FROM KUIPER BELT OBJECT TO COMETARY NUCLEUS

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ABSTRACT

We now realise that many small body populations are related through a common origin in the Kuiper Belt, notably the Centaurs, the Jupiter Family Comets and certain dead-comets. But does primitive material from the Kuiper Belt survive the journey to the inner solar system and can we learn anything about it by studying the comets? We discuss observational evidence and other considerations that relate to this question.

1. GENERAL SPECIFICATIONS

In this paper I want to discuss the evidence for physical relations between Kuiper Belt Objects (KBOs) and comets, in the context of the largely accepted dynamical flow-down of objects from the Kuiper Belt to the inner solar system. This new picture, stemming from a conjecture by Julio Fernandez (1980) and made real by the discovery of the Kuiper Belt in the 1990's, has revolutionised our view of the comets. Before the Kuiper Belt, the nuclei of comets were seen as pristine relics from the accretion disk of the sun. Perhaps they could even be identified directly with the first generation planetesimals (Goldreich and Ward 1973) or at least with loosely bonded aggregates of these planetesimals (Weidenschilling 1997). Now, though, the Jupiter- Family Comets, at least, seem to be escaped collisional fragments produced by $\Delta V \sim 1.5$ km/s collisions between parent bodies in the Kuiper Belt. They could be shocked, and they might carry interesting signatures of collisional and thermal processing from their larger parent bodies. Even after their collisional creation beyond Neptune, the cometary nuclei should be modified as they are scattered by the planets on their way towards eventual detection in the inner solar system. So, interesting questions include "how are objects modified as they make the journey from Kuiper Belt to the region of the inner planets?" and "what are the observational constraints on any such modification?". The answers to these questions are important in the context of well-developed plans to examine the comets up-close via spacecraft. To what extent can we use the results from missions such as Stardust, Deep Impact and Rosetta to understand fundamental properties of the Kuiper Belt Objects? Will we, in fact, measure only heavily processed remnants of the nucleus source population?

In keeping with the flavor of the ACM2002 meeting in Berlin, I will attempt an overview that is "sweeping" in style and will avoid belaboring the text by trying to include full citations to all the related work in the literature. I will, however, try to call attention to other talks and presentations from ACM that are clearly connected to the subject of this overview (these will be listed in the form **Author ACM2002**). In this way, I hope to emphasize broad connections between the A, C and M parts of the subject.

2. KUIPER BELT

The Kuiper Belt is the subject of a number of recent reviews, and so need not be discussed in detail here (see Jewitt 1999, Luu and Jewitt 2002, Schulz 2002). Suffice it to say that there are about 70,000 KBOs larger than 100 km diameter in the observable region of the Kuiper Belt. Extrapolated to kilometer scales, there may be 1 to 10 billion objects with a combined mass of a few tenths of an Earth mass (Jewitt et al. 1998, Trujillo et al. 2001). These seem to be the surviving members of a population that was once ~100 times larger than now.

The Belt contains at least three distinct dynamical regimes and, while there is general agreement that the Kuiper Belt is a source of comets to the inner solar system, there is no concensus about which regime supplies the most comets. The resonant KBOs, which account for a few to 10 percent of the Kuiper belt population by number, have orbit periods in simple ratios of integers to that of Neptune. Most are in the 3:2 resonance at 39 AU and are known as Plutinos, to honor Pluto which is also trapped at this location. Chaotic zones at the boundaries of the resonances are one plausible source of the comets. Collisional fragments from nearby parent bodies could be injected into the chaotic zones and it has also been suggested that Pluto might scatter other Plutinos into unstable orbits (Yu and Tremaine 1999). Their orbital eccentricities would then be excited until the perihelion dropped to ~30 AU, allowing involvement with and prompt scattering by Neptune.

The Scattered KBOs occupy a thick torus with an inner edge near 35 - 40 AU and extending out to distances of at least many 100's of AU. These objects are so-called because of their weak perihelic involvement with Neptune and the likelihood that they have been progressively scattered out by that planet into their present orbits on timescales of order 1 Gyr. The Scattered KBOs may constitute a separate source of cometary nuclei (Duncan and Levison 1997), if the population is large enough. While very uncertain, the number of Scattered KBOs has been estimated from observations as 3×10^4 (Trujillo et al. 2000). There is evidence that some KBOs have perihelion distances too large to permit substantial interaction with Neptune on timescales of the solar system age (Gladman et al. 2002, **Emel'yanenko ACM2002**). These objects may vastly outnumber the known Kuiper Belt Objects but they constitute an unlikely source of comets in the absence of an agent to make these bodies Neptune-crossing. (This is not to say that no such agent exists: it is possible that massive scatterers in the outer Belt, even undetected planets, could inject bodies to Neptune-crossing orbits at a rate sufficient to supply the Jupiter-Family comets).

The majority of the known KBOs belong to the third, 'Classical', group (population ~ 40,000 larger than 100 km diameter), with nearly circular orbits of small inclination ($i \sim 0.1$ rad) and semimajor axes $42 \leq a \leq 47$ AU. These Neptune-avoiding orbits are stable on long timescales, so that the Classicals are not a likely source of comets.

3 CENTAURS

Objects scattered out of the Kuiper Belt and whose dynamics are controlled by strong scattering by the major planets are known as Centaurs. Unfortunately, there is no universal accepted definition of the Centaurs, with confusion arising on two levels. First, Jewitt and Kalas (1998) define objects with q => 5 AU and a <= 30 AU (corresponding to the orbits of Jupiter and Neptune, respectively) as Centaurs. Such objects, unless stabilised in resonances like the 1:1 Jovian Trojans, are guaranteed to be short-lived to gas giant planet encounters. A more liberal definition that is sometimes used is that a Centaur is any object with 5 <= q <= 30 AU, regardless of the semimajor axis. This definition seems unsatisfactory to me, in that it includes Pluto (q = 26 AU) and many of the Plutinos as Centaurs.

A second source of confusion is based on physical attributes. It seems to be widely accepted that some Centaurs (e.g. 2060 Chiron) show coma and can also be labelled "comets". On the other hand, some comets that meet plausible dynamical definitions of Centaurs (e.g. P/SW1 q = 5.7 AU, a = 6.0 AU) are traditionally and inexplicably regarded differently from Centaurs. Another object, C/2001 T4, is both cometary and a Centaur (q = 8.6, a = 13.9 AU). Given that the definition of "Centaur" is dynamical, there is no basis for excluding objects based on the presence of absence of coma.

Some 58 Centaurs (defined by $5 < q < 30$ AU) are known (as of 2002 August 20). Of these, about half have $q > 5$ AU AND $a < 30$ AU, meaning that they have completely decoupled from the Kuiper Belt. Extrapolated down to kilometer radius scales, the number of Centaurs is of order 10 million, while the number that are larger than 50 km in radius is of order 100 (Sheppard et al. 2000). The number of Centaurs reflects the relatively short lifetime of these bodies to ejection by the gas giant planets, variously estimated as 1 to 100 Myr (Dones et al. 1995). Some Centaurs are removed by striking the planets or, more rarely, their satellites. About half are ejected from the solar system, principally by Jupiter. The remainder are injected into orbits that cross the paths of the terrestrial planets. Those that develop comae due to thermally induced outgassing are relabelled "comets".

4 COMETS AND DEAD COMETS

Comets whose motion is strongly controlled by Jupiter are known as Jupiter Family Comets (the formal definition, which for our purposes is little more than a distraction, is that comets with Tisserand Invariants $2 \leq T < 3$ are Jupiter Family Comets). About 200 JFCs are known and lifetime considerations suggest that they are supplied to the inner solar system at a rate of order 1 per 1000 yrs (from the Kuiper Belt). The sentiment is often expressed in the literature and at meetings that the population of JFCs is observationally well established. My view, given that cometary activity may cycle on and off as surface mantles grow and are disrupted, is that such optimism is unfounded and that future, deep all-sky surveys like Pan-Starrs (**Tholen ACM2002**) are needed to reliably assess the population.

Dead (or dormant) comets are observationally difficult to identify, since they look just like asteroids. Some likely dead comets are revealed by their comet-like dynamical characteristics (an opposite example is provided by comet 133P/Elst-Pizarro, also known as asteroid 7968, which has a typical asteroidal orbit). Perhaps 10% of the near-Earth objects are dead comets.

5 BASIS FOR COMPARISON

We possess measurements of rotation, size, shape, density, color, albedo and their corresponding distributions for samples of KBOs, Centaurs, JFCs and candidate dead comets. In most cases, the samples are limited in size but they nevertheless form the main basis for comparison of the different stages of dynamical evolution from the Kuiper Belt to the inner solar system.

6 TIMESCALES

The processes of modification can best be appreciated in terms of a few relevant timescales (Jewitt 1996):

The dynamical lifetimes of orbits in the Kuiper belt are comparable to or longer than the 4.5 Gyr age of the solar system. We adopt

$$\tau_{KB} = 10^9 \text{ to } 10^{10} \text{ yr.}$$

The dynamical lifetime of Centaurs, which provides a measure of the timescale for transport from the Kuiper Belt to the inner solar system is of order (Dones et al. 1996)

$$\tau_C = 10^7 \text{ yr.}$$

Once trapped as a JFC, the median dynamical lifetime to scattering by the terrestrial planets is (Levison and Duncan 1994)

$$\tau_{JFC} = 4 \times 10^5 \text{ yr.}$$

Finally, the timescale for heat to conduct across the radius of a cometary nucleus is of order

$$\tau = r^2/\kappa$$

where κ [m^2 s^{-1}] is the thermal diffusivity of the material, given by $\kappa = k/(\rho\, c_p)$, where k, ρ and c_p are the conductivity, density and specific heat capacity of the bulk material of the nucleus. With nominal values $k = 0.1$ W m^{-1} K^{-1}, $\rho = 1000$ kg m^{-3} and $c_p = 1000$ J kg^{-1} K^{-1}, and expressing the radius in kilometers we have

$$\tau = 3 \times 10^5 r^2 \text{ yr.}$$

We note that

- $\tau = \tau_{KB}$ for $r \sim 100$ km

meaning that bodies smaller than 100 km in scale (i.e. essentially all the known comets) have conductively lost thermal memory of their formation epoch.

- $\tau > \tau_C$ for $r > 5$ km

- $\tau > \tau_{JFC}$ for $r > 1$ km

Therefore, the known Centaurs (all of which are much larger than 5 km in size) and many well-measured cometary nuclei are perpetually far out of internal thermal equilibrium. They can retain trapped volatiles even when their surfaces are strongly heated by the sun. If this were not true, comets arriving in the inner solar system would be largely depleted of volatiles.

Comets and some centaurs lose mass by sublimation in response to solar heating. The timescale for the depletion of mass, at total mass loss rate dM/dt, is

$$\tau_{sub} = \rho\, r^3/(dM/dt)$$

In real comets, mass loss is limited to active areas or vents that occupy only a small fraction of the surface area. The sublimation lifetime may then be written

$$\tau_{sub} = \rho\, r/(f\, dm/dt)$$

in which dm/dt is the mass loss rate per unit area [kg m^{-2} s^{-1}] and f is the "active fraction", defined as the fraction of the surface area from which sublimation actively proceeds. Calculating dm/dt from thermal equilibrium sublimation and substituting plausible values for the parameters we obtain

$$\tau_{sub} = 10^4 (0.01/f)(r/1\text{km}) \text{ yr.}$$

Comparing, we note that (with f = 0.01)

$$\tau_{sub} = \tau_{JFC} \text{ for } r \sim 40 \text{ km.}$$

This means that JFCs smaller than 40 km should, if in equilibrium sublimation with sunlight, lose all their volatiles before their dynamical evolution is complete. We conclude that the comets die either by losing all their volatiles, ending up as wholly refractory, asteroidal appearing bodies moving in comet-like orbits, or by growing a mantle that seals the interior from volatile escape (producing dormant objects, having asteroidal appearance but volatile-rich interiors). While dead comets have long been suspected among the near Earth object population, hard evidence for their abundance has been scant. Albedo measurements (Fernandez et al. 2001) are compatible with a fraction near 10%, as are the most up-to-date dynamical models (Bottke et al. 2002).

As a nucleus loses mass, its shape may also evolve due to anisotropic losses. Therefore, τ_{sub} is also the timescale for the evolution of shape of the nucleus.

Non-central outgassing forces can torque the spin of the nucleus, leading to precession and a change in the scalar angular momentum of the body. The relevant timescale for spin excitation is

$$\tau_{ex} = \left(\frac{\omega \rho r^4}{V_{th} k_T dM / dt} \right)$$

where ω is the spin angular velocity, V_{th} is the thermal velocity of the outgassed matter, k_T is a dimensionless constant representing the moment arm of the torque ($k_T \sim 0.05$; Jewitt 1999) and the other symbols are as defined earlier.

Opposing the excitation is a damping force caused by periodic internal flexture of any body in non-principal axis rotation. The damping timescale is (Burns and Safronov 1973)

$$\tau_{damp} = \mu Q/(\rho K_3^2 r^2 \omega^3)$$

in which μ, Q and K_3^2 are physical properties related to energy dissipation under periodic stress. The canonical values give $\mu Q/K_3^2 \sim 1.5 \times 10^{13}$ N m^{-2}. For a nominal rotation period P = 10 hrs and with r expressed in km, we obtain $\tau_{damp} = 10^8 \ r^{-2}$ [yr].

For bodies that are r < 100 km (i.e. practically all the JFCs) we have

$$\tau_{ex} < \tau_C \text{ and } \tau_{ex} < \tau_{damp}.$$

Therefore, we should expect the nuclei of comets to be in excited rotational states. Evidence that this is so is limited mainly to the nucleus of comet 1P/Halley with suggestive recent reports concerning 2P/Encke. In this instance, I think that absence of evidence is not evidence of absence: it is observationally quite difficult to obtain enough lightcurve data to establish complex rotation. There is an urgent need for more and better observational data on the rotation states of comets.

Lastly, we note that unfettered outgassing torques will drive cometary nuclei towards rotational breakup, this happening at the critical period

$$\tau_r = B(3\pi/G\rho)^{1/2}$$

where B is a shape dependent parameter of order unity (B = 1 for a sphere). This period, of order a few hours, is approached by some small bodies: only monolithic asteroids are known to rotate substantially faster (**Whiteley ACM2002**). Comets indeed split, sometimes tidally (as in the famous case of D/Shoemaker-Levy 9) but sometimes without apparent external perturbation, like recently observed 57P/duToit-Neujmin-Delporte (Figure 1). Perhaps these events are caused by rotational instabilities?

FIGURE 1: Split comet 57P/duToit-Neujmin-Delporte (20 components) imaged UT 2002 July 18, from the University of Hawaii 2.2-m telescope. From Fernandez et al. IAUC 7935.

The size distribution of the KBOs has been measured from the slope of the cumulative luminosity function of these objects (i.e. the cumulative number of objects per square degree of sky, as a function of the apparent magnitude). Different researchers have converged on a power-law type distribution, in which the number of objects with radius in the range r to r+dr is

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

with Γ and q being constants. The best fit value for KBOs is $q = 4.0^{+0.5}_{-0.6}$ (Trujillo et al. 2001). In such a distribution, the mass is spread uniformly in equal logarithmic intervals of radius while the cross-section is dominated by the smallest objects in the distribution.

The Centaurs are, by and large, less well observed than the KBOs. The available data are compatible with $q = 4.0 \pm 0.5$ (Sheppard et al. 2000). This is identical to the value in the Kuiper Belt, as expected if the latter is the source of the Centaurs.

The size distribution of the cometary nuclei has been estimated by Fernandez et al. (1999) based on spatially resolved photometry of active comets. They find $q = 3.6^{+0.3}_{-0.2}$. The same technique used independently by **Weissman and Lowry ACM2002** gives $q = 2.6 \pm 0.03$. The two results are inconsistent at the 5σ level of significance. To understand this, it is important to remember that the cometary nuclei are in general not observed free from the effects of coma. Coma contamination of the nucleus photometric signal may confuse the results obtained by one or (most likely) both of these groups. Furthermore, the short-period comets which form their samples have been discovered by a variety of techniques, each of which must impress onto the sample its own distinction discovery bias. Naively, I expect this bias to favor cometary nuclei with large active areas. It is not obvious that there is a tight correlation between active area and nucleus radius. In any event, whatever the discovery biases are, they are not taken into account in the reports by Fernandez et al or Weissman and Lowry. My opinion is that the cometary nucleus size distributions are essentially undetermined at the present time.

What should we expect? Sublimation lifetimes of otherwise equal bodies vary in proportion to the radius (see above). Thus, in steady state, we expect that a source population with index q should be flattened by sublimation to q-1, as a result of the preferential loss of the smaller objects. With q = 4 in the Kuiper Belt, we expect q = 3 among the JFCs. Cometary splitting acts in the opposite sense, by creating many small nucleus fragments from a larger precursor. Observations show that splitting is frequent (1 event per 100 years amongst the JFCs) but the size distribution of the fragments has not been determined, so the effect on the population distribution is unquantifiable. It should be noted also that the sizes of the measured KBOs and comets are quite different. The KBOs are larger than 100 km diameter while most comets are an order of magnitude smaller. This size difference allows the possibility that the size distributions might differ because of a size gradient, instead of an evolutionary effect.

Is there any hope for measuring this quantity another way? The size distribution of the impact craters on the surfaces of the satellites of outer planets should in principle, through a crater scaling model, provide an estimate that is free of the bias effects mentioned above. Published results are indeed compatible with q = 3, but with a large error bar that encompasses the other values discussed above. On the other hand, Al **Harris ACM2002** presented evidence that crater counts on the Moon provide an implausible value of the size distribution of small near-Earth objects. Since crater scaling relations, especially at small sizes, are thought to be well established, this result is disquieting.

In summary, the size distributions of the KBOs and Centaurs appear identical, within the uncertainties, and consistent with the KBO -> Centaur evolutionary link. Measurements of the size distributions of the cometary nuclei have been attempted, but the reported values are discordant and are, in any case, afflicted by discovery and coma contamination biases that are poorly understood.

8 SHAPE

The shapes of cometary nuclei can be estimated from their rotational lightcurves (strictly, the lightcurve gives only the projection of the shape into the plane of the sky). If the nuclei are collisionally produced splinters (Farinella and Davis 1996) then it seems reasonable to expect that the shape distribution of the nuclei should resemble that of fragments produced in the laboratory by impact experiments. The comparison is made in Figure 2, where we compare the photometric ranges of nuclei reported in the literature with the range distribution of impact fragments measured in the laboratory by Catullo et al. (1984).

The distributions are clearly different, with the comets showing a larger fraction of highly elongated body shapes than the impact fragments. Most probably, this is a simple consequence of aspherical mass loss from the comets, the timescale for which is just τ_{sub} (c.f. **Medvedev ACM2002**).

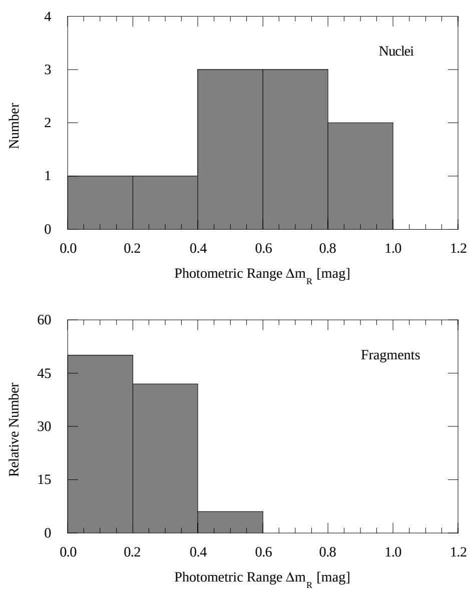

FIGURE 2: Shapes of nuclei and impact fragments compared.

The shapes of the KBOs as determined from their lightcurves are addressed in a separate paper by **Sheppard ACM2002**. Many of these bodies appear to be elongated in response to rapid spin.

9 COLOR

Color is a proxy for composition, albeit one that is convolved with effects due to regolith particle size. It is useful to discuss colors in terms of normalised reflectivity gradients, S' [% /1000 Å]. Mean values of S' are (Jewitt 2002)

KBOs	23 ± 2 (28)
Centaurs	17 ± 5 (9)
Nuclei	8 ± 3 (12)
Dead Comets	7 ± 2 (23)

and, for comparison,

D-Type Asteroids	8.8 ± 0.5 (19)
Jovian Trojans	10 ± 1 (32)

From this table we can conclude that

- The KBOs and Centaurs have consistent mean colors, as is expected if the latter are derived from the former.
- The cometary nuclei are, as a group, less red than the KBOs (a 5σ difference). Figure 3 shows the comparison directly. This is surprising, given that the comets are dynamically evolved Centaurs, and suggests surface modification.
- The candidate dead comets have exactly the same mean S' as the nuclei of active comets.
- The nuclei and dead comets cannot be distinguished from the Trojan asteroids on the basis of color.

Ultrared matter, defined as having S' > 25 %/1000 Å, is largely absent on the surfaces of the cometary nuclei (Phillipe **Lamy ACM2002** reported its detection only on comets 50P/Arend and P/Wild 3, in a combined sample that with Jewitt 2002 exceeds 30 objects) but present on half the KBOs (Figure 3, Jewitt 2002). How can this be? One possibility is that the color difference reflects a color vs. size relation, since the cometary nuclei are, on average, more than 10 times smaller than the observed KBOs. I think this is unlikely because the measured KBOs show no color-size relation over a substantial range of diameters, but I cannot eliminate this possibility.

The more likely explanation is that the active comets have been resurfaced, probably by sub-orbital debris ejected from active regions on the nuclei. The timescale for mantling has been estimated from simple models and is found to be very short inside the orbit of Jupiter (e.g. 10^3 yrs at 3 AU). This explains why the color jump occurs between the Centaurs (some of which are ultrared) and the nuclei. The carrier of the ultrared matter, which we presume to be a highly polymerised organic material formed in the Kuiper Belt (**Moroz ACM2002**), could still exist underneath (and, indeed, be protected by) the ballistically deposited material.

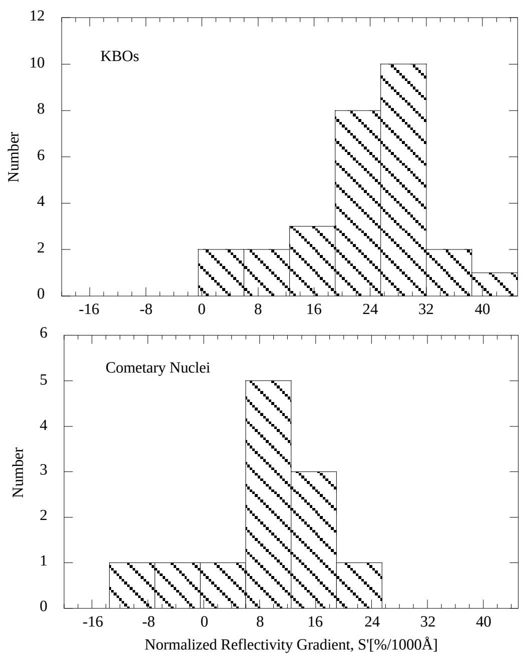

FIGURE 3. Histograms of the normalized reflectivity gradient, S', for cometary nuclei and KBOs. S’ = 0 corresponds to the solar color V-R = 0.35 mag. Objects with S’ > 0 are red. The statistical likelihood that the two samples are drawn from the same parent population is 2 x 10^{-4}, by the K-S test. Adapted from Jewitt (2002).

10 ALBEDO

Albedo is typically measured by comparing the optically scattered and thermally emitted fluxes from an object, measured simultaneously. High albedo objects of a given size are optically bright but thermally faint (because they are cool), whereas low albedo bodies of the same size are optically dark but thermally bright (because they absorb most of the incident solar flux and are hot). Measurements of thermal radiation are challenging, particularly in the outer solar system where the targets are distant and the peak temperatures are low. Nevertheless, we are beginning to collect enough data to detect systematics. The observational situation should improve dramatically with the launch of SIRTF and, later, with submillimeter wavelength measurements from the ALMA array.

The albedo data are summarised in Figure 4.

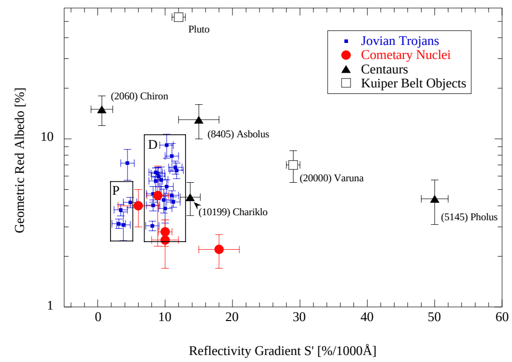

FIGURE 4. Geometric albedo vs. normalized reflectivity gradient for Jovian Trojans, Centaurs, comet nuclei and KBOs.

Rectangles in Figure 4 mark the approximate domains of the P and D asteroid spectral types. Most of the measured Jovian Trojans fall in these spectral domains. Evidently, the few measured cometary nuclei plot in or near the D spectral box, but the Centaurs and KBOs are much more widely dispersed, in both S' and albedo. Again, this argues for an evolution of the surfaces of incoming small bodies, with a systematic decrease in the diversity of albedos and spectral gradients occuring once strong cometary activity begins. This is probably a result of blanketing of the nucleus surface by debris.

11 DENSITY

The bulk densities of various outer solar system bodies are collected in Figure 5. There, a clear trend of density with diameter is apparent, rising from $\rho \sim 500$ kg m^{-3} at diameter < 100 km to 1000 kg m^{-3} at D ~ 800 km to 2000 kg m^{-3} for Pluto and Triton, each with D ~ 2500 km. This trend is too strong to be caused by compression of competent materials, whether they be of rock or ice (at the expected cryogenic temperatures, there is little difference between rock and ice). Porous internal structure provides a more likely explanation, with the magnitude of the porosity decreasing as the object size (and hydrostatic pressure) increases.

The low densities of the smaller objects in Figure 5 cannot be explained without porosity. This could be either microporosity due to an intrinsically granular structure of the material or macroporosity, perhaps caused by collisional shattering and reassembly. There are direct analogs with the main belt asteroids, some of which have been found to be unexpectedly porous (e.g. asteroid Mathilde with ρ = 1300 kg m^{-3}).

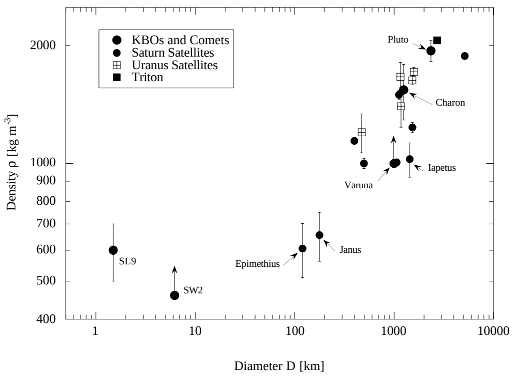

FIGURE 5: Density vs diameter for outer solar system bodies. SL9 and SW2 are comets, Epimethius and Janus are co-orbital satellites of Saturn.

The case of Kuiper Belt Object (20000) Varuna is worth discussion. The albedo (about 5 to 7 % at R-band) and size (diameter about 900 to 1000 km) of this object have been measured by two groups. Despite being half as large as Pluto, Varuna displays a spectacular lightcurve with a range 0.4 mag. and period near 6 hrs (Jewitt and Sheppard 2002). The most plausible physical interpretation is that Varuna is elongated by its rapid rotation. Under the assumption that it is a figure of equilibrium (a MacLaurin or Jacobi spheroid), there is a unique relation between the period, the shape and the density. With period and shape constrained by the lightcurve, the estimated density $\rho \sim$ 1000 kg m^{-3}. This low density could be explained if Varuna consisted of pure ice, but there is no realistic scheme for forming such a body. Instead, we prefer the explanation that Varuna is a porous rock-ice mixture. Simple models show that a volume-averaged porosity near 20 - 25% is needed, if Varuna's rock/ice ratio is to remain cosmochemically plausible. The internal hydrostatic pressures in Varuna are comparatively modest, amounting to ~ 100 bars in the core, so that retention of porosity (whether it be micro or macroporosity) seems plausible. **Bill McKinnon ACM2002** argued that the central porosity is likely to be smaller than this average value, both because of self compression and because of central heating and densification likely to occur in such a large body. I do not disagree with this point, and merely note that the average porosity is weighted by r^2, so that the central porosity has not much effect on the average value.

12 SUMMARY

New observations show that the cometary nuclei are, as a group, less red and more uniformly dark than their dynamical precursors among the Centaurs and Kuiper Belt Objects. Most likely, the differences reflect surface modification of the comets by outgassing, especially by burial under a layer of ballistically deposited debris. A possible scenario is that the ballistic mantle overlies a more primitive, irradiation mantle consisting of highly polymerised organics (the 'ultrared matter' found on many KBOs).

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