FROM COMETS TO ASTEROIDS: WHEN HAIRY STARS GO BALD

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Abstract. We discuss the essential differences between comets and asteroids. Ironically, with the exception of the rocky asteroids in the inner solar system, most of the objects classified as asteroids at and beyond Jupiter's orbit are likely to conceal buried volatiles, and thus are more usefully considered as comets.

Special Note

This is the written version of an invited review lecture given at the 1994 Small Bodies meeting in Mariehamn, Finland. I have retained the reductionist flavor of that lecture, with my aim being to simplify issues which are normally couched, in the literature, in more complicated terms. The style and subject matter form a sequence with two earlier reviews on cometary photometry (Jewitt 1991) and the cometary nucleus (Jewitt 1992). An extensive set of references is included to provide a relatively complete guide to the recent literature on this subject. Independent and complementary reviews of the comet-asteroid relationship have been published by Hartmann *et al.* (1987), Weissman *et al.* (1989), Luu (1994) and McFadden (1994).

1. Introduction

A troubling difference exists between the observational and physical definitions of comets and asteroids.

- Observational Definition: The presence of a spatially resolved, gravitationally unbound atmosphere ("coma") defines a comet.
- Physical Definition: The presence of bulk ice (water or other) defines a comet.

The practical problem is that the vapor pressure of water ice is an extremely strong function of the ice temperature, such that sublimation is unable to support a significant coma at temperatures $T \leq 150$ K. Therefore, even ice-rich comets (by the physical definition) fail to satisfy the observational definition when their ice is cold. The temperature of a freely sublimating ice surface can be computed from the energy balance for a sublimating volatile, which we simplify as

$$\frac{F_{sun}}{R^2}(1-A) = \chi[\varepsilon\sigma T^4 + L(T)\frac{dm}{dt} + C(\frac{\partial T}{\partial x}) + D(\frac{\partial T}{\partial x})] \quad (1)$$

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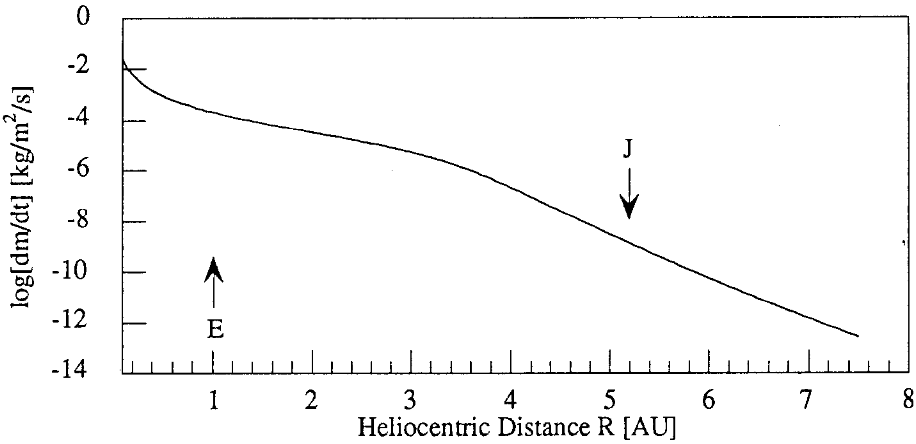

Fig. 1. Sample solution of the energy balance equation (Eq. (1)) for a sublimating water ice nucleus with $\chi = 2$, $A = 0$, $\varepsilon = 1$ and $L = 2 \times 10^6$ J kg^{-1} (see Eq. (1)). Orbits of Earth and Jupiter are marked.

Here, $F_{sun} = 1360$ W m^{-2} is the solar constant, R [AU] is the heliocentric distance, A the Bond albedo. On the right hand side, ε is the emissivity, $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} the Stephan-Boltzmann constant, T [K] the equilibrium temperature, $L(T)$ [J kg^{-1}] the latent heat of sublimation, dm/dt [kg m^{-2} s^{-1}] the specific sublimation rate and C and D represent conduction and gas-phase latent heat transfer down the temperature gradient dT/dx into the nucleus. The parameter $1 \leq \chi \leq 4$ accounts for the non-uniform distribution of solar energy across the surface of the nucleus. The term on the left represents the flux of energy absorbed from the sun. The terms on the right represent, respectively, energy lost from the nucleus surface by radiation, by latent heat of sublimation, by conduction into the interior, and by gas phase transfer into the interior.

Eq. (1) has been solved, subject to appropriate boundary conditions, in exquisite detail (e.g. Prialnik 1989). Here we present a sample solution (Fig. 1) and note a limiting case, namely that of a comet close to the sun ($R \leq 1$ AU). In this limit, the sublimation term dominates all others, and the sublimation rate can be estimated directly from

$$\frac{dm}{dt} \approx \frac{F_{sun}}{R^2 \chi L(T)}(1 - A) \tag{2}$$

For example, with $\chi = 2$, $A = 0$, $R = 1$ AU and $L = 2 \times 10^6$ J kg^{-1} (water ice) we find $dm/dt \sim 3 \times 10^{-4}$ kg m^{-2} s^{-1}, corresponding to a flux of water molecules of 10^{22} m^{-2} s^{-1}. Bright comets (e.g. P/Halley; P/Swift-Tuttle) with peak hydroxyl production rates $Q_{OH} \sim 10^{30}$ s^{-1} must therefore be outgassing from areas ~ 100 km^2. Marginally detectable outgassing ($Q_{OH} \sim$

10^{26} s^{-1}) corresponds to exposed sublimating areas of only 10^4 m^2, or surface areas $\sim$ 100 m on a side.

However, mass loss can be hindered or prevented altogether by an insulating, refractory mantle (as in the near-Earth asteroids (NEAs)) or by having a large heliocentric distance (as in the Jovian Trojans, the Centaurs, and the trans-Neptunian Objects, all of which are presumed to possess ice-rich interiors). Accordingly, to understand the differences between comets and asteroids, we need to consider mechanisms of heat transfer and mantle formation.

2. Heat Transfer

Heat transfer in small bodies proceeds primarily by thermal conduction and, when volatiles are present, by latent-heat effects due to sublimation and condensation. For simplicity, we first consider heat transfer in a non-volatile body. The distribution of temperature with depth is governed by the diffusion equation

$$k\nabla^2 T = \rho c_p \frac{\partial T}{\partial t} - \rho H \tag{3}$$

in which T [K] is the temperature, t [s] is time, k [W m^{-1} K^{-1}] is the thermal conductivity, ρ [kg m^{-3}] the density, c_p [J kg^{-1} K^{-1}] the specific heat capacity and H [W kg^{-1}] is the specific power production in the material (due, for example, to amorphous-crystalline phase changes (e.g. Klinger 1980), or to radioactive elements). Detailed analytic solutions of Eq. (3), subject to appropriate boundary conditions, are part of the classical literature (e.g. Carslaw and Jaeger 1959). For our present purposes, it is more revealing to consider order of magnitude solutions as follows. Setting $H = 0$, dimensional treatment of Eq. (3) shows that the timescale for the transport of heat by thermal conduction is of order

$$\tau \approx \frac{\ell^2}{\kappa} \tag{4}$$

where ℓ [m] is the characteristic dimension of the body and $\kappa = k/\rho c_p$ [m^2 s^{-1}] is the thermal diffusivity. Typical planetary dielectric solids have $\kappa \sim 10^{-7}$ to 10^{-6} m^2 s^{-1}, although values that are orders of magnitude smaller have been suggested for porous amorphous ices (Kouchi *et al.* 1992). To give a very terrestrial example, the conduction cooling time for a pea ($\ell \sim 3$ mm, $\kappa \sim 10^{-6}$ m^2 s^{-1}) is $\tau \sim 10$ s, while that for a potato ($\ell \sim 3$ cm) is $\tau \sim 1000$ s $\sim$ 15 minutes. These timescales are in reasonable agreement with common experience, and the agreement seems enhanced when we remember

TABLE I
Cometary Timescales and Conduction Length Scales

Quantity	Timescale	Magnitude	Conduction Length Scale
Dynamical Lifetime	t_{dyn}	4×10^5 yr	1000 m
Orbital Period	t_{orb}	10 yr	5 m
Rotational Period	t_{rot}	10 hr	5 cm

that Eq. (4) approximates the e-folding time for cooling, and that several e-folding times must elapse before the internal heat of the pea or the potato is lost. Of course, these examples are intentionally frivolous and simplistic (e.g. we have neglected internal transport of heat by steam). But Eq. (4) also shows that the largest body able to cool by conduction in the age of the solar system ($\tau = 4.5$ Gyr $\sim 1.4 \times 10^{17}$ s) is of scale $\ell \sim (\tau\kappa)^{1/2} \sim 100$ km. Smaller bodies must have lost their initial heat and can retain no thermal memory of their formation. Therefore, all but the largest nuclei of short-period comets have interiors that have cooled by conduction of internal heat to the surface followed by (nearly instantaneous) radiation into space.

Table I lists timescales relevant to the propagation of heat in a cometary nucleus, and gives corresponding conduction length scales derived from them using Eq. (4). Several deductions about the internal thermal character of comets may be reached directly from the Table.

- First, the dynamical lifetime of short-period comets against gravitational ejection by the planets is $t_{dyn} \sim 4 \times 10^5$ yr (Levison and Duncan 1994). On this timescale, heat conducts into the nucleus by a distance $\ell_{dyn} \sim 1$ km. Since most well-studied cometary nuclei are larger than 1 km (Table II), we must conclude that these bodies are perpetually out of internal thermal equilibrium, and that deeply buried volatiles may survive even in the old, sun-baked short-period comets typified by P/Encke, P/Arend-Rigaux, and P/Neujmin 1.
- Second, in the $t_{orb} \sim 10$ yr orbital period of a Jupiter-family comet, solar heating of the surface drives a thermal wave of vertical scale-length $\ell_{orb} \sim 5$ m into the nucleus. Essentially all consequences of the annual solar heating.
- Third, the diurnal thermal skin depth (due to axial rotation of the nucleus with a period $t_{rot} \sim 10$ hr (Table II)) is $\ell_{rot} \sim 5$ cm. The presence of strong sunward emission of gas and dust from Halley (Keller *et al.* 1987) and other comets (e.g. Sekanina 1990; Jewitt 1991) shows that cometary outgassing occurs from the diurnal thermal skin and not from deeper layers.

Strong thermally induced stresses are also confined to a layer of thickness $\sim \ell_{rot}$. Several authors (e.g. Tauber and Kührt 1987) have suggested that thermal fracture may occur in these upper layers.

Heat may also be transported by vaporization and condensation of volatiles, assuming that sufficient porosity exists. Detailed models of heat transport have been described by Fanale and Salvail (1984) and Prialnik (1989), among others. The timescale for depletion of volatiles from a sufficiently porous body of radius r_n and density ρ_n is

$$t_{dv} \sim \frac{\rho_n r_n}{dm/dt} \tag{5}$$

With $dm/dt \sim 10^{-4}$ kg m^{-2} s^{-1} at $R = 1$ AU, $t_{dv} \sim 10^3 \times 10^3/10^{-4} \sim 10^{10}$ s $\sim 10^3$ yr. Notice that $t_{dv} \ll t_{dyn}$, suggesting that km-sized comets should lose their volatiles before completing their dynamical evolution (in other words, that many NEAs could be completely devolatilised comets). This would be true but for the formation of surface mantles.

3. Mantles

In comets, the ice and dust are intimately mixed. Sublimation at rate dm/dt leads to a recession of the sublimating surface at rate $dl/dt = \rho^{-1} dm/dt$. For example, at 1 AU, water ice sublimates at $dm/dt \sim 10^{-4}$ kg m^{-2} s^{-1}, and with $\rho = 10^3$ kg m^{-3} the surface shrinks at rate $dl/dt \sim 10^{-7}$ m s^{-1}. Progressive loss of volatiles from the heated surface of a nucleus may leave behind a lag-deposit or cohesionless "rubble mantle", consisting of particles of refractory debris that are too large to be ejected against local gas drag (Whipple 1950; 1951). Balancing the gas drag force against the local gravitational acceleration towards the nucleus, one obtains a critical radius

$$a_c \sim \frac{9 C_D \dot{m} v_{th}}{16 \pi G \rho \rho_n r_n} \tag{6}$$

above which gas drag cannot eject cometary debris. Here, $C_D \sim 1$ is the dimensionless drag coefficient, dm/dt [kg m^{-2} s^{-1}] is the specific mass loss rate, v_{th} [m s^{-1}] is the speed of the escaping gas molecules, $G = 6.67 \times 10^{-11}$ [N kg^{-2} m^2] is the Gravitational Constant, ρ and ρ_n [kg m^{-3}] are the densities of the dust grain and nucleus, respectively, and r_n [m] is the nucleus radius. The multiplier $9/16 \sim 1$ is a function of the shape of the nucleus. Figure 2 shows the critical radius for ejection from spherical nuclei of radii 1 km and 5 km as a function of heliocentric distance (corresponding curves for other volatiles are presented in Luu and Jewitt 1990b). Note that optically dominant μm-sized grains can be ejected out to about the orbit

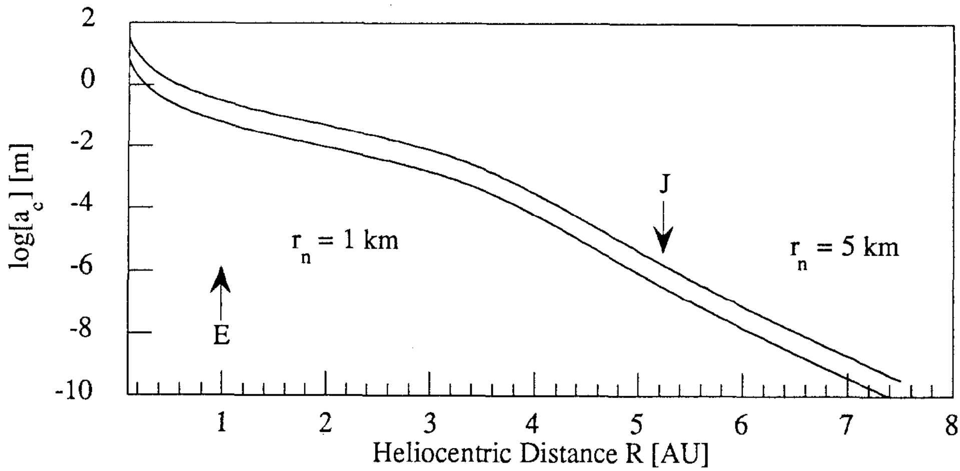

Fig. 2. Maximum ejectable grain size computed from Eq. (6) as a function of heliocentric distance, for a water ice nucleus sublimating in equilibrium with sunlight. The upper and lower curves show the effect of changing the nucleus radius by a factor of 5. Orbits of Earth and Jupiter are marked. Nuclear rotation is neglected. Eq. (6) is strictly invalid for small R, where the particle size exceeds the mean free path for molecular collisions. However, the error amounts to only about 0.6 in $\log(a_c)$, and can be ignored for the purposes of this review.

of Jupiter, while comets active much beyond 5 or 6 AU must be driven by another volatile (e.g. CO; Senay and Jewitt 1994) or another process (e.g. electrostatic charging by the solar wind). At 1 AU, a Halley-sized (5 km) nucleus can retain debris larger than $a_c \sim 5$ cm, while larger particles can be ejected if nuclear rotation creates a lower effective gravitational acceleration. Such particles are thought to clog the surfaces of comets, forming nearly continuous surface mantles of characteristic thickness a few times a_c.

Compelling evidence exists that the surfaces of short-period comets are mantled (but there is no significant evidence for or against mantles on the nuclei of long-period comets). Images of the surface of P/Halley show a dark, inert mantle punctured by regions of strong outgassing (Keller *et al.* 1987). Images of other short period comets show that sublimation is largely confined to active areas (or "vents") which have fractional coverage of the nucleus surface (Table II) $f \sim 10^{-3}$ (comets P/Encke, P/Neujmin 1, P/Tempel 2) to $f \sim 10^{-1}$ (P/Halley). These vents appear to be stable on timescales that are comparable to or longer than the orbit period (Sekanina 1990).

For a nucleus in which solids of size $a \geq a_c$ are common, the rubble mantle growth time is crudely given by $t_m \sim a_c/(dl/dt)$, or

$$t_m \sim \frac{9C_D v_{th}}{16\pi G\rho_n r_n} \tag{7}$$

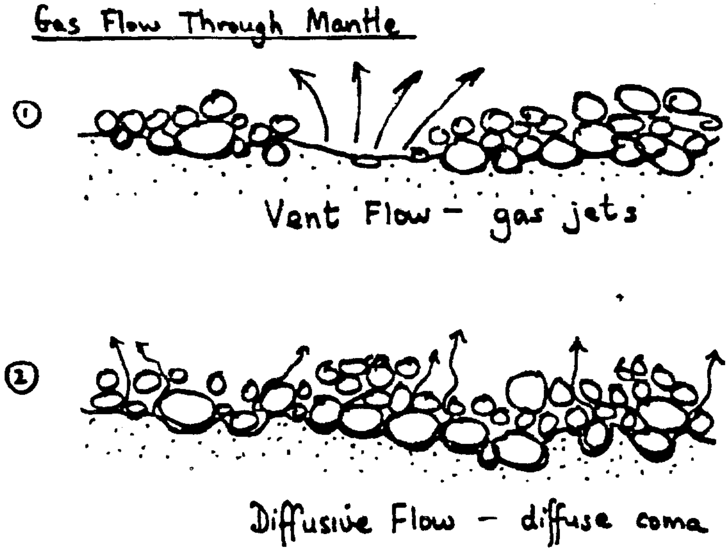

Fig. 3. Modes of gas flow through the cometary surface. 1) vent flow through an impermeable mantle and 2) diffusive flow through a permeable mantle. Gas and dust jets in cometary comae show that vent flow is common. Diffusive flow may also occur but is observationally not well constrained.

For a 1 km radius nucleus, $t_m \sim (9 \times 1 \times 10^3)/(16\pi G 10^3 10^3) \sim 3 \times 10^6$ s ~ 0.1 yr. Two properties of Eq. (7) are worthy of note:

- t_m is independent of heliocentric distance, to first order
- $t_m < t_{orb}$.

Thus, the rubble mantle should be considered as an actively regenerated surface feature, that can grow during a single orbit of an active comet. Orbital evolution of short period comets towards smaller perihelion distances (c.f. orbital integrations in Levison and Duncan 1994) will cause repeated disruption and healing of the rubble mantle (Rickman *et al.* 1990, 1991; Rickman 1992). Rapidly growing rubble mantles choke the flow of gases from the icy interiors of comets and produce the collimated jets recorded in the comae of many comets (e.g. Jewitt 1991; Keller *et al.* 1994). Diffusive flow through weakly permeable mantles is also possible (see Figure 3).

Strengthless rubble mantles are weakly stable, and can be locally disrupted by changes in the insolation (due to orbital evolution) or nuclear spin (due to outgassing torques). For example, the nuclei of many short period comets are rotating prolate spheroids. Centripetal reduction of the local gravity might favor mantle-free "bald spots" at the sharp ends of a prolate spheroid, leading to large outgassing torques, the excitation of precession, further spin-up, possible splitting (Chen and Jewitt 1994), shape evolution and mantle disruption. Such complex cycles of feedback have yet

TABLE II
Properties of Cometary Nuclei (adapted from Jewitt 1991)

Nucleus	T [hr]$^{\alpha}$	R_e [km]$^{\beta}$	p_V^{χ}	a/b^{δ}	f^{ϵ}	Reference
P/Arend-Rigaux	13.56 ± 0.16	5	0.03	1.9/1	0.1-1	1,2
P/Neujmin 1	12.67 ± 0.05	10	0.03 ± 0.01	1.6/1	0.1-1	3,4
P/Encke	15.08 ± 0.08	3.5	0.04^{γ}	3.5/1	0.2	5
P/Halley	7 days?	5	0.04	2/1	10	6,7
P/Tempel 2	8.95 ± 0.01	5	0.02	1.9/1	0.1-1	4,8,9
P/SW2	5.58 ± 0.03	3.1	0.04^{γ}	1.6/1	?	10
P/Levy 1991XI	8.34	5.8	0.04^{γ}	1.3/1	?	11
P/Faye	?	2.4	0.04^{γ}	1.3/1	?	12

α–nuclear rotation period β–effective circular radius χ–visual geometric albedo
δ–projected axis ratio ε–active fraction*100 γ–albedo assumed

1=Jewitt & Meech 1985; 2=Millis *et al.* 1988; 3=Campins *et al.* 1987; 4=Jewitt & Meech 1988; 5=Luu & Jewitt 1990; 6=Jewitt & Danielson 1984; 7=Keller *et al.* 1987; 8=Jewitt & Luu 1989; 9=A'Hearn *et al.* 1989; 10=Luu & Jewitt 1992b; 11=Fitzsimmons & Williams 1994; 12=Lamy & Toth 1994

to be considered in published models of the evolution of the cometary nucleus (Rickman 1992) but they are probably important in real comets. Intergrain cohesion might offset some of the short-term instabilities present in purely gravitationally bound mantles but has typically been neglected in the literature (see Kührt and Keller 1994 for a counter-example). Laboratory simulations of cometary outgassing confirm the basic features of mantle growth outlined here (Grün *et al.* 1991).

It is natural to ask whether mantles could stifle outgassing so efficiently that ice-rich comets might be hidden among the near-Earth asteroids. This question has received much attention from investigators using "proxy indicators" such as the surface colors, body shapes, rotation period distributions and orbital parameters to compare the comets and NEAs (e.g. Hartmann *et al.* 1987; Jewitt and Meech 1988; Weissman *et al.* 1989; Luu and Jewitt 1990c; Binzel *et al.* 1992; McFadden 1994). Unfortunately, the properties of cometary nuclei exhibit wide diversity (Luu 1993), so that proxy indicators are difficult to use, even in a statistical sense. A more satisfactory approach is to search for outgassing directly, and two methods have been tried. First, spectral observations have failed to detect resonance fluorescence lines from cometary molecules (CN, C_2 etc) in NEAs (Cochran *et al.* 1986). A reported detection of the OH 3080 Å band in main-belt asteroid 1 Ceres (A'Hearn and Feldman 1993) awaits confirmation. It would correspond to a water source of order 1 to 10 kg s^{-1}. Second, high resolution measurements of the surface brightness profiles of NEAs place limits on the outgassing about an order of magnitude smaller than outgassing from feeble comets like P/Encke and P/Arend-Rigaux (Luu and Jewitt 1992a). However, most NEAs in the observational sample are smaller than the comets of Table II. The implied limiting active fractions, $f \sim 10^{-3}$ to 10^{-4}, are similar to f for the most feeble comets. Hence, observationally, it appears possible that some of the NEAs are mantled comets. Secular evolution of NEAs to smaller perihelion distances (e.g. Farinella *et al.* 1994) might lead to intermittent mantle disruption and outgassing. Deactivation appears to have occurred in the case of former comet P/Wilson-Harrington (1949 III) (now known as asteroid 1979 VA; Bowell 1992).

4. Trojans

The trojan asteroids of Jupiter librate around the L4 (leading) and L5 (trailing) Lagrangian stable points of that planet, at $R \sim 5.2$ AU. About 200 trojans are presently known; several thousand are thought to exist with diameters ≥ 15 km (Shoemaker *et al.* 1989). Stability calculations suggest that Saturn, Uranus and Neptune might also retain sets of trojans (e.g. Holman and Wisdom 1993) but none is known. A search for these objects is underway on Mauna Kea.

While classified as asteroids on the basis of their lack of coma, the physical nature of the trojans is observationally not well constrained. The optical spectra show only featureless, red continua, with a mean slope, $S' = 10 \pm 4$ %/1000 Å, that is statistically consistent with the mean slope of the optical spectra of cometary nuclei, $S' = 14 \pm 5$ %/1000 Å (Jewitt and Luu 1990; Fitzsimmons *et al.* 1994). The geometric albedos of trojans are 2 to 3 % (e.g. Cruikshank 1977), again comparable to the albedos of cometary nuclei (see Jewitt 1992 for a compilation). The similar optical colors and low albedos may be evidence for common organic compounds on the two classes of object (organics are favored because they provide a natural explanation for the low albedos). Unfortunately, the C-H fundamental vibration at 3.4 μm is unobservable with current technology in even the brightest trojans. Many organics show spectral features in the 1.4 μm to 2.4 μm wavelength range due to overtones and combinations of vibrations of C-H, C-O, C-N and other chemical bonds (Cloutis 1989). However, available spectra of trojans are featureless at signal-to-noise ratios ~ 20, and provide no independent evidence for the presence of organics (Luu *et al.* 1994). Perhaps carbon-rich materials on the surfaces of comets and trojans are so dehydrogenated by cosmic ray bombardment that hydrocarbon features are lost.

The bulk compositions of the trojans are unknown. Unlike the C-type asteroids, the D-types show no evidence for the 3 μm signature of water of hydration (Jones *et al.* 1990). Suggested interpretations are that the D's formed in the absence of appreciable water, or more likely, that they formed at temperatures too low for silicate hydration reactions to proceed. In the latter case, water could be incorporated as bulk ice, especially if the trojans were formed beyond the orbit of Jupiter. According to Fig. (1), low albedo water ice at $R = 5.2$ AU sublimates at $dm/dt \sim 10^{-9}$ kg m^{-2} s^{-1} corresponding to a surface recession rate $(dm/dt/r) \sim 10^{-12}$ m s^{-1} ~ 30 m Myr^{-1}, where $\rho = 10^3$ kg m^{-3} is the density of water ice. This is too small to sustain an observable coma, but sufficient to cause substantial topographical modification if unchecked. Note that the water ice sublimation rate at large R is highly sensitive to albedo and to heat transport by conduction, and our neglect of conduction in Fig. 1 leads to an over-estimate of dm/dt. Even so, we suspect that the dark, reddish surfaces of the trojans are thin rubble mantles, shielding buried ice perhaps just a few centimeters beneath the surface. The detection of outgassing from Jovian trojans represents a formidable observational challenge. Perhaps the best chance for success would occur following mantle disruption by collision with another body, but such events are exceedingly rare.

The origin of the trojan asteroids is a puzzle. Non-gravitational forces due to aspherical outgassing have been suggested as an agent of capture (Rabe 1972; Yoder 1979). However, sublimation of water at 6 AU is very slow and this explanation hardly seems credible for the larger (100 km size) Trojans even if more volatile ices (Senay and Jewitt 1994) were once present at the surface. The "collisional capture" hypothesis of Shoemaker *et al.* (1989) postulates the fragmentation and capture into the 1:1 resonance of precursor Jupiter planetesimals.

5. Centaurs

The orbits of Centaurs cross the orbits of gas-giant planets and are thus chaotic and short-lived (lifetime $\sim 10^6$ yr; Hahn and Bailey 1990; Dones *et al.* 1994). The three well established examples are 2060 Chiron (the only Centaur to display cometary activity; e.g. Hartmann *et al.* 1990; Luu and Jewitt 1990b), 5145 Pholus and 1993 HA$_2$. The three other Centaurs, 1994 TA, 1995 DW$_2$ and 1995 GO are recent discoveries awaiting detailed observational characterisation.

The known Centaurs (Table III) are most likely bright members of a vast population of unstable, outer-planet crossing bodies. For example, the 22nd magnitude object 1994 TA was discovered in a Mauna Kea ecliptic survey of about 3 sq. degrees. Given that the area of the ecliptic band is roughly 10,000

TABLE III
The Currently Known Centaurs*

Object	a [AU]	e	i [deg]	q [AU]	Q [AU]
2060 Chiron	13.74	0.38	6.9	8.52	18.96
5145 Pholus	20.39	0.57	24.7	8.77	32.01
1993 HA_2	24.80	0.52	15.6	11.90	37.70
1994 TA	17.47	0.39	5.4	10.66	24.28
1995 DW_2	24.2	0.22	4.2	18.9	29.5
1995 GO	14.1	0.53	19.1	6.8	21.6

*–elements compiled from the Minor Planet Electronic Circulars produced by Brian Marsden.

sq. deg., we predict that $\sim$ 3000 objects similar to 1994 TA (approximate diameter is 70 km) await discovery by future surveys. Smaller Centaurs should be even more abundant, with perhaps 10^5 to 10^6 present down to km-size. The source of these short-lived objects is plausibly identified with the trans-Neptunian Kuiper Belt (c.f. Fernández 1980; Duncan *et al.* 1988; Bailey 1994; §6).

Curiously, while the Centaurs are *dynamically* similar, their surfaces show dramatic spectral differences. For example, Chiron has a neutral visible spectrum (Hartmann *et al.* 1990; Luu and Jewitt 1990) while Pholus (Fink *et al.* 1992; Mueller *et al.* 1992; Luu 1993) and 1993 HA_2 (Tholen and Senay 1993; Luu 1993) are extremely red. These differences are echoed in the corresponding near infrared spectra. The 2 μm spectrum of Pholus shows deep absorptions (Fig. 4; Davies *et al.* 1993; Luu *et al.* 1994) which are absent in Chiron. The red visual slope and the near infrared features are typically interpreted in terms of a chemically complex "irradiation mantle" that has been processed by long-term exposure to cosmic rays (Andronico *et al.* 1987; Johnson *et al.* 1987; Johnson 1991). Unfortunately, no completely convincing spectral match has been achieved, and it is not even clear whether the spectral features are due to vibrations in the C-H or N-H bonds (Cruikshank *et al.* 1993; Luu *et al.* 1994), or an indeterminate mix of the two (Wilson *et al.* 1994). The neutral, featureless spectrum of Chiron might indicate burial of the irradiation mantle by sub-surface debris excavated by outgassed volatiles.

6. Trans-Neptunians

Twenty eight trans-Neptunians are known at present (August 1995). These objects have heliocentric distances $31 \leq R \leq 46$ AU, apparent red magni-

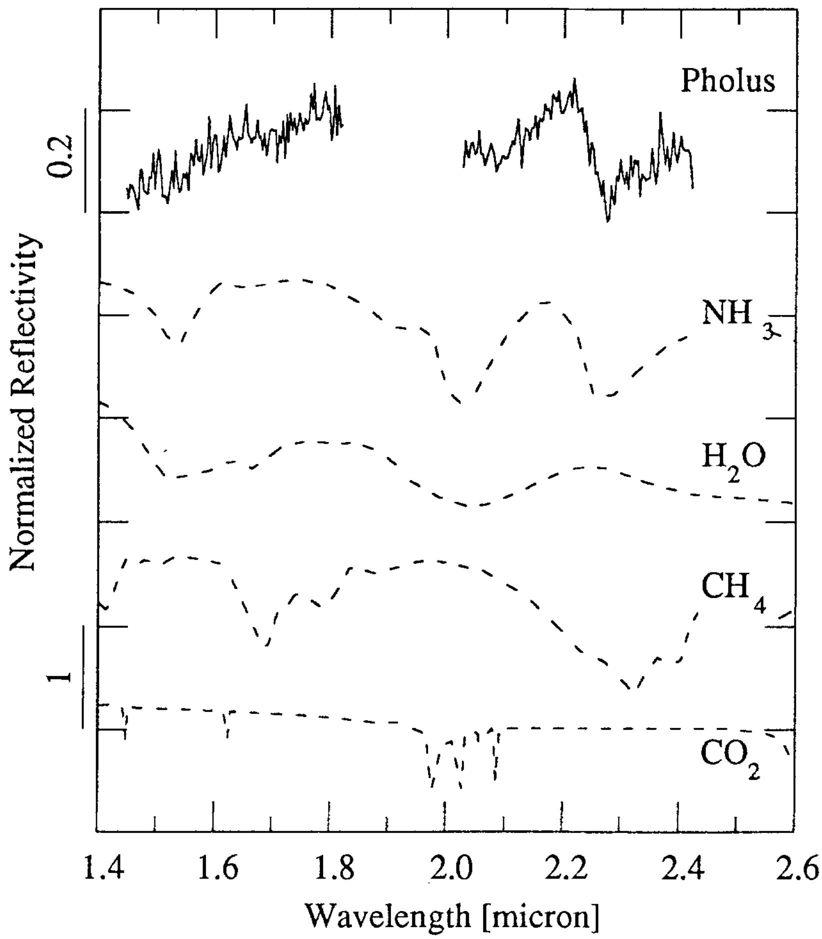

Fig. 4. Near-infrared spectrum of Centaur 5145 Pholus is compared with the reflection spectra of several common ices. A similarity with vibrational overtone and combination bands in the spectrum of NH_3 is evident, but significant differences exist (e.g. at 1.5 μm). Ammonia is not suspected, but another molecule incorporating the N-H bond might be present. Figure from Luu *et al.* (1994).

tudes $21.7 \leq m_R \leq 24.5$ and diameters (computed using an assumed 0.04 geometric albedo) $100 \leq D \leq 380$ km (Jewitt and Luu 1993, 1995). Because of their distance, it is very likely that these objects incorporated water as ice at formation; they are comets according to our physical definition. However, they are sufficiently cold that they sustain no observable comae. To date, only a very tiny fraction of the ecliptic has been searched for trans-Neptunians. The inferred total number of objects having diameters $D \geq 100$ km is $N(D \geq 100) \sim 35,000$, in the heliocentric distance range $30 \leq R \leq 50$ AU. This is several hundred times the population of comparably sized main-belt asteroids, providing a measure of the vastness of this newly discovered population. The number of trans-Neptunians down to 1 km size is probably in the 1 to 10 billion range.

The trans-Neptunians are thought to be ice-rich remnants from the outer edge of the pre-planetary disk out of which the planets accreted 4.5 Gyr ago. Those with semi-major axis $a \geq 40$ AU are probably dynamically long-lived and constitute direct evidence for the existence of Kuiper's Belt (Kuiper 1951; Fernández 1980; Duncan *et al.* 1988). Trans-Neptunians with $a < 40$ AU may be protected from Neptune ($a = 30$ AU) perturbations by the 2:3 mean-motion resonance. The latter objects are thus dynamically equivalent to Pluto. They may have been captured during radial migration of Neptune (in the first few $\sim 10^8$ yrs) caused by angular momentum exchange with surrounding cometesimals in the disk (Malhotra 1993). Fully 50% of the currently known trans-Neptunians may be "Plutinos", and the total population with $D \geq 100$ km in the resonance may number many thousands (Jewitt and Luu 1995). A readable review of the possible conditions of formation and scientific significance of the trans-Neptunians is given by Bailey (1994).

A distinguishing feature of the known trans-Neptunians is their large size, which is itself an artifact of observational selection favoring the closest, largest members of the population. The known trans-Neptunians are 10 to 40 times larger than typical short-period comet nuclei (c.f. Table II), but comparable to the largest Centaur, Chiron (radius ~ 90 km; Campins *et al.* 1994). A crude estimate of the effects of internal radiogenic heating can be obtained from Eq. (3) by neglecting the conductivity term. The temperature change in time Δt is $\Delta T \sim (H/c_p)\Delta t$. This temperature increase continues up to a maximum time $\Delta t \sim \tau$, after which internally liberated heat is lost as rapidly as it is created by conduction to the surface. Thus, the maximum temperature rise sustained by radiogenic heat is

$$\Delta T \sim (\frac{H}{c_p})(\frac{\ell^2}{\kappa}) \tag{8}$$

With $H \sim 10^{-12}$ W kg^{-1} (Stacey 1969), $c_p = 100$ J kg^{-1} K^{-1}, $\kappa = 10^{-7}$ m^2 s^{-1}, we obtain $\Delta T \sim 10^{-2}(\ell/1\text{km})^2$. Sample temperature changes are listed in Table IV.

This is a highly simplistic calculation, but it serves to suggest that radiogenic heating in the larger bodies of the Kuiper Belt might have led to the mobilization of interior volatiles (CO, N_2, possibly CO_2; c.f. Whipple and Stefanik 1966; Yabushita 1993). We should not be surprised if some of the larger trans-Neptunians show geological evidence for cryogenic volcanism and comet-like outgassing, perhaps similar to the geyser-like activity found on Triton.

TABLE IV
Radiogenic Heating

Radius [km]	Example	ΔT [K]
5	Tempel 2, Halley	0.25 K
50	1993 RO, 1993 RP	25 K
100	Chiron, 1993 SB, 1994 JR_1	100 K

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