PHYSICAL PROPERTIES OF COMETARY NUCLEI

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Abstract

New ground-based observations are beginning to reveal the physical properties of cometary nuclei. These properties are reviewed, giving particular attention to the known rotations, shapes and sizes of cometary nuclei, and to the reflection properties of their surface mantles. The properties are discussed in the context of current models of the origin and evolution of comets.

1 Introduction

Scientific interest in cometary nuclei is focussed by the prevailing belief that these are among the most primitive solid bodies in the solar system. Although the details of their formation are unknown, it seems likely that the cometary nuclei accreted in the cool, outer parts of the solar nebula, possibly in the vicinity of Uranus or Neptune (e.g. Yamamoto and Kozasa 1988). Formation and storage at low temperatures are implied by the abundances of highly volatile molecules in comets (e.g. CO, CO_2). For instance, the abundance ratio $CO/H_2O \sim 0.07$ in P/Halley is compatible with nucleus formation at $T \sim$ 48 K (Bar-Nun and Kleinfeld 1989). Donn (1963, 1990) argued that the nuclei must have accreted at low relative velocities in order to avoid impact heating and sublimation of the volatiles. Measurements of the ortho/para spin ratio in water molecules were used by Mumma *et al.* (1987) to estimate a formation temperature $T \sim 30$ K for P/Halley. However, the interpretation of this measurement is a subject of on-going debate (Bocklée-Morvan and Crovisier 1989).

There is currently some uncertainty about the post-formation storage locations of the comets. Oort (1950) proposed that comets from the Uranus-Neptune region were ejected on near-parabolic orbits by these two planets, and subsequently lifted into a large circumsolar "Oort Cloud" by the gravitational perturbations of passing stars. Remnants of the original nucleus accretion zone beyond Neptune (the "Kuiper Belt") have been postulated as an alternate storage location for the short period comets (e.g. Edgeworth

1949; Kuiper 1951; Fernandez 1980; Duncan *et al.* 1988). Most probably, a large fraction of the short period comets emanate from the Kuiper Belt while the long period comets come from Oort's cloud.

In either case, it is clear that the comets must have experienced collisional and thermal histories which are rather different from those of main-belt asteroids. For example, the bulk physical properties (rotations, shapes, sizes) of all but the largest main-belt asteroids are results of disruptive collisions since formation, while their chemical natures indicate high formation temperatures, metamorphism, even differentiation (e.g. Bell *et al.* 1989). In contrast, cometary nuclei in the Oort Cloud would survive the entire age of the solar system without a single catastrophic collision (Stern 1988), and all but the surface layers of the nuclei have been preserved at temperatures $T < 10$ K. The Kuiper Belt, if it exists, would represent an intermediate collisional and thermal environment. In short, the cometary nuclei are of interest because they may be thermally and collisionally unevolved relative to all other solar system bodies. Observations are needed both to establish the physical properties of the nuclei, and to determine the degree to which these properties are primordial.

Special Notes About This Review

The purpose of this review is to describe what is currently known about the physical properties of cometary nuclei. This is an intentionally personal and opinionated review of the subject. I will try to concentrate on group properties over those of individual nuclei so that common trends, if any, will become apparent. I include a rather long set of references, so that the interested reader can use this paper as a guide to the proliferating literature on nuclei. A historical background to this subject may be obtained by reading, in chronological order, the related works by Whipple (1950), Roemer (1966), Sekanina (1976; 1981), Whipple (1982), and A'Hearn (1988). Recent reviews by Keller (1990), Belton (1991) and Jewitt (1991) cover selected aspects of the material described here.

Fundamental Timescales

The complicated physical behavior of comets is determined, in large part, by competition amongst several fundamental timescales, defined below. Several of these timescales are size dependent; here we consider timescales for a 5 km radius nucleus. The fundamental timescales are summarized in increasing order in Fig. 1.

τ_{crit} the critical rotation period at which nuclear gravity equals centripetal acceleration at the surface. For a sphere of density $\rho = 10^3$ kg m^{-3}, τ_{crit} = **3.3 hr**. τ_{crit} will be larger for an elongated nucleus, or for a spherical one of lower density.

τ_{spin}, the spin period of the nucleus. A representative value is τ_{spin} = **10 hr** ~ 10^{-3} yr (Table 1).

τ_{orb}, the orbital period (τ_{orb} ~ **10^1 yr** for Jupiter family comets).

τ_m, the timescale for the growth of a refractory rubble mantle (see §5) thick enough to inhibit sublimation. We adopt τ_m ~ **$10^{2\pm1}$ yr** (Rickman *et al.* 1990; 1991).

τ_{ex}, the "excitation time", equal to the time needed to change the angular momentum vector of the spinning nucleus by, for example, asymmetric outgassing. We adopt τ_{ex} ~ **10^1 yr** (see below, c.f. Samarasinha *et al.* 1986).

τ_{dv}, the timescale for depletion of volatiles in the nucleus, equal to $M/(dM/dt)$, where M is the nucleus mass and dM/dt is the time-averaged rate of loss of mass due to sublimation. We adopt τ_{dv} ~ **10^4 yr**.

τ_{dyn}, the dynamical lifetime of comets in the inner solar system, determined primarily by the rate of dynamical ejection by planets (collisions are comparatively rare). We adopt τ_{dyn} ~ **$10^{5\pm1}$ yr** as representative of the short period comets (e.g. Everhart 1973).

τ_{damp}, the "damping time", equal to the time taken for internal friction to damp excited spin motions of the nucleus. We adopt τ_{damp} ~ **$10^{6\pm1}$ yr** (Burns and Safranov 1973) as appropriate for 1 - 10 km size bodies.

τ_{th}, the timescale for thermal conduction to carry heat to the core of the nucleus, equal to r_n^2/κ, where r_n = nucleus radius and κ = thermal diffusivity. For reference, we take r_n = 5 km (Table 1) and $\kappa = 10^{-7}$ m^2 s^{-1} (c.f. Klinger 1980) to find τ_{th} ~ **10^7 yr**. Note that the much smaller estimates of τ_{th} by Herman and Weissman (1987) and others refer to nuclei smaller than those that have been observed (r_n = 1 km).

τ_{oort}, the lifetime of comets in the storage locations (Oort cloud or Kuiper belt), here taken to be τ_{oort} = **4.5 x 10^9 yr**.

To be sure, each of the above timescales is uncertain, in many cases by more than an order of magnitude. Nevertheless, it is illuminating to briefly consider the consequences of the relative magnitudes of the above timescales. We will return to many of these consequences in later sections.

- First, the inequality $\tau_{dyn} < \tau_{th}$ implies that comets change their orbital parameters (by gravitational scattering among the planets) faster than they can adjust their core temperatures by conduction. Thus, the comets do not attain internal thermal equilibrium once in the planetary region. Deep regions respond sluggishly to variations in the surface insolation due to orbital evolution. The deep interior may preserve ultra-volatile materials

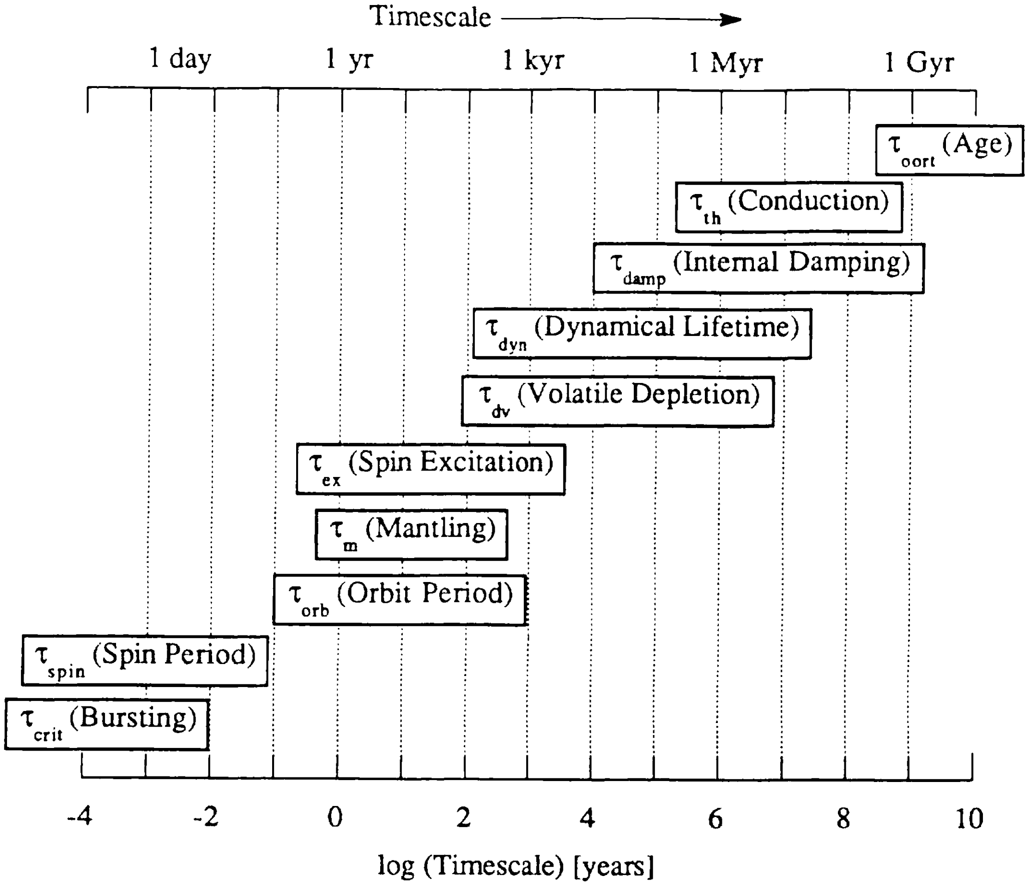

Figure 1 Fundamental timescales appropriate to a 5 km radius short period comet. See discussion in §1.

which are completely baked out of the near surface layers by solar heating. Conversely, $\tau_{th} < \tau_{oort}$ implies that the deep interiors retain no direct memory of the cometary formation temperatures.

- Second, $\tau_{dv} < \tau_{dyn}$ would seem to imply that nuclei can lose their entire volatile contents even before being ejected from the solar system by planetary perturbations, presumably leaving behind "asteroids". However, the second inequality $\tau_m << \tau_{dv}$ suggests that rapid growth of surface mantles can choke nuclear mass loss, and possibly preserve subsurface volatiles even in outwardly "dead" comets (§6).
- Third, $\tau_m < \tau_{dyn}$ implies that cometary mantles adjust to long term changes in the insolation. If true, the mass loss will always be regulated by a surface mantle (§5).
- Fourth, $\tau_{damp} < \tau_{oort}$ implies that excited rotational states resulting from formation will be absent in the present day comets. However, $\tau_{ex} < \tau_{dyn} < \tau_{damp}$ implies that precessional motions subsequently induced by torques due to mass-loss cannot be damped

in the dynamical lifetimes of the comets. The rotation periods of comets may likewise be changed by torques associated with sublimation. Further, $\tau_{ex} \sim \tau_{orb}$ implies that appreciable spin vector changes might occur within one or a few orbits, raising the possibility that such effects might be directly observable in a human lifetime (§3).

• There are more subtle effects. For example, the shapes and moments of inertia of cometary nuclei will be changed by prolonged, asymmetric mass loss. The timescale for the change in shape will be of order τ_{dv}. Since $\tau_{dv} << \tau_{damp}$, we expect that a nucleus initially spinning in the minimum energy configuration will evolve to an excited rotational state as a result of sublimation. Thus, there is an interplay between mantling, mass loss, body shape, precession and spin-state, with changes in one inducing changes in the other.

An even more dramatic example is indicated by $\tau_{spin} \sim \tau_{crit}$, which indicates that cometary nuclei are close to centripetal break-up. The effects of mass loss torques might drive nuclei into a state of internal tensile stress, leading to rotational bursting at period τ_{crit} and to the creation of split comets. Splitting of the nucleus will in turn cause a dramatic change in the shape and moment of inertia of the nucleus, leading to excited rotation and re-mantling of the fractured nucleus on a timescale τ_m(§3).

2 Observational Methods

Nuclei have been studied using observational methods that may be usefully classified as either direct or indirect. The direct methods sample scattered and/or thermal radiation from the nucleus. The indirect methods make use of a secondary property (for example, the morphology of the near-nucleus coma) to infer the properties of the nucleus. The direct methods are more reliable than the indirect ones, but also observationally more challenging. The main practical problem is that cometary nuclei are both small and dark. They are faint when far from the sun, and they are immersed in bright coma when near the sun.

As a result of these problems, it must be stressed that we possess data on a limited and biassed subset of the cometary nuclei. Nuclei of dynamically new comets are excluded, for instance, because they are usually discovered on the basis of their bright comae and so are not susceptible to direct methods.

Direct Methods

• Optical photometry of sunlight scattered from the nucleus was first attempted by Fay and Wisniewski (1978) on comet P/d'Arrest. The approach is identical to that used in the study of asteroids, and not surprisingly works best when the nucleus is devoid of coma, or "asteroidal". The relation between apparent magnitude m_λ and the physical properties of the nucleus is given by

$$p_\lambda C = 2.24 x \, 10^{22} \pi R^2 \Delta^2 \, 10^{0.4(m_{sun} - m_\lambda)} \tag{1}$$

where p_λ is the geometric albedo, C [m^2] is the geometric cross-section, R [AU] and Δ [AU] are the heliocentric and geocentric distances, and m_{sun} is the apparent magnitude of the sun. Evidently, optical photometry alone can reveal only the product $p_\lambda C$. A 5 km radius nucleus with $p_R = 0.04$ has $m_R \sim 14$, when observed at $R = \Delta = 1$ AU. The rotational modulation of C leads to a modulation of the apparent magnitude m_λ. An example is shown in Figure 2. Nucleus rotation lightcurves can be used to estimate the nucleus rotation period, the axis ratio projected in the plane of the sky, and the size of the nucleus (if the albedo is known). In principle, they can also be used to search for evidence of precession, which would appear as a multiple periodicity in the lightcurve. However, no compelling evidence for precession has yet been claimed in nucleus photometry (§3).

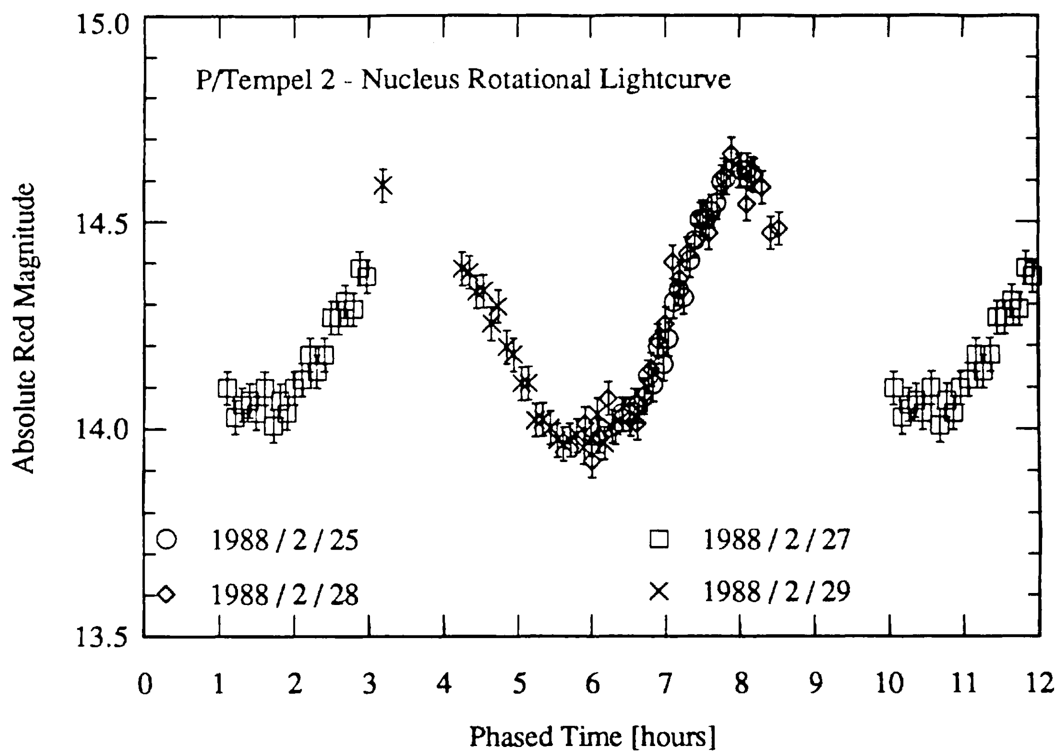

Figure 2 Rotational lightcurve of the nucleus of comet P/Tempel 2 at 6500 Å. The period is 8.95 hours. Figure from Jewitt and Luu (1989).

- Simultaneous optical/IR photometry has been employed by A'Hearn and collaborators in the investigation of several nuclei, to separately determine the geometric albedo and cross-section. Again, the technique is identical to one used previously on asteroids.

The optical brightness of a cometary nucleus is proportional to $p_{\lambda}C$ (Eq. (1)), while the thermal infrared brightness is proportional to (1-A) C, where A is the Bond albedo, and the two albedos are related by $A = p_{\lambda}q$. Here, q is the nucleus phase function, a measure of the angular dependence of the scattered solar radiation. Provided A and p_{λ} can be connected, optical and infrared observations can be used to determine the nucleus cross-section and albedo. This technique was first applied to a comet (P/Schwassmann-Wachmann 1) by Cruikshank and Brown (1983), and has since been applied to comets P/Arend-Rigaux (Tokunaga and Hanner 1985; Brooke and Knacke 1986; Birkett *et al.*, 1987; Veeder *et al.* 1987; Millis *et al.* 1988), P/Neujmin 1 (Birkett *et al.*, 1987; Campins *et al.* 1987) and P/Tempel 2 (A'Hearn *et al.* 1989).

• A limited number of radar and radio detections of nuclei have also been published (Kamoun *et al.* 1982; Goldstein *et al.* 1984; Campbell *et al.* 1989; Harmon *et al.* 1989). While these methods hold enormous potential for the understanding of cometary nuclei, they are restricted to near-Earth comets for reasons of signal-to-noise.

Indirect Methods

• The Halo Method was described in detail by Whipple (1982). It consists of using the radii and expansion speeds of concentric circular halos to estimate the rotation periods of cometary nuclei. Unfortunately, the method yields periods different from those obtained by direct methods, and appears unreliable (presumably because the halo expansion speeds are not sufficiently well known). Indeed, the physical nature of the halos (are they gas or dust?) was never clear.

• In the Jet Curvature Method (e.g. Larson *et al.* 1987; Klavetter and A'Hearn 1992) the curvature of cometary dust and gas jets is interpreted as a result of collimated emission from a rotating nucleus. In a time, t, ejected matter will travel a radial distance $r = u\ t$, while the nucleus turns through an angle $\theta = 2\ \pi\ t\ /\ \tau_{spin}$, where u is the ejection speed and τ_{spin} is the rotation period. Together these equations describe a spiral, and give the period $\tau_{spin} = 2\ \pi\ r\ /\ (u\ \theta)$ in terms of the curvature $r\ /\ \theta$. This method was applied most prominently to P/Halley (c.f. Larson *et al.* 1987), where a period $\tau_{spin} \sim 2.2$ days was deduced.

The practical problems with this method are (1) the ejection velocity u is not well known, (2) we observe only the projection of the jets into the plane of the sky, so that the true curvature is difficult to determine, (3) radiation pressure may distort the jets, especially at larger radii (larger flight times), and (4) the jets may evolve on timescales < τ_{spin}.

- Coma photometry (e.g. Millis and Schleicher 1986; Schleicher *et al.* 1991; Feldman *et al.* 1992) has been used to monitor cyclic temporal variations in the mass loss rate from comets. These variations are interpreted as diurnal variations due to nucleus rotation.

This method is useful only if $\tau_{cross} < \tau_{spin}$, where τ_{cross} is the diaphragm crossing time (Jewitt 1991). If $\tau_{cross} > \tau_{spin}$, then the projected photometry diaphragm contains particles ejected from more than one complete period of rotation, and the rotational modulation becomes heavily smoothed. A 10 arcsec radius diaphragm used to observe a comet at geocentric distance $\Delta = 2$ AU gives $\tau_{cross} \sim 8$ hours. Rotation periods $\tau_{spin} < 8$ hours could not be detected under these circumstances. In addition, it has yet to be shown that rotation is the only process capable of producing cyclic modulation of the production rate.

3 Shapes and Rotations

In comets Arend-Rigaux, Neujmin 1 and Tempel 2, the thermal infrared and scattered optical intensities vary in phase (see Fig. 3). This shows that the lightcurve variations are produced by rotation of an aspherical nucleus, and not by surface albedo spots (optically bright spots would have low temperatures and thermal emission, producing anti-correlated optical/IR lightcurves). Derived physical parameters of 7 relatively well-observed cometary nuclei are summarized in Table 1. In Fig. 4 we show the nucleus lightcurve range versus the period for each of 7 well-studied cometary nuclei. Also plotted for comparison in Fig. 4 are data for small and moderately sized main-belt asteroids from Binzel and Mulholland (1983) and Barucci *et al.* (1992). The figure shows that the nuclei exhibit systematically larger lightcurve ranges than comparable main-belt asteroids, and that the nuclei, as a group, are highly elongated objects (Jewitt and Meech 1988). Chiron has the smallest range of the plotted nuclei; indeed, it is possible that Chiron's rotational variations are due to albedo markings rather than aspherical shape. The statistical significance of the difference in Fig. 4 is better than 99%. There is, in contrast, little evidence for the claim (e.g., Wallis 1984) that the rotation period distribution of the nuclei is significantly different from that of small main-belt asteroids. An implicit result of Fig. 4 is that the nuclei are prolate rather than oblate in shape, since oblate bodies in rotation about their minor axes exhibit no rotational variations.

The comparison between comets and asteroids is taken further in Fig.5. There it may be seen that the mean lightcurve range increases from main-belt asteroids ($\Delta m \sim 0.2$) to Trojan asteroids ($\Delta m \sim 0.4$; Hartmann *et al.* 1988), to comets ($\Delta m \sim 0.7$; Jewitt and Meech 1988). The plotted Trojan asteroids are an order of magnitude larger than the

Table 1 Observational Parameters of Cometary Nuclei

Nucleus	$m_R(1,1,0)$[A]	Δm_R[B]	T(hrs)[C]	p[D]	R_{eff}[E]	Axis Ratio[F]	f[G]	S'(%/10^{3}Å)[H]
P/Arend-Rigaux	13.9±0.1[2]	0.7±0.1[2]	13.56±0.16[6,2]	0.03[6]	5[6]	1.9 / 1[2,6]	0.1-1[6]	16±3[6†]
P/Neujmin 1	12.2±0.2[7]	0.5±0.1[3,7]	12.67±0.05[3,7]	0.03±0.01[3]	10[3]	1.6 / 1[3,7]	0.1-1[3]	15±4[7]
P/Encke	14.5±0.5[4,11]	0.62±0.05[11]	15.08±0.08[11]	0.04?[11]	3.5?[11]	1.8 / 1[11]	0.2[4]	11±2[11]
P/Halley	13.7±0.2[1,7]	1.0±0.1[1,7]	≥ 18[7]	0.04[1,5]	5[5]	2 / 1[5]	10[5]	6±3[8]
P/Tempel 2	14.3±0.1[9]	0.7±0.1[9]	8.95±0.01[9]	0.02[10]	5[10]	1.9 / 1[9]	0.1-1[9]	20±3[7,9]
2060 Chiron	6.3 ± 0.1[12]	0.09±0.01[12]	5.91780[13]±	≥0.04[14]	≤150[14]	1.1 / 1[12]	?	-3±0.5[13]
P/SW-2[15]	14.6 ± 0.1	0.5±0.1	5.58 ± 0.02	0.04?	3.1?	1.6 / 1	?	?

Key

A -- Absolute red magnitude of nucleus
B -- Apparent photometric range of nucleus rotational lightcurve
C -- Rotation period (hours)
D -- Visual geometric albedo
E -- Radius of an equal-area circle
F -- Lower limit, inferred from Δm except for P/Halley
G -- The ratio (active area x 100) / (total surface area of nucleus)
H -- Reflectivity gradient in V - R wavelength range
† -- Color is U - B rather than V - R

References (Chronological)

(1) Jewitt and Danielson. 1984.
(2) Jewitt and Meech. 1985.
(3) Campins, A'Hearn, and McFadden. 1987.
(4) Jewitt and Meech. 1987.
(5) Keller *et al.* 1987.
(6) Millis, A'Hearn, and Campins. 1988.
(7) Jewitt and Meech. 1988.
(8) Thomas and Keller. 1989.
(9) Jewitt and Luu. 1989.
(10) A'Hearn *et al.* 1989.
(11) Luu and Jewitt. 1990.
(12) Bus et al. 1989.
(13) Luu and Jewitt. 1990b.
(14) Jewitt and Luu. 1992.
(15) Luu and Jewitt. 1992.

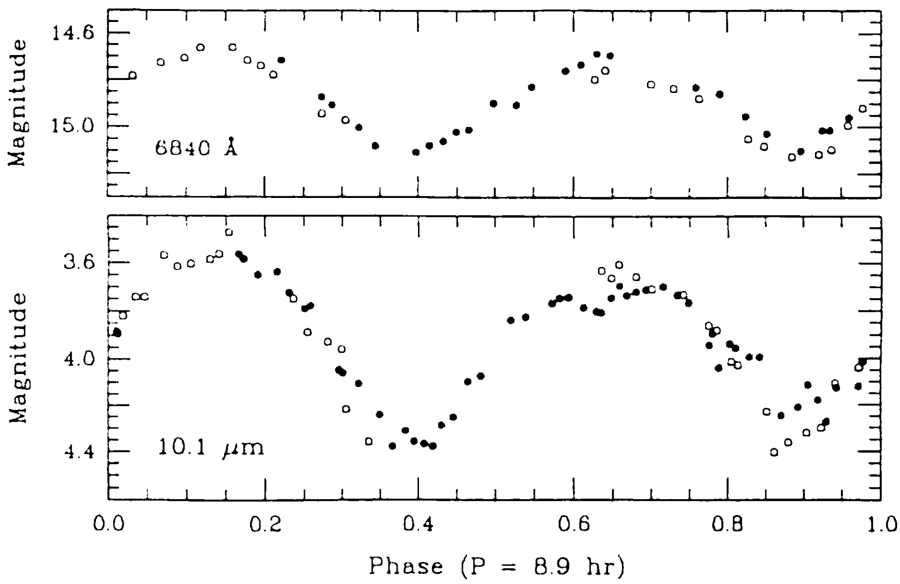

Figure 3 Simultaneous reflected optical (6840 Å) and thermal IR (10 μm) lightcurves of the nucleus of P/Tempel 2. Figure from A'Hearn et al. (1989). The lightcurves vary in phase.

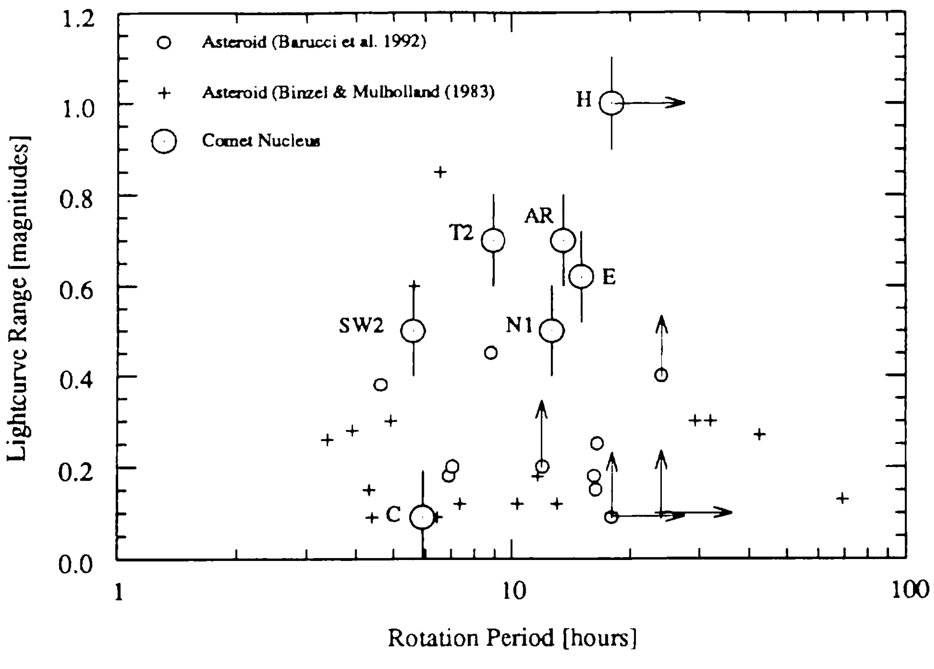

Figure 4 Lightcurve period vs. lightcurve range for cometary nuclei and main-belt asteroids. The asteroids from Barucci et al. (1992) are 30 - 50 km in diameter while those from Binzel and Mulholland (1983) are mostly 10 - 20 km diameter. The nuclei (diameters in Table 1) are identified AR = P/Arend-Rigaux, C = 2060 Chiron, E = P/Encke, H = P/Halley, N1 = P/Neujmin 1, SW2 = P/Schwassmann-Wachmann 2 and T2 = P/Tempel 2.

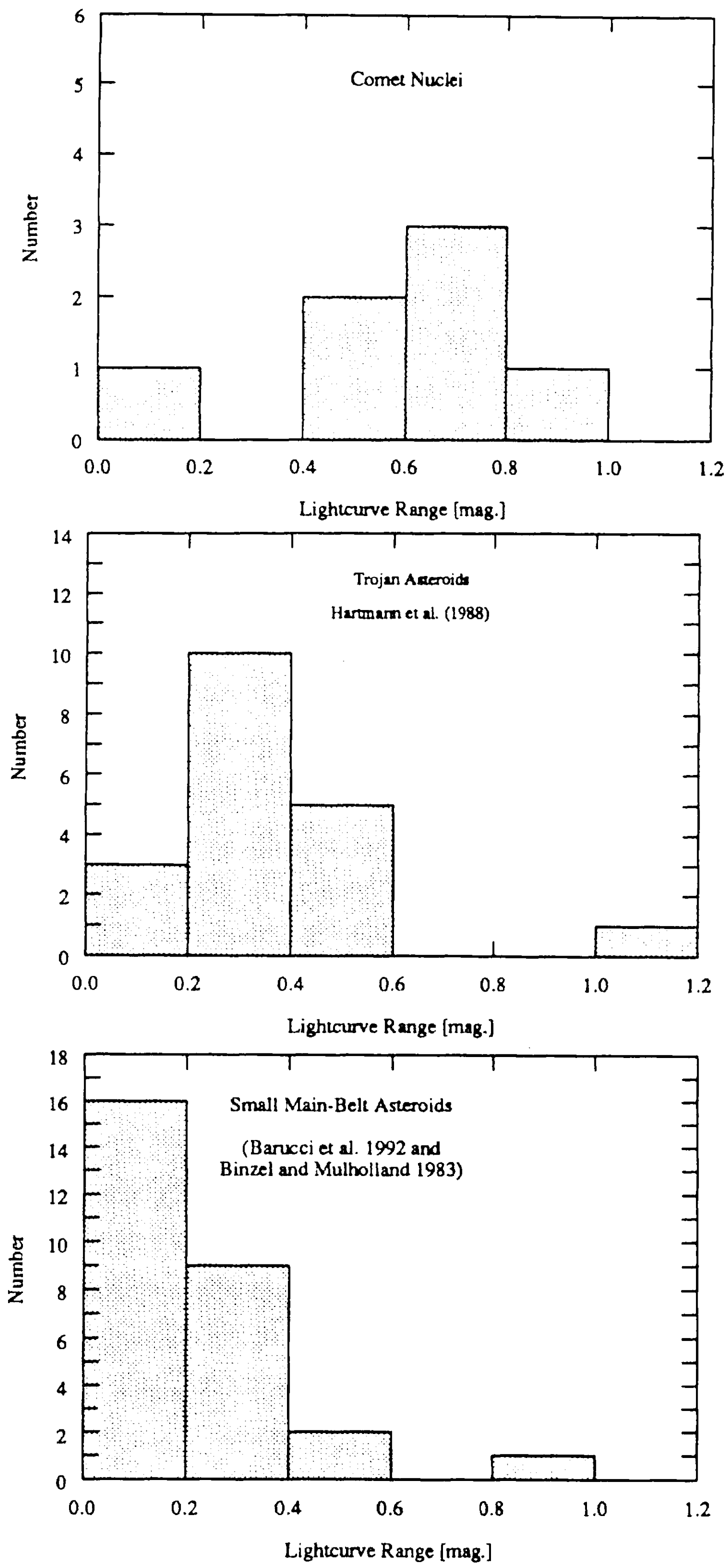

Figure 5 Distribution of lightcurve range for comets (top), Trojan asteroids (middle) and small main belt asteroids (bottom).

majority of plotted cometary nuclei (2060 Chiron is an exception), so that it is possible that differences in Fig. 5 reflect size-dependent effects (Binzel and Sauter 1992). The shapes of the main-belt asteroids are consistent with an origin by fragmentation in high energy collisions (Capaccioni *et al.* 1984), but this origin cannot account for the 2:1 axis ratios of the cometary nuclei. How might these extreme shapes be explained?

Primordial Shapes

- Random agglomeration of cometesimals in the solar nebula would produce irregular nuclei (Donn 1990). Under some circumstances, nuclei with 2:1 axis ratios can be produced by agglomeration of equal-sized cometesimals (Jewitt and Meech 1988).
- Photometric ranges $\Delta m \sim 0.7$ mag., corresponding to axis ratios $a/b \sim 2$, would be naturally explained if many nuclei were contact binaries.

Modified Shapes

- Protracted mass loss should lead to modification of the initial nucleus shape (Jewitt and Meech 1988). As noted above, if $\tau_{dv} < \tau_{dyn}$, the loss of volatiles may change the shape of the nucleus in response to solar heating. However, if $\tau_m < \tau_{dv}$ (as seems likely based on the presence of mantles on all short period comets observed to date), the loss of volatiles and the shape evolution of the nucleus will be controlled by the surface mantle. Therefore, it is not clear whether nuclei undergo substantial shape evolution due to mass loss.
- As an extreme case of mass loss, splitting will cause a change in the shape of the nucleus. If splitting is caused by spin-up (§4), the likely effect would be to break off extremities of the nucleus and so to decrease the axis ratio. However, the cause of splitting is unknown, so that we cannot be sure even of the sense of the change in shape it produces.

Spin-Up and Precession

In the absence of external torques, the nucleus should spin about its axis of maximum moment of inertia (minimum energy of rotation), with a period determined by the primordial angular momentum acquired at the time of formation. Excited (precessional) motions acquired at formation would be damped by internal friction, since $\tau_{\mathrm{damp}} << \tau_{\mathrm{oort}}$ (§1). However, both the linear and the angular momentum of the nucleus may be changed by mass ejection in response to solar heating. Anisotropy in the mass loss gives rise to a net force on the nucleus, resulting in the familiar "non-gravitational" acceleration (Whipple 1950), while non-central mass loss produces a torque on the nucleus, changing the spin.

Consider a uniform nucleus in which the momentum of escaping material makes a moment-arm P with the center of the nucleus. The scalar torque exerted by the mass loss is

$$T = u_{th} P \frac{dM}{dt} \tag{2}$$

where dM/dt [kg s^{-1}] is the mass loss rate and u_{th} [m s^{-1}] is the ejection speed of the material. This torque equals the rate of change of the spin angular momentum,

$$\frac{dL}{dt} = k M_n r_n^2 \frac{d\Omega}{dt} \tag{3}$$

where Ω [s^{-1}] is the angular velocity, k is the coefficient of inertia and r_n and M_n are the nucleus radius and mass. Combining Eqs. (2) and (3), the resultant timescale for change of the angular momentum $\tau_{ex} \sim L / (dL/dt)$ is (to within numerical factors of order unity)

$$\tau_{ex} \sim \frac{\Omega \rho r_n^5}{u_{th} P \frac{dM}{dt}} \tag{4}$$

Substituting $\Omega = 2\pi / 10$ hours, $\rho = 10^3$ kg m^{-3}, $r_n = 5000$ m, $k = 0.4$, $u_{th} = 10^3$ m s^{-1}, $dM/dt = 10^3$ kg s^{-1} and $P = r_n$, we obtain $\tau_{ex} \sim 10^8$ s ~ 3 years (c.f. Samarasinha *et al.* 1986; Wilhelm 1987). This is a lower limit because $P = r_n$ is the maximum allowable moment-arm, and because $dM/dt = 10^3$ kg s^{-1} is sustained for only a few months per orbit, even in comets with small perihelion distances. However, it seems likely that non-central mass loss is capable of changing the spin of a 5 km nucleus on timescales of the same order as τ_{orb}. Smaller nuclei would be relatively more susceptible to spin-up (Eq. 4), while giant nuclei (e.g. Chiron) presumably retain their primordial spins.

One natural consequence of the spin-up of a cometary nucleus would be that these bodies are sometimes driven to centripetal instability. Then, depending on the tensile strength, the nucleus may be disrupted or split by its own spin. If the nuclei consist of aggregated, weakly-bonded cometesimals (e.g. Donn 1990) it is easy to imagine a separation along pre-existing cometesimal boundaries. In this simple scenario, the split comets should be found spinning near their (shape-dependent) centripetal limits. There is presently no *direct* evidence for the spin up of a cometary nucleus, although indirect evidence (based on coma photometry) has been presented for the spin up of comet Levy (Schleicher *et al.* 1991; Feldman *et al.* 1992).

Equation (4) also gives the timescale for the excitation of nuclear precession. Because

τ_{ex} is small compared to the nuclear damping τ_{damp} and dynamical lifetimes τ_{dyn}, we expect that cometary nuclei should, in general, precess. It is something of a surprise that *direct* evidence for nuclear precession is non-existent; the lightcurves of cometary nuclei are, to date, all consistent with simple rotation (see references in Table 1). One possibility is that internal friction in the nucleus is dramatically underestimated (c.f. Burns and Safronov 1973), so that excited rotational states are quickly damped. A more likely possibility is that we have not yet obtained photometric sequences of sufficient length and accuracy to identify multiple periodicities in nucleus lightcurves. Collection of direct photometric evidence for precession in one or more cometary nuclei is an important objective of present cometary astronomy.

The non-gravitational accelerations of comets are due to reaction forces due to anisotropic mass loss (Whipple 1950). In some comets, the non-gravitational accelerations exhibit long term variations that have been attributed to slow nucleus precession (e.g. Whipple and Sekanina 1979; Sekanina 1981). The precessing oblate spheroid model of the cometary nucleus applied to many comets by Sekanina is undermined by the recent finding that cometary nuclei are prolate in shape, rather than oblate (c.f. Jewitt and Meech 1988). Furthermore, the standard non-gravitational force model has been generalised by Yeomans and Chodas (1989), with the result that the derived acceleration parameters are found to be highly model-dependent. In any case, secular variations in non-gravitational acceleration could equally well be caused by temporal evolution of the surface distribution of active areas (see §5).

There is observational evidence for periodicity on two different timescales in comet P/Halley (e.g. Larson *et al.* 1987; Millis and Schleicher 1986), and this has been widely interpreted as evidence for nuclear precession (e.g. Wilhelm 1987; Peale and Lissauer 1989; Watanabe 1989; Belton *et al.* 1991; Samarasinha and A'Hearn 1991). One troubling aspect of the Halley work is that the 2.2 and ~7 day periodicities are determined using different (indirect) observational methods (e.g. jet morphology in the former case, coma photometry in the latter). As we have already noted (§2), we do not fully understand the various indirect methods that have been applied with vigor to P/Halley. The curvature of jets is almost certainly influenced by nucleus rotation, but also by radiation pressure, and by projection of the 3-dimensional jet onto the plane of the sky. Disentangling these influences may be very difficult; in the presence of noisy or under-sampled data, it may be impossible. While the net evidence for precession in Halley is strong, it would be stronger if founded on one of the direct observational methods described in §2. The constancy of the non-gravitational acceleration of P/Halley led Yeomans (1986) to conclude that "There is no evidence for any precessional motion of the comet's spin axis", although this statement strictly refers to the absence of precessional motions on timescales comparable to the orbital period.

4 Internal Properties

The bulk density of the nucleus is one of the few physical properties unlikely to have been changed by evolutionary effects. In principle, the density can be estimated from the rate of mass loss, dM/dt [kg s^{-1}], and from the non-gravitational acceleration g [m s^{-2}] using

$$\rho = \frac{\xi\, u_{th}}{g\, V} \frac{dM}{dt} \qquad (5)$$

where V [m^3] is the nucleus volume, and u_{th} [m s^{-1}] is the velocity at which sublimated materials depart from the nucleus. The dimensionless factor ξ accounts for the angular dependence of the mass loss ($\xi = 0$ for isotropic mass loss, $\xi = 1$ for collimated flow). It is a source of considerable uncertainty in the density estimate (but see A'Hearn and Schleicher 1988). This method has been applied most carefully to comet Halley (for which $V \sim 500$ km^3), yielding $\rho = 600$ (+900, -400) kg m^{-3} according to Sagdeev *et al.* (1988), and either $\rho = 300 \pm 100$ kg m^{-3} or $\rho = 700 \pm 200$ kg m^{-3} according to Rickman (1989). The range of derived densities for this single (well-observed) object is a measure of the difficulty inherent in the application of Eq. (5) to a real comet.

A rotating spherical nucleus of density ρ [kg m^{-3}] will be in a state of internal tension if the rotation period is less than a critical value

$$\tau_c\,[hours] = 3.3\left(\frac{1000}{\rho}\right)^{1/2} \qquad (6)$$

The critical periods of rotating elongated nuclei are larger than 3.3 hours, and suggest an alternate route to the nucleus density. The short rotation periods and elongated shapes of some comets can be used to place a lower limit to ρ, under the assumption that the nucleus is not in a state of internal tensile stress. By this method, the density of P/Tempel 2 was bounded as $\rho \geq 300$ kg m^{-3} (Jewitt and Luu 1989) and that of P/Schwassman-Wachmann 2 (SW2) as $\rho \geq 460$ kg m^{-3} (Luu and Jewitt 1992b). These "centripetal densities" are somewhat dependent on the assumed shape of the nucleus, but they appear to rule out ultra-low densities ($\rho < 100$ kg m^{-3}), and they are consistent with densities recently proposed on the basis of random agglomeration models ($\rho \sim 500$ kg m^{-3}; Donn 1990). In these models, densification occurs because of ram-pressure as individual porous particles are accreted onto the growing nucleus. Only the largest cometary nuclei have hydrostatic pressures sufficient to cause compression and densification. For example, in 2060 Chiron ($r_n \sim 10^5$ m), the hydrostatic pressure is $P_C \sim G\, \rho^2\, r_n^2 \sim 10^6$ N m^{-2}, greater than the compressive strength of Terrestrial snow (Donn 1963).

The tensile strength, σ_t , of the nucleus has been estimated using observations of certain comets that have split when passing near the sun (Whipple 1963). The method assumes that the splitting is caused by the gradient of solar gravity across the diameter of the nucleus, and yields $\sigma_t < 10^4$ N m^{-2}. In fact, the physical cause of splitting is unknown; some comets split far from the sun where they cannot possibly be influenced by the gradient of solar gravity (Whipple and Stefanik 1966; Sekanina 1982). In the context of recent agglomeration models (e.g. Yamamoto and Kozasa 1988; Donn 1990), it is not clear whether σ_t represents the tensile strength of the nuclear matter, or is simply an estimate of the contact force between cometesimal sub-units in the nucleus. In either case, the estimated strengths are very small. The tensile strength of a human hair is 3 orders of magnitude greater than σ_t, above. If the nucleus were completely strengthless, its shape would be one of the figures of rotational equilibrium (Chandrasekhar 1987). Weakly bonded aggregates of cometesimals might deform under rotation to adopt a figure close to one of rotational equilibrium. The shape of the nucleus of P/Tempel 2 is close to such a figure (Sekanina 1991).

An honest but dispiriting summary of the internal properties would be that the nucleus density is known to be within a factor of a few of ρ = 1000 kg m^{-3} (c.f. Peale 1989), the tensile strength is suspected to be very small, while the rôle played by centripetal forces in shaping the nucleus is potentially profound, but highly uncertain.

5 Surface Properties

The visual geometric albedos of comets are very small (Table 1) with an average p_v = 0.03 ± 0.01 (4 nuclei; Tokunaga and Hanner 1985; Brooke and Knacke 1986; Campins *et al.* 1987; Veeder *et al.* 1987; Millis *et al.* 1988; A'Hearn *et al.* 1989). For reference, the geometric albedo of pure snow exceeds 0.9, while that of the Moon is 0.11. It is somewhat counter-intuitive that the most ice-rich bodies in the solar system should also be the darkest. The measured albedos are among the smallest known, and are incompatible with surfaces of pure snow or ice. Instead, the albedos refer to non-volatile mantles, and suggest a carbon-rich composition (c.f. Gradie and Veverka 1980; Cruikshank 1987). Among the known asteroids, only the D-types possess comparably low albedos and they, too, are suspected of having complex hydrocarbon surfaces (Gradie and Veverka 1980).

A refractory mantle inhibits sublimation in two distinct ways (Shul'man 1972b). First, the mantle overlies and insulates the sublimating surface, reducing the sublimation rate. Second, gas flow through the mantle is limited by the diameter and tortuosity of the open channels between grains in the mantle. Models and laboratory experiments suggest that mantle thicknesses of millimeters to centimeters can severely inhibit gas flow from beneath (Grün *et al.* 1991). In the case of the comets, it is not known if the mantles are practically impermeable to gas flow from beneath. However, it *is* well known that gas flow is strongest at localized "active areas" or vents.

The fraction of the nucleus surface area that is mantled can be estimated by comparing the water production rate from a comet with the rate expected from a bald nucleus of equal size. Active fractions (see Table 1) range from $f \sim 0.1$ (Halley) to $f \sim 0.001$ - 0.01 (Encke, Tempel 2, Arend-Rigaux). The preponderance of small f suggests that mantles grow quickly towards near - complete coverage of the nucleus, and play a major role in stifling the loss of volatiles from comets. Active areas are responsible for fine structure in the inner coma, including the collimated jets imaged in many comets.

Two distinct processes have been proposed for the formation of cometary mantles (Fig. 6). The Type 1 or "irradiation mantle" is produced by prolonged irradiation of the surface layers of the nucleus by high energy (MeV to GeV) cosmic rays (Shul'man 1972a; Donn 1976; Johnson 1991). High energy particles break and re-assemble chemical bonds in molecular solids near the nucleus surface, leading to the formation of new compounds and radicals. The irradiated layer has mass column density $\sim 10^3$ kg m^{-2} (Shul'man 1972a; Johnson *et al.* 1987) corresponding to thickness $d_m \sim 1$ m if formed in water ice with $\rho = 10^3$ kg m^{-3}, increasing to $d_m \sim 10$ m if the surface layers are highly porous ($\rho = 10^2$ kg m^{-3}). The timescale for chemical conversion of this surface layer (determined by the flux of cosmic rays) is $10^{8\pm1}$ yrs (Shul'man 1972a). Laboratory experiments show that hydrogen is preferentially liberated during irradiation in reactions such as $H_2O \rightarrow O + H_2$ and $2\,CH_4 \rightarrow C_2H_6 + H_2$. Therefore, the Type 1 mantle is expected to consist of a water-depleted, refractory, structurally complex material, rich in carbon, nitrogen and oxygen. Laboratory examples of similar materials are known as "kerogens" or "tholins" (Cruikshank 1987). The color of the Type 1 mantle is a function of the fluence and energy of the radiation and of the composition (Andronico *et al.* 1987). Notice that the Type 1 mantles are thick, and would exist on "fresh" comets newly entering the planetary region.

The Type 2 or "rubble mantle" consists of refractory solids that are too large to be ejected from the cometary nucleus by gas drag. It is thus a gravitationally bound armor that grows on the nucleus as a by-product of outgassing (e.g. Shul'man 1972b; Fanale and Salvail 1984). Such a mantle may also develop weak cohesion which may help to stabilise it against subsequent ejection (c.f. Kajmakov and Sharkov 1972; Storrs *et al.* 1988). It is clear that the timescale for the growth of the Type 2 mantle is a complicated function of the

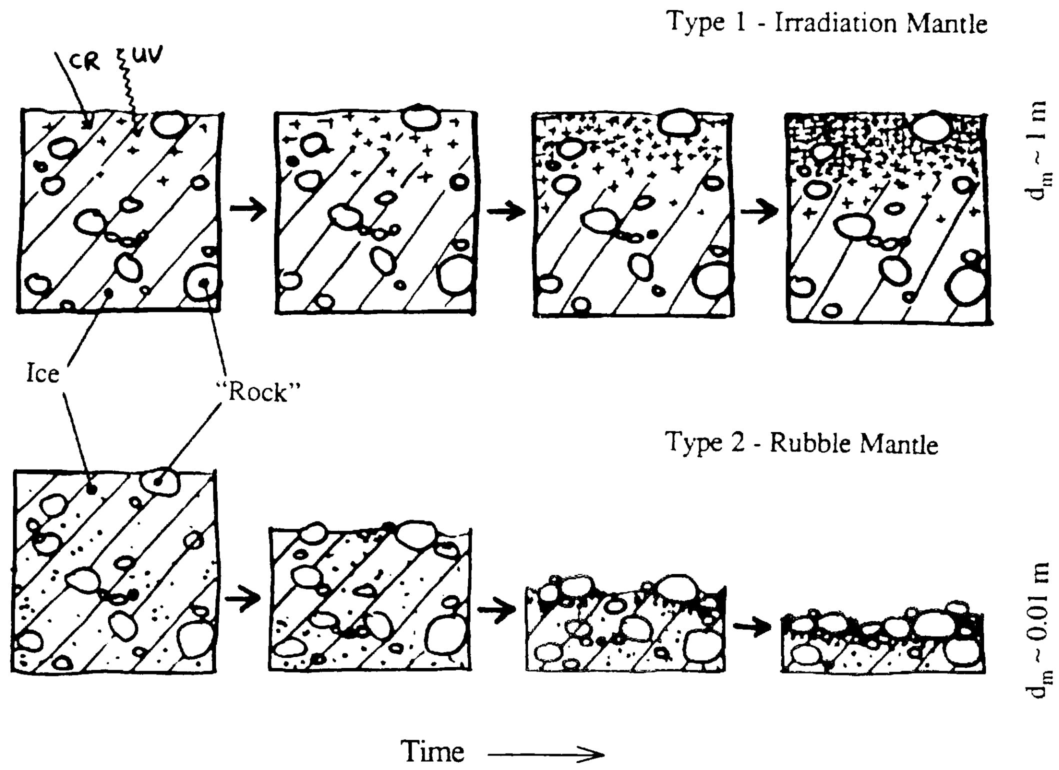

Figure 6 *(a) Type 1 or "irradiation mantle". The ice-rock mixture near the nucleus surface is irradiated by cosmic rays, producing a meter-thick ion-damaged mantle (small crosses). (b) Type 2 or "rubble mantle". The sublimation surface moves into the nucleus, progressively exposing large particles that cannot be ejected by gas drag. These collect at the surface, choking further sublimation.*

nucleus mass, spin, and orbit, being shorter for large, slowly rotating nuclei than for small, rapidly spinning ones. In numerical simulations of short period comets, Rickman *et al.* (1990) found timescales for mantle growth comparable to the orbital periods of many comets. Thus, some Type 2 mantles might be ephemeral cometary structures varying in response to seasonal and orbital changes in the comet. A comet whose orbit undergoes secular shrinkage might form a mantle, only to have it repeatedly disrupted and re-formed as the orbit evolves towards smaller perihelion distances. Indeed, Rickman *et al.* (1991) reported indirect observational evidence for the formation of stable mantles on timescales $\tau_m \sim (10 \text{ to } 30)\ \tau_{orb} \sim 10^{2\text{-}3}$ yr. Centripetal acceleration may also affect the rate of growth of the Type 2 mantle. A gravitationally bound rubble mantle could not grow on the apex of the prolate nucleus of P/SW2, for instance, if the density were ≤ 460 kg m^{-3} (§4). One wonders whether rapid rotation naturally favors the exposure of active areas on the rotational extremities of cometary nuclei. Such locations would maximize the torques due to mass loss, enhancing spin up.

We expect that the Type 1 mantle should be severely damaged by outgassing upon entry of the comet to the inner solar system. It may be cracked and ejected by gas drag, or simply buried by the growth of a Type 2 rubble mantle.

In thermal equilibrium at heliocentric distance $R = 1$ AU, the rate of sublimation of dirty water ice (albedo 0.04) is of order $dM/dt \sim 10^{-4}$ kg m^{-2} s^{-1}. The corresponding rate at which a sublimation surface would move into the nucleus is $\rho^{-1}\, dM/dt \sim 10^{-7}$ m s^{-1} for $\rho = 10^3$ kg m^{-3}, or about 1 cm per day. (This rate scales roughly as R^{-2}, provided $R < 1$ AU). Thus, in a comet which spends several months inside $R = 1$ AU, a few meters of material may be preferentially lost from active areas by sublimation (c.f. Sekanina 1990). The effect of this sinking of the sublimation surface relative to the surrounding mantle is unknown. On timescales of 10's or 100's of orbits, the active areas would "dig their own graves", by becoming so deep as to be self-shadowing. Presumably, the adjacent mantle re-adjusts (by collapse?) as the sublimation surface recedes from the mantle surface. Sudden mantle readjustments may produce outbursts in cometary activity.

As yet, no adequate near infrared reflection spectra of nucleus mantles have been obtained, so that the chemically diagnostic fundamental vibration bands of molecular bonds are unobserved. However, in the optical, there is new evidence that the spectra of cometary nuclei are remarkably diverse (Luu 1992), ranging from the slightly blue Chiron (optical reflectivity gradient $S' = -3 \pm 0.5$ % / 1000 Å) to the red P/Tempel 2 ($S' = 20 \pm 3$ % / 1000 Å; Spinrad *et al.* 1979; Jewitt and Luu 1989; A'Hearn *et al.* 1989). Why such a large range of colors should exist among objects with (presumably) similar dynamical and chemical histories is a mystery. Laboratory reflectance measurements of mantles formed from ice/carbon/silicate mixtures yield reflectance spectra which are too blue ($S' < 2.2$ % / 1000 Å) to match a majority of the nuclei (Stephens and Gustafson 1991). According to these authors, the blue color results partly from Rayleigh scattering by submicron silicate grains, emphasizing that both composition and geometric effects are important in determining the color of a particulate surface. Spectra of irradiated ice mixtures exhibit a range of optical colors, but the colors are not simple functions of the fluence, and it is difficult to extract quantitative information from the published laboratory studies. In the context of the Type 1 vs. Type 2 paradigm described above, the majority of short period comets should exhibit Type 2 rubble mantles. Differences in color among different mantles of Type 2 presumably reflect variations in mean particle size and composition. A comparison of colors of nuclei and Trojan asteroids is shown in Fig. 7.

An object that seems to support the irradiation vs. rubble mantle hypothesis is the distant object 5145 (1992 AD). It has an optical reflection spectrum that is redder than that of any asteroid or comet measured to date. Carbon-rich "kerogen" surface coatings have

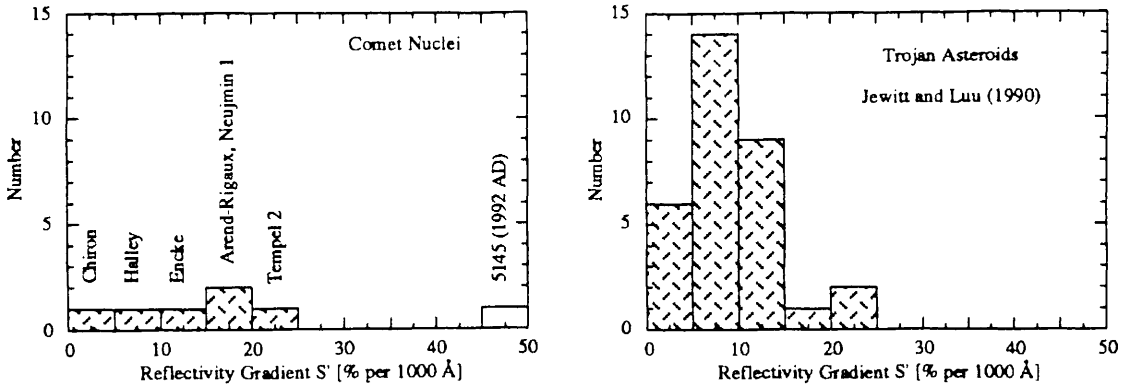

Figure 7 Distribution of S' among cometary nuclei and Trojan asteroids (from Jewitt and Luu 1990 and Luu 1992).

been proposed to account for this redness (Fink *et al.* 1992; Luu 1992; Mueller *et al.* 1992). However, the spectral contrast between 1992 AD and (the otherwise similar object) 2060 Chiron is striking (Fig. 8). One is tempted to identify the red color of 1992 AD with a Type 1 mantle, not yet destroyed or buried by cometary activity. The more neutral color of Chiron would then be a Type 2 mantle formed as a result of the activity displayed by this object. This is an attractive, self-consistent but non-unique explanation of the difference seen in Fig. 8. It could be observationally tested if the color of 1992 AD were observed to become less red following a period of mass loss.

6 Asteroids & Comets

Dead comets might contribute to the population of near-Earth asteroids (NEAs). Attempts to directly detect weak mass loss from NEAs have so far proved negative; their active fractions must be $f < 10^{-4}$ and their mass loss rates $dM/dt < 0.1$ kg s^{-1} in order to have escaped detection (Luu and Jewitt 1992a). It is possible that dead comets are occasionally reactivated (by collisions with interplanetary debris or by gas pressure cracking) so that objects now classified as NEAs would be recognized as comets at some future date, and vice versa (c.f. Kresak 1987).

Hartmann *et al.* (1987) reported that those NEAs having close orbital similarities to comets were predisposed to be dark and red, and used this conclusion to equate these objects with dead comets. However, the purported parent of the Geminid meteor stream, 3200 Phaethon, has a comet-like orbit but is one of the bluest known asteroids (S' = -9 % / 1000 Å; Luu and Jewitt 1990c). Comet 2060 Chiron is also slightly blue

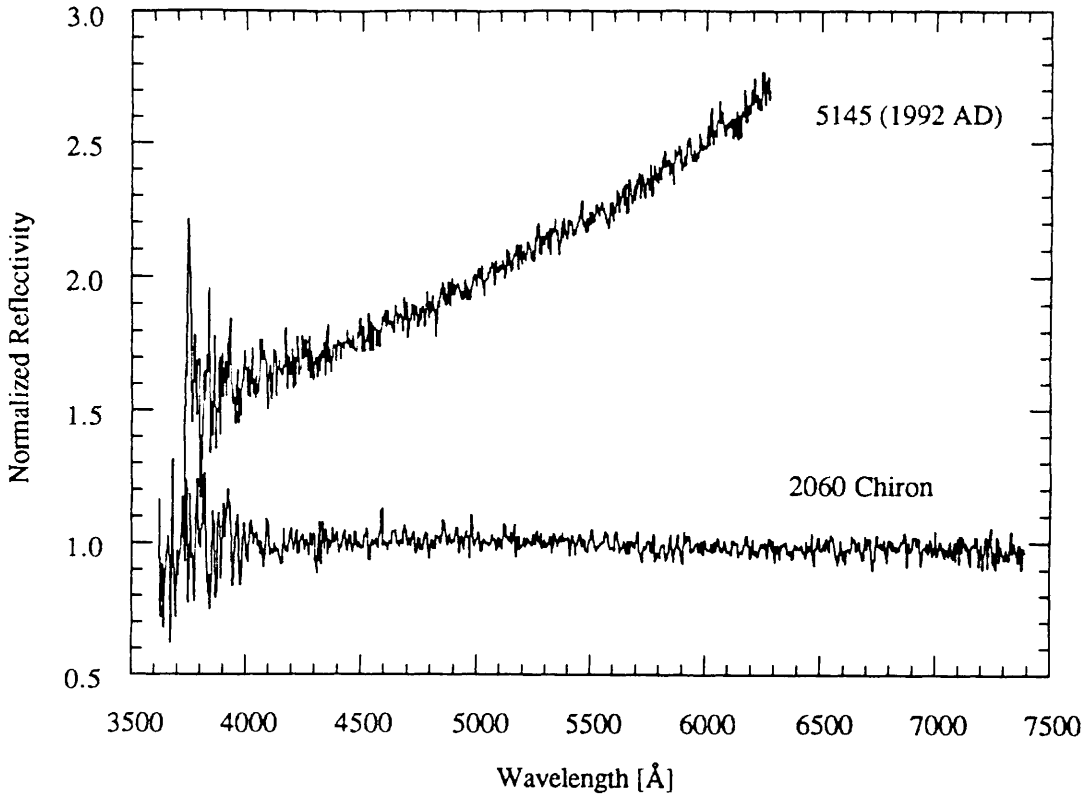

Figure 8 *Reflection spectra of 5145 = 1992 AD (top: S' = 46 % / 1000 Å) and 2060 Chiron (bottom: S' ~ -3 % / 1000 Å). Spectra are normalised to unity at 5000Å; the spectrum of 5145 is offset by 1 unit for clarity. The spectrum of 5145 was obtained UT 1992 March 11 at the Multiple Mirror Telescope by Jane Luu (Center for Astrophysics, Harvard Univ.). The Chiron spectrum is from Luu and Jewitt (1990).*

(S' = -3 % /1000 Å; Luu and Jewitt 1990a) and the nucleus of P/Halley is dark but not significantly red (S' = 6 ± 3 % / 1000 Å; Keller 1990). Thus, neither cometary nuclei nor their suspected asteroidal counterparts can be uniquely distinguished on the basis of red colors, and the applicability of Hartmann *et al.*'s reasoning is unclear.

Water would have survived as a solid in the solar nebula at radial distances $R > 5$ AU. Thus, the Trojan asteroids could retain substantial quantities of water ice at depths large compared to the diurnal thermal skin depths ($d \sim$ few cm). The surfaces of D-type asteroids (prevalent in the Trojan clouds) are anhydrous, leading Jones *et al.* (1990) to suggest that water was incorporated in these objects as ice, and was never warm enough to form hydrated silicate alteration products of the type observed in less primitive asteroids. Direct evidence for buried ice is difficult to obtain. Weak but prolonged diffusive flow of water vapor through a mantle might deposit local surface frosts that could be detected spectroscopically. Unusually energetic collisions with other asteroids might expose buried ice and activate temporary, sublimation-driven comae, although this occurrence would be extremely rare. No gas features were suspected in 20 Å resolution spectra of 32 Trojan asteroids (Jewitt and Luu 1990).

It is intriguing to note that the reflection spectra of nuclei can be matched object-by-object with spectra of Trojan asteroids (Jewitt and Luu 1989), consistent with the pervasive presence of low albedo organics (kerogens?) in the outer solar system (Cruikshank 1987). In fact, in terms of their spectra and their albedos, there is presently no clear difference between the cometary nuclei and the Trojan asteroids (Jewitt and Luu 1990). The elongated shapes of the larger Trojans are further reminiscent of cometary nuclei, although the extreme 2:1 axis ratios seen in the comets are apparently rare among the Trojans (Hartmann *et al.* 1988; Hartmann and Tholen 1990). Temporary captures of comets at the Jovian Lagrangian L4 and L5 points are well known (e.g. Carusi *et al.* 1985). Whether some of the Trojans are physically equivalent to captured comets is not clear. However, their primitive natures and presumed ice-rich interiors make this possibility deserving of close theoretical and observational attention.

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References

A'Hearn, M. F. (1988). Observations of Cometary Nuclei. Ann. Rev. Earth. Planet. Sci. **16**, 273-293.

A'Hearn, M. F., and Schleicher, D. G. (1988). Comet P/Encke's Nongravitational Force. Ap. J., **331**, L47-L51.

A'Hearn, M. F., Campins, H., Schleicher, D. G., and Millis, R. L. (1989). The Nucleus of P/Tempel 2. Ap. J. **347**, 1155-1166.

Andronico, G., Baratta, G., Spinella, F., and Strazzulla, G. (1987). Optical Evolution of Laboratory-Produced Organics, Astron. Ap., **184**, 333-336.

Bar-Nun, A., and Kleinfeld, I. (1989). On the Temperature and Gas Composition in the Region of Comet Formation. Icarus, **80**, 243-253.

Barucci, M., Martino, M., and Fulchignoni, M. (1992). Rotational Properties of Small Asteroids: Photoelectric Observations. A. J., **103**, 1679-1686.

Bell, J., Davis, D., Hartmann, W., and Gaffey, M. (1989). Asteroids: The Big Picture. In Asteroids II, ed. R. Binzel. Univ. Arizona Press, Tucson, pp. 921-948.

Belton, M. J. S. (1991). Characterization of the Rotation of Cometary Nuclei. In Comets In The Post - Halley Era, eds. R. Newburn, M. Neugebauer and J. Rahe. Kluwer Academic Publishers, Netherlands. pp. 691-721.

Belton, M., Julian, W., Anderson, A., and Mueller, B. (1991). The Spin State and

Homogeneity of Comet Halley's Nucleus. Icarus, **93**, 183-193.

Binzel, R., and Mulholland, D. (1983). A Photoelectric Lightcurve Survey of Small Main Belt Asteroids. Icarus, **56**, 519-533.

Binzel, R., and Sauter, L. (1992). Trojan, Hilda, and Cybele Asteroids: New Lightcurve Observations and Analysis. Icarus, **95**, 222-238.

Birkett, C., Green, S., Zarnecki, J., and Russell, K. (1987). IR and Optical Observations of Low Activity Comets P/Arend-Rigaux and P/Neujmin 1. Mon. Not. Royal Astr. Soc., **225**, 285-296.

Bocklée-Morvan, D., and Crovisier, J. (1989). The Ortho/Para Ratio in Comets. In Asteroids, Comets, Meteors III, eds. C. I. Lagerkvist. Reprocentralen HSC, Uppsala, pp. 263-265.

Brooke, T. Y., and Knacke, R. F. (1986). The Nucleus of Comet P/Arend-Rigaux. Icarus, **67**, 80-88

Burns, J., and Safronov, V. (1973). Asteroid Nutation Angles. Mon. Not. Roy. Astr. Soc., **165**, 403-411.

Campbell, D. B., Harmon, J. K., and Shapiro, I. I. (1989). Radar Observations of Comet P/Halley. Ap. J., **338**, 1094.

Campins, H. C., A'Hearn, M. F., and McFadden, L. (1987). The Bare Nucleus of Comet Neujmin 1. Ap. J., **316**, 847-857.

Capaccioni, F., Cerroni, P., Coradini, M., Farinella, P., Flamini, E., Martelli, G., Paolicchi, P., Smith, P. N., and Zappala, V. (1984). Shapes of Asteroids Compared with Fragments from Hypervelocity Impact Experiments. Nature, **308**, 832-834.

Carusi, A., Kresak, L., Perozzi, E., and Valsecchi, G. B. (1985). Long-Term Evolution of Short-Period Comets. Adam Hilger, Bristol, England.

Chandrasekhar, S. (1987). Ellipsoidal Figures of Equilibrium. Dover, New York.

Cruikshank, D. (1987). Dark Matter in the Solar System. Adv. Space Res., **7**, 109.

Cruikshank, D. P., and Brown, R. H. (1983). The Nucleus of Comet P/Schwassmann-Wachmann 1. Icarus, **56**, 377-380.

Donn, B. (1963). Origin and Structure of Icy Cometary Nuclei. Icarus, **2**, 396-402.

Donn, B. (1976). In The Study of Comets, edited by B. Donn *et al.*, NASA SP-393, Washington DC, pp. 611-621.

Donn, B. D. (1990). The Formation and Structure of Fluffy Cometary Nuclei from Random Accumulation of Grains. Astron. Ap., **235**, 441-446.

Duncan, M., Quinn, T., and Tremaine, S. (1988). The Origin of Short Period Comets. Ap. J., **328**, L69-L73.

Edgeworth, K. E. (1949). The Origin and Evolution of the Solar System. Mon. Not. Roy. Astr. Soc., **109**, 600-609.

Everhart, E. (1973). Examination of Several Ideas of Comet Origins. A. J., **78**, 329-337.

Fanale, F. P., and Salvail, J. R. (1984). An Idealized Short-Period Comet Model. Icarus, **60**, 476-511.

Fay, T. D., and Wisniewski, W. (1978). The Lightcurve of the Nucleus of Comet d'Arrest. Icarus, **34**, 1-9.

Feldman, P., Budzien, S., Festou, M., A'Hearn, M., and Tozzi, G. (1992). UV and Visible Variability of the Coma of Comet Levy (1990c). Icarus, **95**, 65-72.

Fernandez, J. A. (1980). On the Existence of a Comet Belt Beyond Neptune. Mon. Not. R. astr. Soc. **192**, 481-491.

Fink, U., Hoffmann, M., Grundy, W., Hicks, M., and Sears, W. (1992). The Steep Red Spectrum of 1992AD: An Asteroid Covered With Organic Material? Icarus, **97**, 145-149.

Goldstein, R. M., Jurgens, R. F., and Sekanina, Z. (1984). A Radar Study of Comet IRAS-Araki-Alcock 1983d. A. J., **89**, 1745-1754.

Gradie, J., and Veverka, J. (1980). The Composition of the Trojan Asteroids. Nature, **283**, 840-842.

Grün, E. *et al.* (1991). Laboratory Simulation of Cometary Processes. In Comets In The Post - Halley Era, eds. R. Newburn, M. Neugebauer and J. Rahe. Kluwer Academic Publishers, Netherlands. pp. 277 - 297.

Harmon, J. K., Campbell, D. B., Hine, A. A., Shapiro, I. I., and Marsden, B. G. (1989). Radar Observations of Comet IRAS-Araki-Alcock 1983d. Ap. J., **338**, 1071-1093.

Hartmann, W., Tholen, D., Cruikshank, D. (1987). The Relationship of Active Comets, Extinct Comets, and Dark Asteroids. Icarus, **69**, 33-50.

Hartmann, W. K., Tholen, D., Goguen, J., Binzel, R., and Cruikshank, D. P. (1988). Trojan and Hilda Asteroid Lightcurves. Icarus, **73**, 487-498.

Hartmann, W. K., and Tholen, D. J. (1990). Comet Nuclei and Trojan Asteroids: A New Link and a Possible Mechanism for Comet Splittings, Icarus, **86**, 448-454.

Herman, G., and Weissman, P. R. (1987). Internal Temperatures of Cometary Nuclei. Icarus, **69**, 314-328.

Jewitt, D. C. (1991). Cometary Photometry. In Comets In The Post - Halley Era, eds. R. Newburn, M. Neugebauer and J. Rahe. Kluwer Academic Publishers, Netherlands. pp. 19 - 65.

Jewitt, D. C., and Danielson, G. E. (1984). Charge Coupled Device Photometry of Comet P/Halley. Icarus, **60**, 435.

Jewitt, D. C., and Meech, K. J. (1985). Rotation of the Nucleus of Comet P/Arend-Rigaux. Icarus, **64**, 329-335.

Jewitt, D. C., and Meech, K. J. (1987). CCD Photometry of Comet P/Encke. A. J., **93**, 1542-1548.

Jewitt, D. C., and Meech, K. J. (1988). Optical Properties of Cometary Nuclei and a Preliminary Comparison with Asteroids. Ap. J., **328**, 974-986.

Jewitt, D. C., and Luu, J. X. (1989). A CCD Portrait of Comet P/Tempel 2. A. J., **97**, 1766 - 1790.

Jewitt, D. C., and Luu, J. X. (1990). CCD Spectra of Asteroids II. The Trojans as Spectral Analogues of Cometary Nuclei, *A. J.*, **100**, 933-944.

Johnson, R., Cooper, J., Lanzerotti, L., and Strazzulla, G. (1987). Radiation Formation of a Non-Volatile Comet Crust. Astron. Ap., **187**, 889-892.

Johnson, R. (1991). Irradiation Effects in a Comet's Outer Layers. J. Geophys. Res., **96**, 17553-17557.

Jones, T. D., Lebofsky, L. A., Lewis, J. S., and Marley, M. S. (1990). The Composition and Origin of the C, P and D Asteroids. Icarus, **88**, 172-192.

Kajmakov, E. A., and Sharkov, V. I. (1972). Laboratory Simulation of Icy Cometary Nuclei. In The Motion, Evolution of Orbits, and Origin of Comets, IAU Symp. 45, eds. Chebotarev *et al.*, D. Reidel, Dordrecht. pp. 308-315.

Kamoun, P., Campbell, D., Ostro, S., Pettengill, G., and Shapiro, I. (1982). Comet Encke: Radar Detection of the Nucleus. Science, **219**, 293-296.

Keller, H. U. (1990). The Nucleus, in Physics and Chemistry of Comets, edited by W. F. Huebner, Springer-Verlag, Berlin.

Klavetter, J., and A'Hearn, M. F. (1992). CN Jet Velocity in Comet P/Halley. Icarus, **95**, 73-85.

Klinger, J. (1980). Influence of a Phase Transition of Ice on the Heat Balance of Comet Nuclei. Science, **209**, 271.

Kresak, L. (1987). Dormant Phases in the Aging of Periodic Comets. Astron. Ap., **187**, 906-908.

Kuiper, G. P. (1951). On the Origin of the Solar System. In Astrophysics, edited by J. A. Hynek, McGraw Hill, New York, pp. 357-424.

Larson, S., Sekanina, Z., Levy, D., and Senay, M. (1987). Comet P/Halley Near-Nucleus Phenomena in 1986. Astron. Ap., **187**, 639-644.

Luu, J. X. (1992). CCD Spectra of Comet Nuclei and Comet Nucleus Candidates. Icarus, submitted.

Luu, J. X., and Jewitt, D. C. (1990a). Cometary Activity in 2060 Chiron. A. J., **100**, 913-932.

Luu, J. X., and Jewitt, D. C. (1990b). The Nucleus of P/Encke. Icarus, **86**, 69-81.

Luu, J. X., and Jewitt, D. C. (1990c). CCD Spectra of Asteroids: I. Near-Earth and 3:1 Resonance Asteroids. A. J., **99**, 1985-2011.

Luu, J. X., and Jewitt, D. C. (1992a). High Resolution Surface Brightness Profiles of Near-Earth Asteroids. Icarus, **97**, 276-287.

Luu, J. X., and Jewitt, D. C. (1992b). Near-Aphelion CCD Photometry of Comet P/Schwassmann Wachmann 2. A. J., in press.

Millis, R. L. and Schleicher, D. G. (1986). Rotational Period of Comet Halley. Nature, **324**, 646-649.

Millis, R. L., A'Hearn, M. F., and Campins, H. C. (1988). An Investigation of the Nucleus and Coma of Comet P/Arend-Rigaux. Ap. J., **324**, 1194-1209.

Mueller, B., Tholen, D., Hartmann, W. and Cruikshank, D. (1992). Extraordinary Colors of Asteroidal Object (5145) 1992AD. Icarus, **97**, 150-154.

Mumma, M. J., Weaver, H. A., and Larson, H. P. (1987). The Ortho-Para Ratio of Water in P/Halley. Astron. Ap., **187**, 419-424.

Oort, J. H. (1950). The Structure of the Cloud of Comets Surrounding the Solar System and a Hypothesis Concerning Its Origin. Bull. Astr. Inst. Netherlands, **11**, 91-110.

Peale, S. J. (1989). On the Density of Halley's Comet. Icarus, **82**, 36-49.

Peale, S. J., and Lissauer, J. (1989). Rotation of Halley's Comet. Icarus, **79**, 396-430.

Rickman, H. (1989). The Nucleus of Comet Halley: Surface Structure, Mean Density, Gas and Dust Production. Adv. Space Res., **9**, No 3, 59-71.

Rickman, H., Fernandez, J. A., and Gustafson, B. A. S. (1990). Formation of Stable Dust Mantles on Short Period Comet Nuclei. Astron. Ap., **237**, 524-535.

Rickman, H., Froeschle, C., Kamel, L., and Festou, M. C. (1991). Nongravitational Effects and the Aging of Periodic Comets. A. J., **102**, 1446-1463.

Roemer, E. (1966). The Dimensions of Cometary Nuclei. Mem. Soc. R. Sci. Liege. 15th Series 15, 23-28.

Sagdeev, R. Z., Elyasberg, P. E., and Moroz, V. I. (1988). Is the Nucleus of Comet Halley a Low Density Body? Nature, **331**, 240-242.

Samarasinha, N., A'Hearn, M., Hoban, S., and Klinglesmith, D. (1986). CN Jets of Comet P/Halley - Rotational Properties. In Proc. 20th ESLAB Symp., ed. B. Battrick, ESA SP-250, Heidelberg.

Samarasinha, N., and A'Hearn, M. (1991). Observational and Dynamical Constraints on the Rotation of Comet P/Halley. Icarus, **93**, 194-225.

Schleicher, D., Millis, R., Osip, D., and Birch, P. (1991). Comet Levy (1990c): Groundbased Photometric Results. Icarus, **94**, 511-523.

Sekanina, Z. (1976). A Continuing Controversy: Has the Cometary Nucleus Been Resolved? In The Study of Comets Part 2, edited by B. Donn, NASA SP-393, Washington DC, pp. 537-587.

Sekanina, Z. (1981). Rotation and Precession of Cometary Nuclei. Ann. Rev. Earth Planet. Sci., **9**, 113-145.

Sekanina, Z. (1982). The Problem of Split Comets in Review. In Comets, edited by L. L. Wilkening, Univ. Arizona Press, Tucson.

Sekanina, Z. (1990). Gas and Dust Emission from Comets and Life Spans of Active Areas on their Rotating Nuclei. A. J., **100**, 1293-1314.

Sekanina, Z. (1991). Comprehensive Model for the Nucleus of P/Tempel 2 and its Activity. A. J., **102**, 350-388.

Shul'man, L. M. (1972a). The Chemical Composition of Cometary Nuclei. In The

Motion, Evolution of Orbits, and Origin of Comets, IAU Symp. 45, eds. Chebotarev *et al.*, D. Reidel, Dordrecht. pp. 265-270.

Shul'man, L. M. (1972b). The Evolution of Cometary Nuclei. In The Motion, Evolution of Orbits, and Origin of Comets, IAU Symp. 45, eds. Chebotarev *et al.*, D. Reidel, Dordrecht. pp. 271-276.

Spinrad, H. Stauffer, J., and Newburn, R. L. (1979). Optical Spectrophotometry of Comet P/Tempel 2 Far from the Sun. P. A.S. P., **91**, 707-711.

Stephens, J. R., and Gustafson, B. A. S. (1991). Laboratory Reflectance Measurements of Analogues to Dirty Ice. Icarus, **94**, 209-217.

Stern, S. A. (1988). Collisions in the Oort Cloud. Icarus, **73**, 499-507.

Storrs, A. D., Fanale, F. P., Saunders, R. S., and Stephens, J. B. (1988). The Formation of Filamentary Sublimate Residues (FSR) from Mineral Grains. Icarus, **76**, 493-512.

Tokunaga, A. T., and Hanner, M. S. (1985). Does Comet P/Arend-Rigaux Have a Large Dark Nucleus? Ap. J., **296**, L13-L16.

Veeder, G., Hanner, M., and Tholen, D. (1987). The Nucleus of Comet P/Arend-Rigaux. A. J., **94**, 169-173.

Wallis, M. K. (1984). Rotation of Cometary Nuclei. Phil. Trans. R. Soc. London A **313**, 165-170.

Watanabe, J. (1989). Rotational Motion of the Nucleus of Comet P/Halley. Pub. Ast. Soc. Japan, **41**, 897-918

Whipple, F. L. (1950). A Comet Model I. The Acceleration of Comet Encke. Ap. J., **111**, 375-394.

Whipple, F. L. (1963). On the Structure of the Cometary Nucleus. In The Solar System IV: The Moon, Meteorites, and Comets. Eds. B. M. Middlehurst and G. J. Kuiper, Univ. Chicago Press, Chicago.

Whipple, F. L. (1982). The Rotation of Cometary Nuclei. In Comets, edited by L. L. Wilkening, Univ. Arizona Press, Tucson.

Whipple, F. L., and Stefanik, R. (1966). On the Physics and Splitting of Cometary Nuclei. Nature et Origine des Cometes, Univ. de Liege, **37**, 33-52.

Whipple, F. L. and Sekanina, Z. (1979). An Asymmetric Outgassing Model for Cometary Nongravitational Accelerations. A. J., **98**, 1083-1093.

Wilhelm, K. (1987). Rotation and Precession of Comet Halley. Nature, **327**, 27-30.

Yamamoto, T., and Kozasa, T. (1988). The Cometary Nucleus as an Aggregate of Planetesimals. Icarus, **75**, 540-551.

Yeomans, D. K. (1986). Physical Interpretations from the Motions of Comets Halley and Giacobini-Zinner. In Proc. 20th ESLAB Symp., ed. B. Battrick, ESA SP-250, Heidelberg, pp. 419-425.

Yeomans, D. K., and Chodas, P. W. (1989). An Asymmetric Outgassing Model for Cometary Nongravitational Acclerations. A. J., **98**, 1083-1093.

DISCUSSION

T. OWEN: Have you or others checked any of the Trojan asteroids for evidence of cometary activity ?

D. JEWITT: Yes, Luu and I have imaged Trojan asteroids to search for weak continuum comae, without success. I believe that Degewij, in his PhD thesis, reported several spectroscopic observations of Trojan asteroids. From memory, the limiting mass loss rates were of order 1 kg/sec, from the continuum method. These observations by no means exclude the idea that the Trojans are mantled, volatile-rich bodies ("comets").

M. BELTON: Regarding the origins of vents ... has anyone studied the collisional history of periodic comets ? It would surely be peculiar if only the comets were the only objects in the solar system not to be affected by collisions.

D. JEWITT: Yes, we looked at that in the context of the re-activation of dead comets (Icarus, June 1992). One needs to active about 10^{-4} of the geometric area to sustain an observable coma. Impacts large enough to do this are very rare (1 per 10^{6-7} yr, I recall), in fact, comparable to the dynamical lifetimes. Whole-surface erosion by micrometeorites will thin the mantle on a shorter time, but it is still difficult to reactivate a dead comet using impacts. Internal disruption , due to sublimation pressure at the mantle base, might be more efficient, particularly if the comet evolves toward smaller heliocentric distances and higher temperatures.

M. BELTON: On the origin of the elongated shape ... it seems to me that the mechanism of aspherical sublimation that you mentioned leads to an object in an unstable rotational state. This key, over a longer timescale decays interacting with the pattern of the sublimation. So it may be that it is really the **coupling** between rotation and some of the mechanism that you listed that leads to the typically elongated state.

D. JEWITT: Yes, it's a nice idea. Unfortunately, we don't know the timescale for a nucleus to eject a significant fraction of its total mass. For Halley, ($M \sim 10^{15}$ kg, dm/dt $\sim 10^{3}$ kg/sec) this time is of order 10^{12} sec = 10^{4} - 10^{5} yr. But the mantled fraction limits the mass loss, and thus the volatile depletion time may be determined by the mantle growth time. Thus there is a dependent relation between the mantling time, the mass loss time, the time for the excitation of precession, and possibly the time for spin-up and rotational fragmentation of the nucleus. It's all connected.