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THE NATURE OF COMET NUCLEI

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The icy-conglomerate model of comet nuclei has dominated all others since its introduction by Whipple (1950). It provided a basis for understanding the non-gravitational motions of comets which had perplexed dynamicists up to that time, and provided a focus for understanding cometary composition and origin. The image of comets as "dirty snowballs" was quickly adopted. Such images carried with it the notion that cometary surfaces must have high albedos, much like a snow-covered field in winter. This view began changing as it was realized that (1) comets were primitive bodies, (2) the most primitive meteoritic material, though most likely deriving from asteroids, was carbonaceous and dark, and (3) it only took a small amount of dark material to significantly reduce the albedo of ice (Clark 1982). Groundbased observations also suggested that comets might actually be dark objects (Hartmann *et al.* 1982; Cruikshank *et al.* 1985). This was dramatically confirmed when the *Giotto* and *Vega* spacecraft flew past the nucleus of Halley's comet in 1986. The nucleus was found to be so dark that it reflected only about 5% of the incident sunlight (Keller *et al.* 1986; Sagdeev *et al.* 1986).

So, how much of the dirty snowball is actually dirt?

Estimates based on mass-loss rates determined from gas and dust emissions observed from the Earth tended to place the refractory to volatile mass ratio between 0.1 and 1 (Greenberg 1982; Delsemme 1982). Thus, comets were primarily ice, both by mass and volume. The dust impact experiment on *Giotto* determined that there was a greater population of large particles than had been previously assumed - particles not easily seen at visual wavelengths from the ground. Based on these measurements it was estimated that Halley had a refractory to volatile mass ratio of 2 (McDonnell *et al.* 1991).

Recent analysis of comet dust trails, a phenomenon discovered by the *Infrared Astronomical Satellite* (Sykes *et al.* 1986a), suggests that the refractory to volatile mass ratio for short-period comets should be around 3 (Sykes and Walker 1991). Thus, a comet would be around 50% refractory material by volume (compressed) and 75% by weight. Such a mixture at outer-solar system temperatures would be best described as a frozen mudball.

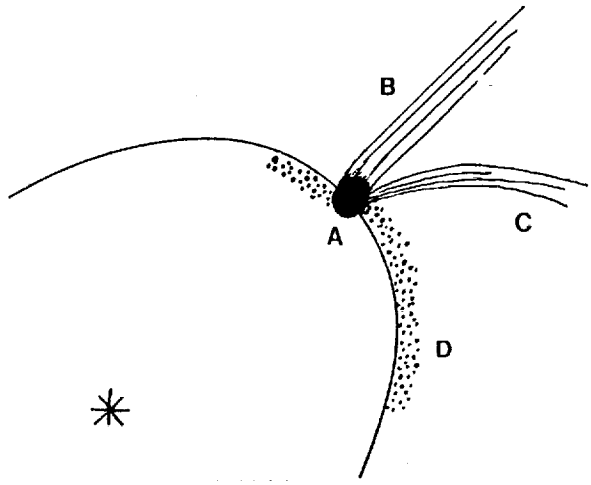

Figure 1. Comets generally exhibit a variety of phenomena at visual wavelengths including (a) the coma, (b) an ion tail, and (c) a dust tail. The *Infrared Astronomical Satellite* was the first to detect the comet dust trail (d) consisting of large particles moving slowly away from the nucleus along orbital paths very close to that of the parent comet (from Sykes and Walker 1991).

Trails are not to be confused with either cometary comae or *tails* (Fig. 1). They consist of large - mm to cm size - particles moving at velocities of meters/sec relative to their parent comet (Sykes *et al.* 1986b). Because of these low velocities and their relative insensitivity to radiation pressure, trails are found very close to the orbital path of their parent comet. They extend over only a portion of their parent orbit, always connected to the orbital position of the nucleus, and their lengths limited by the effects of gravitational perturbations (which can result in relatively sudden shifts in orbits independently for the parent comet and trail particles).

On the basis of an exhaustive survey of the IRAS data, giving consideration to observational selection effects in that data, we inferred that all short period comets have trails - though only 8 were detected at the time of the IRAS mission. The generality of the trail phenomenon is important, because what we learn about the specific trails observed may then be extended to the rest of the short-period comet population.

Mass loss rates have been calculated for trail particles and compared to total mass loss rates for the same comets on the basis of visual wavelength observations (Kresák and Kresáková 1987). These latter calculations assume a refractory/volatile mass ratio of 0.33, and consider the detailed orbital evolution of these comets over the past 100 years. They are compared to the trail mass loss rates in Figure 2. In each case it is found that the trail mass loss rates exceed those based on estimates of gas production and small dust particles. This suggests that trails are a significant if not principal mechanism of mass loss in short-period comets (Sykes and Walker 1991).

Trail particles are quickly devolatilized in the inner solar system (Lien 1990) and therefore consist of purely refractory particles. Such large mass loss rates in refractory particles implies a much larger fraction of the nucleus consists of refractory material than

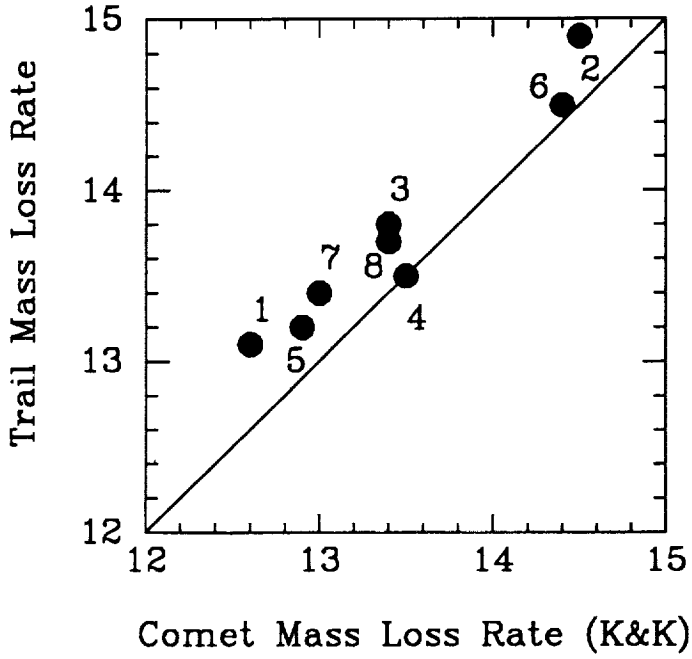

Figure 2. Trail mass loss rates determined by Sykes and Walker (1991) compared to total comet mass loss rates as determined by Kresak and Kresakova (1987) for (1) Churyumov-Gerasimenko, (2) Encke, (3) Gunn, (4) Kopff, (5) Pons-Winnecke, (6) Schwassmann-Wachmann 1, (7) Tempel 1, and (8) Tempel 2. Units are in Log (grams/century).

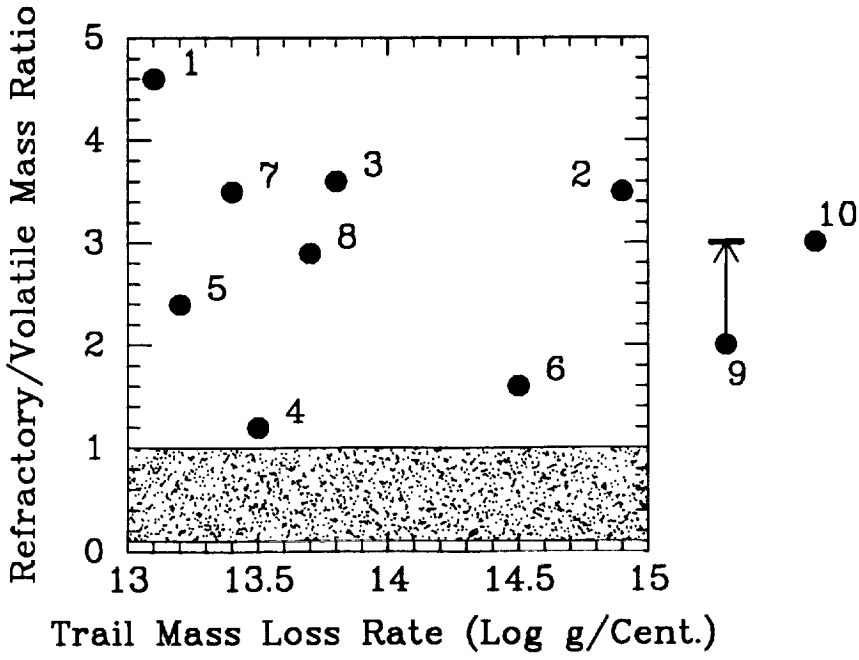

Figure 3. Refractory to volatile mass ratios are shown for trail comets as enumerated above. For comparison, values are shown for (9) Halley (McDonnell *et al.* 1991) and (10) Pluto and Triton (see text). The shaded area spans the canonical ratios between 0.1 and 1.

had previously been estimated. Estimating gas mass loss rates from Kresák and Kresáková (1987), refractory/volatile mass ratios are calculated for each of the trail comets and are shown in Figure 3. The average ratio is 2.9. This is consistent with an upper limit of ~ 3 estimated for Halley (McDonnell *et al.* 1991), which was arrived at by extrapolating their size distributions to include an estimate of the largest liftable mass from the surface.

Such a large increase in the refractory fraction of comet nuclei does not necessarily mean that they are correspondingly dense. Trails represent the first stage in the dynamical evolution of meteor streams (Sykes *et al.* 1986a), and the mass density of meteor stream particles range between 0.2 and 1 g/cm^3 (Lindblad 1986). Interplanetary dust particles collected by aircraft experiments which have very low density "fairy-castle" structure are thought to be cometary in origin (Frandorf *et al.* 1982). To date, no meaningful constraints exist for the mass density of any comet (Peale 1989). Canonical values of ~ 1 g/cm^3 are based on the intuitive picture of comets as balls of water ice. In the case of comets being "mudballs" low densities would require that they be fairly "foamy" objects with a lot of interior spaces or voids. Such interiors are suggested by the primordial rubble pile model of Weissman (1986) and the fluffy aggregate model of Donn (1990).

A large refractory/volatile ratio reinforces current ideas about the formation location of short-period comets. Dynamical studies (Duncan *et al.* 1988) suggest that short-period comets come from the Kuiper Belt which is hypothesized as a disk of comets extending from about 30 to over 100 AU from the Sun. The Kuiper Belt itself is thought to have been populated primarily by comets which formed in the region of Uranus and Neptune and were then injected into the Belt as a consequence of gravitational encounters with the forming or newly formed planets (e.g. Fernández and Ip 1981). Fortunately, there are two icy bodies which would have accreted from comets forming in this region for which we have good determinations of their size and mass: Triton and Pluto. Both have mass densities very close to 2 g/cm^3 (Smith *et al.* 1989; Tholen 1990) which is what we would expect for objects half of whose volume was refractory (3 g/cm^3), and the other half is ice (1 g/cm^3). Thus, our new insight into the nature of comet nuclei, gained from the study of dust trails, is consistent with short-period comets sharing the same formation location as Triton and Pluto.

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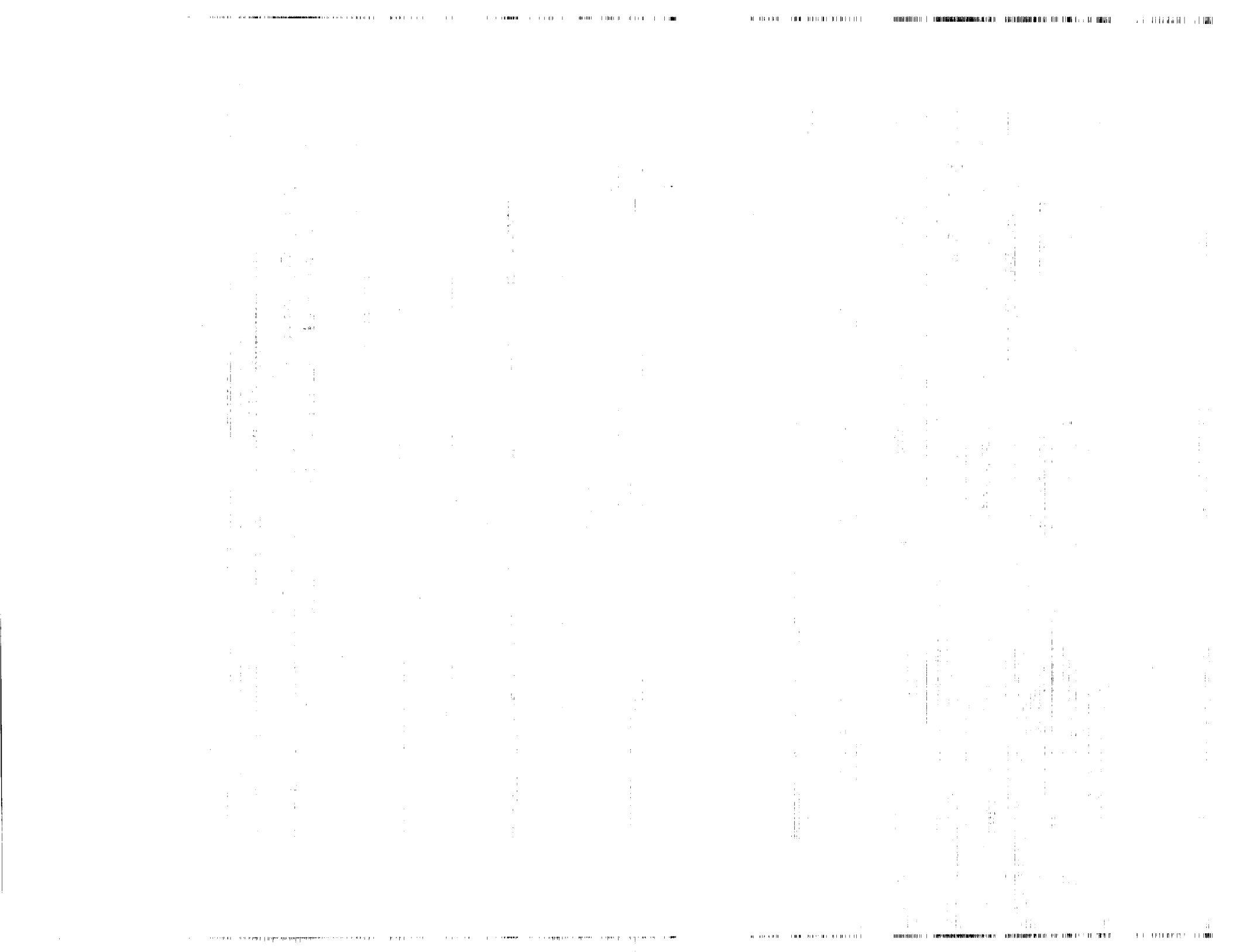
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