizes from $0.1 \leq a \leq 100$ μm. Therefore, most Kuiper Belt particles will be collisionally destroyed while en-route to the Earth. On the other hand, the rate of production of Zodiacal dust is only $\sim 10^4$ kg s^{-1} (Leinert et al. 1983), so that even small amounts of surviving Kuiper Belt debris might contribute measurably to the Zodiacal dust complex (c.f. Table 2).

Some nearby stars possess disks in which the dust lifetimes (to Poynting- Robertson drag and collisional shattering) are short compared to the stellar age (Smith and Terrile 1984, Jayawardhana et al. 1998, Koerner et al. 1998, Trilling and Brown 1998, Schneider et al. 1999). In these disks, dust might be generated by collisional grinding of larger, parent bodies, just as in the Kuiper Belt. Images of HR 4796A show a 70 AU radius, ring-like morphology that is highly suggestive of our own Kuiper Belt. The famous disk of β Pictoris extends to ~ 1000 AU. As mentioned above, the quantities of dust (estimated from the scattering optical depths) are 3 to 4 orders of magnitude larger than the dust content of the Kuiper Belt. It is tempting but conjectural to associate this difference with a collisionally more active phase in the lives of circumstellar debris rings. Future observations with sensitive ground- and space-based coronagraphs will presumably show that Kuiper Belts are common if not ubiquitous around other stars.

IV.   Relation to the Short-Period Comets and Centaurs

Objects that are dislodged from the Kuiper Belt as a result of intrinsic dynamical instabilities (Duncan et al. 1995) or mutual gravitational scattering (Ip and Fernandez 1997) eventually fall under the gravitational control of the gas giant planets. The prime candidates for these ex-KBOs are the "Centaurs", whose orbits intersect those of the gas giant planets and which are consequently highly chaotic and short-lived. Their eventual fate is (1) to be scattered close to the Sun, where they sublimate and are recorded as short-period comets, (2) to be scattered out of the solar system, or (3) to impact a planet or the sun. A useful practical definition is that the Centaurs are objects having both perihelion distance and semi-major axis between the orbits of Jupiter (5 AU) and Neptune (30 AU). By this definition, there are 11 known Centaurs (Table 3). Three (P/Schwassmann-Wachmann 1, P/Oterma and 2060 Chiron) display comae at least part of the time indicating their volatile-rich cometary nature (P/Schwassmann-Wachmann 1 is a prodigious source of carbon monoxide, indicating formation at temperature $< 50K$, Senay and Jewitt 1994). The remaining six have been stellar in appearance in all observations to date, but presumably contain buried ice. The Centaurs are important because they provide the dynamical link between the KBOs and the short-period comets and, on

the more practical side, they are much closer (brighter) than the typical KBOs, and therefore make much easier targets for physical study.

The populations of Kuiper Belt Objects, Centaurs and short-period comets should be in the approximate ratio $n_{KBO} : n_C : n_{SPC} \sim t_{KBO} : t_C : t_{SPC}$. Here, $t_{KBO} \sim 10^{10}$ yr, $t_C \sim 10^6$ to 10^7 yr (Asher and Steel 1993; Hahn and Bailey 1990; Dones et al. 1997; Levison and Duncan 1997) and $t_{SPC} \sim 10^5$ yr (Levison and Duncan 1994) are the respective dynamical lifetimes. With 10^5 KBOs larger than 100 km in diameter, we would expect to find $n_{KBO} : n_C : n_{SPC} \sim 10^5 : (10^2 - 10^1) : 1$. Currently, only 3 Centaurs with diameters > 100 km are known (1997 CU_{26}, Chiron and Pholus; Table 3) compared with 10 to 100 expected. The majority of such objects should be located just interior to Neptune (Levison and Duncan 1997) and sky surveys sensitive to these objects are far from complete (the most telling evidence of incompleteness is that the largest Centaur, 1997 CU_{26}, is also one of the most recently discovered). There is presently no short-period comet with diameter near 100 km.

V. Physical Properties

A. Albedos

The apparent optical brightness of a body viewed in reflected sunlight is proportional to the product of the geometric albedo with the cross-section, and given by

$$p_R r^2 \phi(\alpha) = 2.25 \times 10^{22} R^2 \Delta^2 10^{0.4(m_\odot - m_R)} \tag{4}$$

Here, p_R is the geometric albedo, α is the phase (Earth-object-Sun) angle, the heliocentric and geocentric distances, R and Δ, are expressed in AU, while $m_\odot$ and m_R are the apparent magnitudes of the sun and Kuiper Belt object, respectively. In Eq. (4) $\phi(\alpha)$ is a phase function that describes the angular dependence of the scattered light, reasonably approximated by $\phi(\alpha) = 10^{-0.04\alpha}$. At the small phase angles attained by KBOs ($\alpha < 2°$), $\phi(\alpha) = 1$ provides a good first approximation.

The thermal flux density is given by

$$S_\nu = \frac{\epsilon_\nu B_\nu(T) \pi r^2}{\Delta^2} \tag{5}$$

where ϵ_ν is the emissivity, and $B_\nu(T)$ [W m^{-2} sr^{-1} Hz^{-1}] is the Planck function. The effective surface temperature T[K], is a complicated function of the emissivity, Bond albedo and thermal diffusivity of the body, as well as of the heliocentric distance and rotation vector (Spencer et al. 1989). Eqs. (4) and (5) contain too many unknowns to allow a unique solution for radius or albedo. Nevertheless, measurements of main-belt asteroids have shown that useful estimates for radius and albedo may be obtained from Eqs. (4) and (5) using judiciously assumed values of the unknown parameters.

In the case of the KBOs, thermal emission has yet to be detected, and the albedos remain unknown. At $T \sim 50$ K, the Planck maximum falls near 60μm, a wavelength which is inaccessible from the ground. Marginal ($\leq 3\sigma$) detections of 1993 SC and 1996 TL$_{66}$ obtained using the ISO satellite imply low (few percent) albedos (Nick Thomas, private communication). Future orbiting infrared satellites (e.g., SIRTF) may be able to detect thermal radiation from KBOs with greater significance. Rayleigh-Jeans emission (800 μm wavelength) may also be detected using submillimeter detectors on ground based interferometers (such as the Submillimeter Array nearing completion on Mauna Kea).

In principle, occultations of background stars might be used to determine the sizes of KBOs (c.f. Bailey 1976). Optical observations would then give the albedos directly, through Eq. (4). Astrometry of KBOs is presently good at the ± 0.3" level, while the largest angular diameters subtended by KBOs are of order 0.02" (for 1996 TO$_{66}$). Consequently, meaningful predictions of occultations by KBOs cannot yet be made and, to date, no occultation observation has been attempted. The Taiwanese-American Occultation Survey (TAOS) experiment should detect occultations by previously unseen KBOs within the next 5 years. However, most of these objects will be so small that optical detections will be impossible, and the albedos will remain unmeasured.

All KBO diameters reported in the literature have been derived under the assumption of a red geometric albedo $p_R = 0.04$. This is not unreasonable, given that both short-period comets and Centaurs probably originated in the Kuiper Belt, and these objects have red geometric albedos mostly in the range $0.02 \leq p_R \leq 0.05$. The existence of a wide diversity of colors (Luu and Jewitt 1996; Jewitt and Luu 1998; Tegler and Romanishin 1998) suggests that different KBOs very

possibly could have different albedos. On the other hand, the extreme color differences between Centaurs 2060 Chiron, 5145 Pholus and 1997 CU_{26} are not matched by a wide range in the measured albedos (0.14 +0.06/-0.03, 0.044 ± 0.013 and 0.045 ± 0.010, respectively; Jewitt and Kalas 1998).

B. Colors

Most KBOs are too faint for spectroscopy and observers have resorted to broadband colors as low-resolution (but higher in signal-to-noise) substitutes. Optical colors for $\sim$ 20 KBOs are now available (Luu and Jewitt 1996; Green et al. 1997; Tegler and Romanishin 1998), as well as near-infrared colors for a handful of KBOs (Jewitt and Luu 1998). The B-V vs. V-R colors are plotted in Fig. 7a, while V-R vs. R-I colors are plotted in Fig. 7b.

Surprisingly, the KBOs (Luu and Jewitt 1996; Green et al. 1997; Jewitt and Luu 1998) and Centaurs (Romanishin et al. 1997; Davies et al. 1998) exhibit a wide spread of colors, ranging from nearly neutral to very red (Fig. 7a). Tegler and Romanishin (1998) confirm this diversity of KBO colors but further report that the B-V and V-R colors of KBOs and Centaurs are bimodally distributed (Fig. 7b), suggesting the existence of two distinct surface types. The optical-infrared V-J index varies widely among KBOs, but is not obviously bimodal (Jewitt and Luu 1998). A statistically significant (3 σ) but unexpected and unexplained correlation between the absolute red magnitude and V-J has also been reported (Jewitt and Luu 1998).

Fig. 7 shows that the KBOs and Centaurs are indistinguishable in broadband color-color plots, consistent with a common origin. However, their color distributions are unmatched by those of comet nuclei and asteroids (Fig. 8), thanks to some extremely red KBO and Centaur surface materials (V-R > 0.6) that seem to be rare or absent among comets and asteroids. The absence of extremely red material on the cometary nuclei is consistent with progressive destruction, or burial, of irradiation mantle formed in the Kuiper Belt (c.f. Cruikshank et al. 1998), but might also be an observational artifact, since few nuclei have yet been measured.

Laboratory experiments suggest that KBOs might be covered by "irradiation mantles," produced by high energy particle irradiation of surface ices. When carbon-containing ices (e.g., methane or CO) are irradiated by high energy particles (cosmic rays and UV photons), this

irradiation leads to the selective loss of hydrogen while encouraging the formation of complex carbon compounds (e.g., see Moroz et al. 1998 and references therein). The result is a solid residue (having a column density of $\sim 10^3 kg m^{-2}$, corresponding to a thickness $\sim 1m$ in solid ice) that is dark due to its complex carbon compounds. Exactly how the color and albedo change with time depends on the initial composition and the irradiation fluence (Moroz et al. 1998). The composition of the mantle is quite different from the interior, which retains pristine ice. The mantle thickness and strength are uncertain, but may be sufficient to survive upon the object's first entry into the inner solar system.

C. Spectra

Wilson et al. (1994) were able to fit the optical spectrum of Centaur 5145 Pholus with "Titan tholins," chemically complex hydrocarbon mixtures produced by UV irradiation of simple ices. Cruikshank et al. (1998) obtained a fit for both the optical and near-infrared spectra of Pholus with a model consisting of carbon black (61.5%) and an intimate mixture (38.5%) of olivine, Titan tholin, H_2O ice, and CH_3OH ice (Fig. 9). Water ice has been reported on Centaur 1997 CU_{26} (Brown et al. 1998; Brown and Koresco 1998) although its surface is very dark ($p_R = 0.045 \pm 0.010$; Jewitt and Kalas 1998). On the other hand, 2060 Chiron is spectrally bland (Luu et al. 1994). Spectral fitting models are non-unique, but there is consensus that organics of some type are present on the surface of Pholus, while the identification of water on CU_{26} also appears secure. Color diversity among the KBOs is thus matched by spectral and compositional diversity among the Centaurs.

Spectra of only three KBOs have been reported. The smoothed reflectance spectrum of 1993 SC (Brown et al. 1997) shows prominent absorptions that have been qualitatively interpreted as hydrocarbon features (Fig. 10). In contrast, the spectrum of 1996 TL_{66} is neutral, with no apparent absorption features (Luu and Jewitt 1998). The spectrum of 1996 TO66 shows absorptions at 1.5 and 2.0 μm indicative of water ice. The differences among the KBOs are intriguing, but it would be premature to attempt an interpretation. Spectra of higher quality are urgently needed in order to make progress in this field.

D. Origin of Color Diversity

The diversity of the colors is a surprise in the sense that all KBOs should be exposed to cosmic rays and thus should have irradiation man-

tles with similar colors. Three simple explanations have been suggested for the origin of the color diversity (Luu and Jewitt 1996). Firstly, it is possible that the KBOs possess intrinsically different compositions, and that the different colors are tracers of compositional variations. For example, asteroids in the Mars-Jupiter belt show different compositions that seem to be related to their sites and temperatures of formation. However, the KBOs probably formed in-situ, in the presence of a very slight radial temperature gradient ($T \propto R^{-1/2}$). Temperature differences across the 35 to 50 AU zone likely amounted to only ~ 10 K. It is hard to see how strong compositional differences might arise from such small differences in the formation temperature. A second explanation is that occasional collisions in the Kuiper Belt puncture the irradiation mantles on some objects, excavating craters, and showering nearby regions with impact debris. The freshly excavated material would be unirradiated, and thus should be of a different composition (more ice-rich, less red?) than the irradiated mantle. This mechanism requires that the timescales for resurfacing and for radiation damage of the surface layers are comparable, to avoid saturation of the color at one or the other extreme. One testable prediction of the resurfacing hypothesis is that KBOs should show rotational modulation of albedo and color, corresponding to local blanketing by excavated debris. Another is that albedo and color should be closely related. The bimodal color distribution of KBOs (Tegler and Romanishin 1998), if independently confirmed, would seem to rule out impact resurfacing as an explanation for the color diversity. Thirdly, Moroz et al. (1998) have observed that the color of light reflected from laboratory bitumen samples is a function of the effective particle size in the scattering surface.

E. Structure

The observed few-hundred km diameter KBOs have thermal diffusion times ($\tau \sim r^2/\kappa$, where $r[m]$ is radius and κ $[m^2 s^{-1}]$ is thermal diffusivity) comparable to or longer than the age of the solar system. Energy liberated in these bodies by the decay of radioactive elements is trapped and must contribute to an increase in the central temperature of magnitude

$$\Delta T \sim H r^2/(\kappa c_p) \qquad (5)$$

where $H[W kg^{-1}]$ is the power production per unit mass due to ra-

dioactivity and c_p $[Jkg^{-1}K^{-1}]$ is the specific heat capacity of the bulk material. With $H \sim 10^{-12}Wkg^{-1}$ (the heating rate measured for carbonaceous chondrite material, diluted by a factor of 4 to account for the presence of substantial ice), $\kappa \sim (1$ to $10) \times 10^{-7} m^2 s^{-1}$ and $c_p \sim 10^3 Jkg^{-1}K^{-1}$, we estimate $\Delta T[K] \sim (10$ to $100)(r/100[km])^2$. Objects of a few 100 km radius may experience internal heating sufficient to mobilise interior volatiles, giving rise to a compositionally layered structure in the KBOs. This, in turn, would complicate our understanding of the compositional significance of short-period comets, if these are indeed collisional fragments from the upper layers of 100 km scale KBO parents. One might even expect that the larger KBOs should be predisposed to out-gas their super-volatiles (CO, N_2), giving rise to surface frosts and systematic variations in albedo and surface color with radius. The limiting case, Pluto, has long been known to sport a high albedo, patchily frosted surface that is probably not typical of the smaller KBOs. Outgassing due to mobilization of internal volatiles might be responsible for some of the color and spectral variation observed amongst the KBOs.

VI. Major Questions

We end with ten leading questions about the Kuiper Belt.

1) What is the size distribution of KBOs at the smallest (< 50 km) and largest (> 500 km) scales? Are the size distributions of the classical, resonant and scattered object sub-classes equal? Is there observational evidence for a cut-off in the size distribution at large radii? Is Pluto unique?

2) What are the albedos of KBOs? Is there an albedo-color relation as expected from collisional resurfacing?

3) What is the origin of the spectral diversity exhibited by the KBOs? Are the optical colors bimodal? Are the colors compositionally diagnostic or indicative of other effects (e.g. particle size variations)?

4) Can compelling evidence be found for compositional differences between the Kuiper Belt (short-period) and Oort Cloud (long-period) comets? Different temperatures in the source zones of the long-period comets (5 - 20 AU) and the short-period comets (30 - 40 AU) should, for example, lead to major variations in the abundances of super-volatiles

(e.g. N_2, CO) between the two groups, yet no such differences have been reported.

5) Are small (1 to 10 km) KBOs present in numbers sufficient to supply short-period comets to the inner solar system for 4.5 Gyr? If the comets originate in the Kuiper Belt, precisely where (in chaotic zones associated with resonances, among the scattered objects, or elsewhere)?

6) Was the ancient Kuiper Belt much more massive than the present-day Kuiper Belt and, if so, how was the original mass depleted? What, if anything, can the cratering rates on the outer planet satellites tell us about the time dependence of the Kuiper Belt mass? Was the early Kuiper Belt massive enough to collisionally produce dust in quantities sufficient to rival the dust rings circling some nearby, main-sequence stars (e.g. β Pic)?

7) How common is binarity in the Kuiper Belt? Presently, only Pluto is known to hold a satellite. If Charon's presence indicates a once more active collisional regime, then it is reasonable to suppose that other KBO binaries await discovery.

8) What are the relative populations in the mean-motion resonances and what do these tell us about the population mechanism (c.f. Malhotra 1995, 1996)?

9) What processes were responsible for the excitation of the velocity dispersion in the Classical Kuiper Belt?

10) What role has been played by collisions in shaping the present-day Kuiper Belt? Are the nuclei of short-period comets the collision fragments of larger bodies (c.f. Farinella and Davis 1996)?

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FIGURE CAPTIONS

Figure 1. Plan view of the Kuiper Belt showing the orbits of the Kuiper Belt objects known as of June 1999. Orbits of Jupiter (J) and Neptune (N) are marked, as are the first four scattered KBOs. The majority of the KBOs follow orbits in the 30 to 50 AU radius band. The region shown is 260 AU x 340 AU. Figure prepared by Chad Trujillo, University of Hawaii.

Figure 2. Semimajor axis versus eccentricity for Kuiper Belt Objects. Filled circles denote multi-opposition orbits. Empty circles denote orbits computed from astrometry taken within a single opposition. Pluto is marked by X. Neptune is at $(a,e) = (30,0)$. The dashed lines mark $q = 30$ AU and $q = 35$ AU. Objects above the upper line are Neptune-crossers. Scattered Kuiper Belt Object 1996 TL$_{66}$ ($a,e = 85$ AU, 0.59) is off scale and not plotted. Vertical lines mark the locations of mean-motion resonances.

Figure 3. Same as Figure 2 but on a larger scale to show the scattered Kuiper Belt Objects. All four scattered KBOs fall along the perihelion distance q = 30 AU line.

Figure 4. Luminosity function of the Kuiper Belt excluding photographic surveys. The lines show fits to the data from Luu and Jewitt (1998) and Gladman et al. (1998), discussed in the text. Chiang and Brown (1999) report a CLF close to that of Luu and Jewitt.

Figure 5. Histogram of inclinations of Kuiper Belt Objects, plotted with a 5 degree bin size. The Plutinos and Classical KBOs are shown separately. Only multi-opposition orbits have been used in the histogram. The two populations have similar mean inclinations. However, the Plutinos are deficient in both high ($i > 20deg$) and low ($i < 5deg$) inclination orbits relative to the Classical objects.

Figure 6. Heliocentric distance at discovery vs. apparent red magnitude. Solid circles mark objects found in the 8k survey (JLT98, from which this figure is taken). Crosses denote simulated objects that passed the survey detection criteria. The classical Kuiper Belt is taken to extend to maximum semi-major axis $a_{max} = 200$ AU. The KBOs obey a power law size distribution with index $q = 4.0$, and all have albedo $p_R = 0.04$. Plutinos have been included in proportions needed to yield an apparent Plutino fraction $P_a \approx 0.35$. The radial density index in the classical Kuiper Belt is taken to be $p = 2$ in both models and, in the particular simulation shown here we have chosen $r_{max} = 500$ km. Diagonal lines show the apparent magnitude as a function of heliocentric distance for KBO radii 50, 100, 200 and 400 km.

Figure 7. (a). B-V color plotted against V-R color for KBOs (filled circles) and Centaurs (empty circles). The color of the Sun is marked. Error bars are 1 σ. Data from Luu and Jewitt 1996 (b). Same as (a) but showing data from Tegler and Romanishin 1998. Note that many objects are common to both panels.

Figure 8. Histograms of the V-R color index computed for five different dynamical classes of object. KBOs and Centaurs share a common, large color range. The nuclei of comets and the Jovian Trojans display a smaller

color dispersion and seem to lack the extremely red material present on some KBOs and Centaurs. The Near Earth Objects, included here only for reference, are comparatively blue, and quite distinct from the other classes. Figure modified from Luu and Jewitt 1996.

Figure 9.   Composite optical and near-infrared spectrum of Centaur 5145 Pholus. The model is an intimate mixture of olivine (to provide absorption near 1.5μm), Titan tholin (the red optical slope), water ice (the 2μm absorption), methanol ice (the 2.27μm absorption), and carbon black (Cruikshank et al. 1998).

Figure 10.   Optical - infrared reflectance spectra of 1993 SC and 1996 TL_{66}. The 1993 SC spectrum has been smoothed to a resolution 0.08μm (by Brown et al. 1997). The 1996 TL_{66} spectrum is shown unsmoothed (Luu and Jewitt 1998) and is featureless, ruling out a surface of pure water ice. The spectra have been vertically displaced for clarity.