INTERRELATIONS BETWEEN COMETS AND ASTEROIDS

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ABSTRACT. Various aspects of comet/asteroid distinctions and interrelations are reviewed with emphasis on recent work and paying special attention to the following problems: characteristics of cometary activity at large heliocentric distance and uniqueness of comet P/Schwassmann-Wachmann 1 with respect to physical properties, the rôle of Trojans and other small bodies in the outer planetary system concerning comet/asteroid classification, possibilities for physical evolution of comets into asteroids, orbital and dynamical overlap of the comet and asteroid populations, and the cometary versus asteroidal origin of Earth-approaching asteroids. With regard to these latter questions it is argued that recent discoveries indicate a more substantial probability for Jupiter family comets to develop into asteroidal objects than earlier believed, and several examples of cometary association for newly discovered Apollo-Amor asteroids are also referred to. However, the fractional cometary contribution to the traditional Apollo-Amor asteroid population (aphelia far inside Jupiter's orbit) apparently can not yet be reliably estimated.

1. INTRODUCTION

Comets and asteroids, the two major types of interplanetary objects, are both considered to carry important information on the origin and evolution of the Solar System. It is thus essential to understand their interrelations as well as distinctions and the possible evolutionary links connecting them. Many reviews have been devoted to these problems (e.g. Kresák 1977, 1979, 1980, 1983; Degewij and Tedesco 1982) and the present paper will mainly deal with new results, attempting to evaluate the impact of many recent findings, both observational and theoretical. Our approach will be to consider, in succession, a number of different aspects of the comet/asteroid distinction, i.e., the observational, physico-chemical, genetical and dynamical aspects.

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2. OBSERVATIONAL AND PHYSICO-CHEMICAL DISTINCTIONS

Observationally, the distinction between asteroids and comets is quite clear. An asteroid always appears stellar (angular diameter < 1"), but a comet develops a diffuse coma due to gas production from a solid nucleus (Whipple 1950), giving rise to an expanding atmosphere entraining grains of dust and ice. Nonetheless, comets sometimes appear stellar, especially at relatively large distances from the Sun, and there are a number of examples of asteroidal designations given to objects identical to known comets or later recognized as comets. Some of these were recently found by Nakano (1984) including a pre-discovery observation of comet P/Smirnova-Chernykh as asteroid 1967 EU. There are also examples of preliminary cometary designations which have been changed into asteroidal (such as 1977t Lovas = 1977 YA), since the activity reported at the discovery observation failed to be confirmed. Such cases are rare, but they should not always be regarded only as curiosities, since they may provide clues as to specific requirements for the onset of cometary activity or the existence of variable or sporadic activity among comets.

Of more profound significance than the observational classification would be a comet/asteroid distinction referring to the physico-chemical properties of the objects. This may be formulated simply as asteroids being dominated by refractory materials (metals, silicates) and comets containing large quantities of volatile compounds (ices). For reviews of the general constitution of asteroids, see e.g. Chapman et al. (1978) or Gaffey and McCord (1979), and for cometary nuclei, see e.g. Whipple and Huebner (1976), Delsemme (1977a) or Greenberg (1982).

Certainly, asteroids are not completely deprived of volatiles. The 3μm absorption due to H_2O has been identified in the reflectance spectrum of Ceres (Lebofsky 1978; Lebofsky et al. 1981), and Larson et al. (1979) found that such data for both Ceres and Pallas were consistent with surface minerals containing water of hydration. The shapes of the reflectance curves characteristic of RD-type asteroids have a likely analogue among the C1 and C2 carbonaceous chondrites (Degewij and van Houten 1979) containing a hydrated clay mineral matrix (see Dodd 1981) and their colours resemble kerogen-containing, low-temperature carbonaceous condensates (Gradie and Veverka 1980). Indications of volatile material contained in asteroids are as yet restricted to the C and RD types, and thus they become more important as more remote groups of asteroids are considered.

On the other hand, it is clear that for an object to be observed as a comet, it must also have physico-chemical characteristics of the cometary type, i.e., large quantities of ice must be present near its surface. However, even with an icy surface there is no guarantee that an object will display cometary activity. This depends on the orbital parameters, mainly the perihelion distance, and perhaps also on the evolutionary status of the object. Typical variations with heliocentric distance of sublimation rates of various ices as induced by absorption of solar radiation were found by Delsemme and Miller (1971) assuming an isothermal cometary nucleus with the mean insolation for a spherical body. Recent work has considered different improvements of this approximation, such as e.g. the use of latitude-dependent mean diurnal insolations (Cowan and A'Hearn 1979) or treatment of heat flow inside the nucleus (Weissman and Kieffer 1981; Rickman and Froeschlé 1983). Lacking a systematic exploration of the influence of such effects on the expected activity limit, we can only estimate this limit within a factor two, where the lower bound is set by the isothermal approximation and the upper bound corresponds to a subsolar point unaffected by heat conduction. For a H_2O-dominated nucleus, then, using visual and infrared albedos = 0.1, the normalizing distance r_o entering into the g(r) function in the standard expression for the nongravitational force (Marsden et al. 1973; Marsden 1974) would fall between 2.8 AU and 5.6 AU. For different choices of the albedos this range would be modified (Marsden et al. 1973), and for other cosmochemically likely substances such as CO_2 or CO it occurs much further from the Sun (Marsden 1974; see Delsemme 1985). According to Delsemme, the principal reason to believe comets in general to be dominated by H_2O ice is the tendency for cometary activity to follow the behaviour predicted for this case. Nevertheless, cometary activity at large distances from the Sun is still a relatively unexplored phenomenon, and the limited observations at hand appear to allow a wide range of theoretical interpretations.

3. P/SCHWASSMANN-WACHMANN 1 AND THE JUPITER-SATURN RESERVOIR

It is of interest in this connection to consider the trans-Jovian intermediate reservoir of comets suggested by Kresák (1972a) and evidenced by numerical simulations of cometary capture such as those performed by Everhart (1972, 1977) and Fernández and Ip (1983a). The number of potentially active comets in this reservoir, as restricted to the Jupiter-Saturn region, was estimated using Monte Carlo simulations by Rickman and Vaghi (1976) and Froeschlé and Rickman (1980) to be $\sim 10^4$. "Potentially active" means that at least upon reduction of the perihelion distance during capture into the Jupiter family the objects will display cometary activity.

Comet P/Schwassmann-Wachmann 1 has an orbit typical of the Jupiter-Saturn reservoir and must be regarded as one of its members. Thus it is unique at least in the respect that it is, as yet, the only member discovered in an orbit of this class. The question as to whether it is also unique with respect to its violent and frequent outbursts (5-8 magnitudes; Whipple 1980) is closely connected to the size of its nucleus. Estimates of the diameter have been quoted as 20-25 km (Kresák 1979) with a large uncertainty depending on the range of possible albedos (see Roemer 1966). Recently Cruikshank and Brown (1983) found a value of appr. 40 km corresponding to a geometric albedo $p_v = 0.13$.

If P/Schwassmann-Wachmann 1 is indeed the only member of the Jupiter-Saturn reservoir exhibiting the phenomenon of frequent, violent outbursts, then there is nothing strange about the fact that no other member has yet been discovered. It is reasonable to expect that even among 10^4 objects, the nucleus of P/Schwassmann-Wachmann 1 is one of the biggest. This can be seen by a comparison with the sample of long-period comets which passed perihelia inside Jupiter's orbit during the last 400 years. Using an influx rate of Oort cloud comets of 5 yr^{-1} per AU of

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perihelion distance (Weissman 1980a, 1982), we get a contribution of 10000 objects. The number of passages of old long-period comets is more difficult to estimate, since observational selection dependent on the perihelion distance is more serious. Taking Everhart's (1967) estimate of 8000 passages during the 127 years from 1840 to 1967 with perihelia inside 4 AU, we get appr. 25000 such passages, and a conservative extrapolation to 5 AU increases this by 20% to 30000. Furthermore, if intrinsically much fainter objects (in general not possible to observe) are also included, the old comets certainly outnumber the new ones by a large factor (see e.g. Kresák 1982; Weissman 1982). Hence as a very conservative estimate we may consider our long-period comet sample to be at least as large as the Jupiter-Saturn reservoir. According to the analysis by Kresák (1979), among the long-period comets there are only two - comets 1729 and 1882 II - that have indisputably an intrinsic brightness high enough for their nuclei to be as large as, or possibly somewhat larger than, the above-quoted values for P/Schwassmann-Wachmann 1. Some uncertainties are nevertheless connected with these two objects: comet 1882 II being a Sun-grazer, probably a fragment of a very big parent comet (Marsden 1967), and comet 1729 having a large perihelion distance (4.05 AU) and most likely being a new comet from the Oort cloud. In both these cases there are reasons to believe that standard methods for the translation from observed to absolute brightness and from absolute brightness to nuclear diameter may give misleading results.

Thus we definitely have no reason to suspect that there should be any cometary nuclei much bigger than that of P/Schwassmann-Wachmann 1 in the Jupiter-Saturn reservoir. In the absence of outbursts, with the low albedo values recently considered for cometary nuclei (e.g. Veeder and Hanner 1981; Hartmann et al. 1982; Whipple 1983a; Weissman 1984), they may all easily have escaped detection. The problem then is to explain why P/Schwassmann-Wachmann 1 should be unique among all the objects in similar orbits to display the outbursts. The mechanism causing these outbursts has not yet been identified, and none of the different suggestions that appear plausible at present (Froeschlé et al. 1983) is able to explain such a uniqueness. This holds for the volatile pocket hypothesis involving sudden exposures of CH_4 (Whitney 1955) or CO_2 or CO (Cowan and A'Hearn 1982) on the surface of the nucleus, the phase transition hypothesis invoking an amorphous-cubic phase transition proceeding in isolated bursts (Patashnick et al. 1974; Froeschlé et al. 1983; Klinger 1983a,b), and the free-radical hypothesis where the energy feeding the outbursts is supposed to originate in the recombination of free radicals trapped in the ice (Haser 1955; Donn and Urey 1956; for a suggestion concerning ion molecular clusters, see Shul'man 1983). Likewise, the model recently proposed by Hartmann et al. (1982) where outbursts occur due to gas pressure accumulating in a dusty regolith would not predict P/Schwassmann-Wachmann 1 to be unique.

Obviously, we must consider the possibility that P/Schwassmann-Wachmann 1 is not at all unique in the Jupiter-Saturn reservoir producing frequent outbursts by a factor 100 or more in brightness. Although the evolutionary aspects of the above hypotheses have not yet been worked out, at least the phase transition hypothesis would predict outbursts to be a commonplace phenomenon for a certain range of cometary

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orbits characterized by orbital mean temperatures (Klinger 1983a) near the value of P/Schwassmann-Wachmann 1 (120 K) and moderate eccentricities. There is one further important restriction, namely, that the comet should never have made any visit into the Jupiter family, thus allowing amorphous ice to exist near the surface of the nucleus. Similarly, Hartmann et al. (1982) indicate a rather broad range of orbital motions (relatively circular orbits at 4-7 AU from the Sun) for their mechanism to be effective.

Taking such restrictions into account, only a subset of the 10^4 members of the Jupiter-Saturn reservoir already considered would be candidates for outbursts, but apparently this subset may still contain a large number of comets. If this is so, we must again consider the question why P/Schwassmann-Wachmann 1 is the only of these as yet discovered. It is impossible at present to give a detailed answer to this question, since there may well be a considerable spread in the outburst amplitudes for different comets depending e.g. on dust/gas ratios. However, as a reasonable estimate we would have to assume that all the other comets displaying outbursts must have nuclear diameters at least approximately ten times lower than P/Schwassmann-Wachmann 1. If the value by Cruikshank and Brown (1983) is indeed trusted as referring to light scattered by the solid nucleus of P/Schwassmann-Wachmann 1, this assumption appears reasonable. It is interesting to note in this connection that Festou and Atreya (1983) found a possible production of H atoms from P/Schwassmann-Wachmann 1 using Ly-α observations. The derived production rate was $\gg 10^{30}$ s^{-1} and made these authors conclude that the nucleus of P/Schwassmann-Wachmann 1 is at least ten times bigger than those of other comets, whose gas production rates have been measured near the Earth. Parent molecules have not been identified: the detection of CO^+ in P/Schwassmann-Wachmann 1 by Cochran et al. (1980) and Larson (1980) strongly indicates the presence of CO (Festou and Atreya 1983), but the presence of an atomic hydrogen coma would show that a hydrogen-bearing molecule must also be produced in large quantities from the nucleus.

4. ACTIVITY LIMITS AND INTERNAL HEAT SOURCES

Thus, even though the activity exhibited by P/Schwassmann-Wachmann 1 may be of a somewhat different kind as compared to other observed comets, it appears possible that objects dominated by H_2O ice may have an effective activity limit well beyond Jupiter's orbit under certain circumstances. Further work is needed to settle this question, both theoretically and observationally.

Obviously, the discussion of activity limits is closely related to the long-standing question of internal heat sources in cometary nuclei, as shown by the above examples of suggested mechanisms for the outbursts of P/Schwassmann-Wachmann 1. There is little doubt that such internal heat sources may exist in most if not all comets, but much work remains to be done in order to estimate quantitatively their importance. For the time being, variations in cometary activity at large distances from the Sun may be explained both by compositional differences and differences

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in the action of internal heat sources. One example is given by the well-known fading of long-period comets after their first apparition as newcomers from the Oort cloud (e.g. Oort and Schmidt 1951; Kresák 1982; Bailey 1985) which appears particularly serious for comets with large perihelion distances (Marsden and Sekanina 1973; Marsden et al. 1978). One possible explanation is that the nuclei of Oort cloud comets have a particularly volatile surface layer, either due to a chemical inhomogeneity (Marsden and Sekanina 1973) or due to effects of long-term cosmic-ray bombardment (Whipple 1977; see also Brown et al. 1982; Johnson et al. 1983). Another possibility is that the amorphous-cubic phase transition sweeps through the surface layer of a nucleus coming directly from the Oort cloud, thereby increasing the gas production significantly at large distances from the Sun (Smoluchowski 1981).

In conclusion, there is apparently a broad interval of heliocentric distance where objects with icy surfaces may or may not develop cometary activity. The inner boundary may be put at $r \simeq 5$ AU, as evidenced by the relatively inert icy surfaces of most Galilean satellites. The outer boundary may be at least as far as $r \simeq 15$ AU, judging from observations of the tails of some new comets from the Oort cloud (Sekanina 1973a) or from recent observations of comet P/Halley (West 1983). According to Hartmann et al. (1981, 1982), the surface of asteroid 2060 Chiron may be at least partly icy, as expected from the cometary nature of its dynamical behaviour (Scholl 1979; Oikawa and Everhart 1979).

5. ICY INTERIORS, ROCKY SURFACES

Next, let us consider the possible existence of objects whose surfaces are asteroidal but whose bulk compositions are of the cometary type involving large quantities of ice. Two different types of observed asteroids may belong to this category. One of them is best represented by the Trojans, but may count members among all classes of outlying asteroids in stable orbits. The other type includes the Aten, Apollo and Amor groups of Earth-crossing or Earth-approaching asteroids (Shoemaker et al. 1979).

The general background to these ideas is the conception that the ice/dust mixture characteristic of a cometary nucleus may turn into an inert dust layer as the ice sublimates from the surface (see Mendis 1984). The reason in the case of a typical comet passing perihelion within 3 AU of the Sun would be that there is a critical size of a dust grain where the pressure of the sublimating gas is just sufficient to carry the grain off the gravitational field of the nucleus (Whipple 1951; Whipple and Huebner 1976), and all grains larger than this critical size are thus bound to fall back to the nucleus. Even if this concerns a very minor fraction of the grains, they may accumulate on the surface as time goes on into an inert mantle seriously affecting the sublimation of the underlying ice (Dobrovolsky and Markovich 1972; Mendis and Brin 1977, 1978; Brin and Mendis 1979; Brin 1980). This idea was recently developed by Horányi et al. (1983) into the "friable-sponge model" of the dust mantle. Depending on e.g. the dust/ice ratio of the cometary material, this mantle may develop into an insulating crust terminating the cometary activity altogether (Brin 1980; Horányi et al. 1983; Mendis 1985), until possibly the crust is broken by a meteoroid impact.

Nevertheless, there may be significant local variations in the build-up of this crust making the nucleus spotty, or strong latitudinal variations caused by the rotation of the nucleus or seasonal insolation effects such as seem to be present on P/Encke (Whipple and Sekanina 1979). Evidence for spottedness or localized activity among the nuclei of short-period comets in general is abundant (e.g. Whipple 1977, 1980, 1982, 1983a,b; Sekanina 1981a,b).

This discussion refers to comets with reasonably small perihelion distances, as already indicated, and thus the resulting asteroidal objects with cometary interiors might be found among the Aten-Apollo-Amor asteroids. Let us also consider the possible evolution of objects consisting of a dust/ice mixture moving in orbits in the Jupiter-Saturn region! For the expected composition with H_2O dominating the ice, the sublimation flux in most cases will be extremely small, so that a very large fraction of the dust grains remain on the surface. If the object can be trapped for a long time in the inner parts of this region, e.g. as a temporary Jovian satellite, it might be possible to obtain a crust thick enough to protect the object even after a reduction of the perihelion distance. This speculation may be worthy of further consideration since it conforms to a dynamically attractive evolutionary path for supplying Earth-approaching asteroids from the cometary source (Kresák 1979; see below).

The Trojan asteroids constitute a group of objects which may be quasi-permanently trapped near Jupiter's orbit (see Greenberg and Scholl 1979) ever since the early stages of evolution of the Solar System. If this is so, then comparison with the estimated bulk composition of Ganymede and Callisto indicates that the Trojans should have been formed out of a material containing a substantial fraction of ice. Possibly this holds true even for their present structure (Hartmann et al. 1982): their interiors may contain large quantities of ice, while since a long time their surface layers have been outgassed by sublimation. Collisional events (see Hartmann 1979) might temporarily cause some rejuvenation, exposing ice at the surfaces, but no long-lasting gas production can be expected. Some evidence against a bulk composition dominated by ice for the Trojan asteroids is, however, found in the estimated density of 2.5 g/cm^3 for 624 Hektor, the largest Trojan (Weidenschilling 1980). This value is derived on the assumption that Hektor is an equilibrium binary system, which seems to be the most likely explanation of its large-amplitude light variations (see Farinella et al. 1982). An alternative model of a very elongated Jacobi ellipsoid would imply a density of only 1 g/cm^3 but would be dynamically unstable.

A very important recent finding is the association between the surface material on RD asteroids and cometary dust, i.e., the refractory constituent of cometary nuclei. This was predicted from cosmogonic considerations by Gradie and Veverka (1980), and subsequently strong observational support for this idea has been found by Hartmann et al. (1982) and by Hartmann and Cruikshank (1984). Degewij and Tedesco (1982) find a preponderance of RD-type reflectivity spectra among Trojans in the two clouds together (72%), and Degewij and van Houten (1979) formulated the question: "Are the RD-type objects extinct cometary nuclei?" The idea of a genetic association between Trojans and comets, however, dates much further back. Rabe (1971, 1974) considered dynamical evidence in support of such an association, but Kresák (1979) showed that this evidence can not be upheld. Future observations are needed in order to settle the question if the Trojans have icy interiors.

6. GENETIC CLASSIFICATION

In the preceding sections we have paid some attention to different possibilities for comets to appear as asteroids, i.e., for objects observationally classified as asteroids to have the physico-chemical properties of cometary nuclei. One example is given by the "future comets" that are bound to display activity upon a major reduction of the perihelion distance, and a possible representative of this group is 2060 Chiron. Another example may be extinct cometary nuclei deactivated by gradual build-up of an insulating crust of dust. Possible representatives may be found among asteroids in "cometary orbits" (see below) or more generally among Earth-approaching asteroids.

The evolution of a comet into an asteroid may, however, proceed in a different way, if the nucleus contains an inner core of refractory material (see Whipple 1977; Wilkening 1979; Degewij and Tedesco 1982). After exhaustion of the volatile material by sublimation, then, there would remain an object having asteroidal characteristics both observationally and physico-chemically. Obviously, though, it would be genetically distinct from usual asteroids. Hence there is also some interest in a genetic comet/asteroid distinction referring to the physico-chemical properties with which the object was formed.

It is not yet known with certainty what fraction, if any, of the cometary nuclei may contain refractory cores. To some extent, different theories for the origin of comets yield different predictions about this, depending e.g. on the assumed place of formation. As remarked by Kresák (1982): "Different authors put the origin of comets practically anywhere between the asteroid belt and the interstellar medium interacting with the outskirts of the Solar System". Nevertheless, it is fair to say that, at present, very few scientists favour the asteroid belt as the place of origin of comets. This idea goes back to Oort's (1950) classical paper but was also considered by van Flandern (1977) in an hypothesis invoking a recent cometary origin. Convincing arguments that comets must have formed (and stayed) at larger distances from the Sun were given by Delsemme (1977b).

Generally speaking, the rocky-core/icy-mantle structure of cometary nuclei appears more plausible, the closer to the Sun one imagines the comets to have formed, since the higher maximum temperatures reached in the Solar nebula (Cameron and Pine 1973; Cameron 1978a) make it more likely to have a significant time lag between the condensation of refractories and volatiles during the subsequent cooling (see Greenberg 1983). Another possible reason for large-scale differentiation of cometary nuclei might be radiogenic heating by short-lived isotopes such as

^{26}Al, leading to melting of the ice, as indicated e.g. by Degewij and Tedesco (1982). The obvious requirement of rapid condensation and grain accretion under this hypothesis again makes birthplaces closer to the Sun more favourable to the development of rocky cores.

The ultimate aim of the stepwise succession of observational, physico-chemical and genetic comet/asteroid distinctions so far considered is, of course, to be able to place constraints on the cosmogonic processes representing the origin of each separate class of objects. Unfortunately, the serious uncertainty concerning the origin of comets makes it impossible to say to what extent the asteroidal and cometary birthplaces may join to each other in a continuous manner, thus e.g. allowing to consider distant asteroids and outer Jovian satellites as being in some sense intermediate objects between the two classes. A complete and systematic review of the theories of cometary origin was given by Delsemme (1977a).

Of the more recent issues, let us briefly consider the Uranus-Neptune accretion zone mechanism of comet formation, the possibility of a dense inner "core" of the Oort cloud and the suggestion of Oort cloud dissipation and replacement by molecular cloud encounters. Fernández (1980a, 1982) and Fernández and Ip (1981) have presented dynamical evidence in favour of the Uranus-Neptune region as the place of formation of comets, earlier suggested e.g. by Kuiper (1951), Safronov (1972) and Whipple (1972). In particular, Fernández and Ip (1983b) found that capture of short-period comets (orbital periods < 13 yr) from a reservoir in the Uranus-Neptune region by gravitational interactions with the giant planets is much better able to maintain the presently observed population than corresponding captures from near-parabolic, Oort cloud orbits. Due to the very long time-scale for scattering cometesimals from the Uranus-Neptune region (Öpik 1973; Ip 1977; Fernández 1980b), the formation of the Oort cloud by this mechanism would still be taking place at present (Fernández and Ip 1981).

However, arguments have also been advanced for cometary formation at much larger distances ($\sim 10^4$ AU) from the Sun (Biermann and Michel 1978; Biermann 1981; see also Greenberg 1985), and intermediate possibilities involve the formation of a very large number of comets at heliocentric distances $\sim 10^2$ AU (e.g. Cameron 1962, 1978b). At least in this latter case the Oort cloud would be expected to have a dense inner "core", as argued also by Hills (1981). This core has attracted much attention recently (see Bailey 1983a; Weissman 1984) since it may offer an explanation to many different phenomena, such as otherwise unmodelled perturbations on the outer planets (Bailey 1983b; see also Whipple 1964, 1972), supply of short-period comets (Fernández 1980a; cf. Fernández and Ip 1983b), a low-temperature sky background detected by IRAS (Low et al. 1984; Bailey 1984 ; cf. Bailey 1983a,c), or replenishment of the outer parts of the Oort cloud after dissipation by encounters with Giant Molecular Cloud Complexes (van den Bergh 1982; Bailey 1983d; Weissman 1984). These encounters have been found to make the outer parts of the Oort cloud dynamically unstable over a time-scale $\sim 10^8$ years (Napier and Staniucha 1982; Clube and Napier 1982; Napier 1982), and gravitational capture of new comets from these star-forming regions was proposed as a source for replenishment (Clube 1983; Clube and Napier 1984; see also

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Valtonen and Innanen 1982; Valtonen 1983). For further discussion of these issues, see Clube and Napier (1983) and Weissman (1983).

Let us briefly return to the possibility of identifying 2060 Chiron genetically as a comet. It must be noted that its diameter of several hundred km (see Kowal 1979) would necessarily make it a very unusual comet, as seen from the above discussion of the sizes of cometary nuclei. The cometary identification of Chiron appears more plausible on the hypothesis of the Uranus-Neptune accretion zone as the origin of comets than it does if even more remote birthplaces are imagined. A much larger number of comets is naturally expected to move in Chiron-like orbits, if the source is very close, and thus the existence of a giant object appears less unlikely. If the diameter-frequency relation for cometary nuclei in the vicinity of 10^2 km has the same slope as that for asteroids presented by Zellner (1979), then a value of 40 km for the diameter of P/Schwassmann-Wachmann 1 as the biggest among 10^4 objects would imply an estimate of 10^7 objects in the Saturn-Uranus region as the maximum number out of which Chiron could be expected to be the biggest. The Oort cloud should then contain some 10^4 - 10^5 Chiron-sized comets and, of course, possibly some even bigger ones. Such an estimate is in no conflict with the estimated mass of the Oort cloud (see Weissman 1982), but apparently a large fraction of this mass may be contributed by exceptionally big objects.

In conclusion to the discussion of cometary birthplaces, we note that the vast majority of authors recently put the origin of comets far outside Jupiter's orbit. Hence to the extent that primordial objects remain in the Jupiter-Saturn region (these will have to be locked into stable resonances or satellite motions; see Lecar and Franklin 1973, 1974; Everhart 1973a,b; Froeschlé and Scholl 1979), they might in fact be genetically unrelated to both asteroids and comets.

7. DYNAMICAL CLASSIFICATION

In the previous sections we have come across several possibilities for comets to develop into asteroids or at least to have an asteroidal appearance. In order to identify such cases among the multitude of observed objects, it has proved essential to use the orbital properties (e.g. Kresák 1977, 1979). In the analysis by Kresák (1979) three different parameters were considered: the aphelion distance (Q), the minimum approach distance to Jupiter (ρ), and the Tisserand invariant (T).

In particular, T turned out to provide a clear separation of asteroids and comets in general. To quote from Kresák: "...the definition of a cometary orbit as one of $T < 3$ without resonance, and of an asteroidal orbit as one which either has $T > 3$ or librates around a simple resonance ratio, sets a very good dividing line between the two populations". The stability of T has been disputed (see Everhart 1976), and of course it is an invariant only in the circular, restricted 3-body problem (Sun-Jupiter-object). However, perturbations ΔT resulting from Jupiter's orbital eccentricity have been shown to be small (e.g. Froeschlé and Rickman 1981), and if one limits attention to typical objects under observation, having perihelia within or near Jupiter's orbit,

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Jupiter is indeed the dominant perturber of their orbits, so that the ΔT:s caused by other planets are almost always relatively small. These facts have been stressed by Kresák (1972, 1977, 1980) and the empirical separation of comets and asteroids with respect to the dividing line at T = 3 remains a fact, proving the importance of T under most circumstances in question.

Very few objects definitely crossed this boundary, as of the beginning of 1979. Most conspicuously among the comets, a group of three objects (P/Oterma, P/Smirnova-Chernykh and P/Gehrels 3) was found in temporary motion near the 3/2 resonance with relatively small aphelion distances and values of T between 3 and 3.05, following low-velocity encounters with Jupiter ("quasi-Hilda type motions"; see Kresák 1979). In the case of P/Oterma, this motion took place during 1937-63 and was thus already terminated (Kazimirchak-Polonskaya 1967; Marsden 1970a; Carusi et al. 1981). Additional examples are known from orbital integrations of other short-period comets outside the observed time interval, and the phenomenon of temporary captures into low-eccentricity orbits near the 3/2 resonance appears to be quite common (Kresák 1979).

Among the asteroids there were only two cases of $T < 2.9$ occurring without any libration in mean longitude or critical argument to protect the object from encountering Jupiter. One of these was 1373 Cincinnati with present-day osculating elements $a = 3.4$ AU; $Q = 4.5$ AU; $i = 39^\circ$, which turns out to avoid encounters with Jupiter due to libration of the argument of perihelion around 90° (Kozai 1962; Marsden 1970b; Froeschlé and Scholl 1979). The other case was 944 Hidalgo, the only asteroid known at that time to approach Jupiter rather closely (minimum distance = 0.38 AU in 1673; Marsden 1970b) and generally considered the primary candidate for being an extinct cometary nucleus (Degewij and Tedesco 1982).

Indeed, the minimum approach distance to Jupiter has been shown to provide another interesting distinction between short-period cometary and asteroidal orbits: comets tend to approach Jupiter closely while asteroids tend not to approach Jupiter (Marsden 1970b), and as of 1979 only Hidalgo among the asteroids had $\rho < 1$ AU, while among the short-period comets ($P < 20$ yr) only P/Encke, P/Arend-Rigaux and P/Neujmin 1 had $\rho > 0.8$ AU. As remarked by Marsden (1970b), the latter two comets are known for their low level of activity thus making them the most asteroidal comets both regarding physical appearance and dynamical behaviour. As remarked by Kresák (1979), both Hidalgo, P/Arend-Rigaux and P/Neujmin 1 have typically cometary values of T, and they can not be expected to settle into stable orbits of the asteroidal type. Over a time-scale $\sim 10^3$ yr their motions are indeed relatively stable, in spite of the approaches to Jupiter by Hidalgo, and due to resonance librations by the two comets (Marsden 1970b), but consideration of a longer time interval might well change this situation.

Apparently the occurrence of relatively stable motion of a short-period comet over $\sim 10^3$ yr gives a possibility for the object to develop asteroidal characteristics, probably by growth of an inert crust on the nucleus. Such a process should be strongly dependent on the perihelion distance, but the details of this dependence have not yet been worked out. Let us remark in this connection that the long-term perturbations of Hidalgo's orbit as estimated analytically by Kozai (1979) allow its perihelion distance to drop as low as 1.1 AU.

A couple of comets have been found in fairly stable orbits near the 1/1 resonance with Jupiter, involving temporary mean longitude librations. This holds for P/Slaughter-Burnham (Marsden 1970b; Rabe 1972) with a present perihelion distance of 2.5 AU and P/Boethin (Benest et al. 1980, 1982, 1983) with a present perihelion distance of 1.1 AU. However, these objects may approach Jupiter rather closely (P/Slaughter-Burnham to 0.29 AU in 2075 and P/Boethin to 0.5 AU in 1909), and hence the long-term behaviour of their motions may be affected by serious uncertainties.

8. NEW CANDIDATES FOR EXTINCT COMETS

The most interesting feature to be noticed at present in connection with the dynamical comet/asteroid distinction is the recent addition of a number of asteroids in cometary orbits. In particular, for Mars-crossing or Mars-tangent objects (perihelion distance $q < 1.67$ AU) there was a very clear separation of comets from asteroids in 1979 such that all asteroids except 6344 P-L with $Q = 4.21$ AU (determined from very few observations and seriously uncertain) had $Q < 4.1$ AU, while all comets except P/Encke had $Q > 4.6$ AU. This situation has now changed drastically. Table I lists some orbital data for newly discovered asteroids with $q < 1.67$ AU and $Q > 4$ AU, and it is readily seen that nine of these have $Q \gtrsim 4.3$ AU. In fact, three are even Jupiter-crossers (1982 YA, 1983 SA and 1984 BC), and while the quality of the orbits of 1982 YA and 1984 BC is inferior, the orbit of 1983 SA is already quite well-determined. Furthermore, the Tisserand invariants of these three objects are deeply inside the cometary domain ($T < 2.9$), and five more are situated in the interval $2.95 < T < 3.00$. Obviously, with regard to Kresák's classification as quoted above, it is of interest to examine whether the objects with $T < 3$ librate around simple resonance ratios.

Indeed a preliminary investigation in the elliptic restricted three-body problem Sun-Jupiter-object (Hahn and Rickman 1984) shows such librations to exist in four cases, as indicated in Table I. Two of these refer to the above-mentioned Jupiter-crossers, and 1982 YA is thus protected from approaching Jupiter to within 1 AU during a considerable time by libration at the 5/3 resonance, while the libration of 1983 SA is the second one known, after 279 Thule, at the 4/3 resonance. This latter libration is also confirmed by Benest et al. (1985) using more complete dynamical models, and in both investigations it is found to be broken after < 1000 yr in the future, whereafter encounters to within less than 0.4 AU of Jupiter occur. 1984 BC, on the other hand, as yet does not appear to librate and shows moderately close encounters with Jupiter. The closest encounters are, however, found for 1983 XF (also with a well-determined orbit) in connection with a large-amplitude libration at the 2/1 resonance. After the termination of this libration, in both the quoted investigations, very close encounters with Jupiter are found.

Table I. Orbital properties of ten recently discovered asteroids with Q > 4 AU according to the investigation by Hahn and Rickman (1984). The number of observations and the observational arc refer to the orbit treated in this investigation, and the minimum distance to Jupiter (ρ) and the librational property correspond to the motion over appr. ± 1000 yr.

Asteroid	T	Q(AU)	q(AU)	i(°)	No. of obs.	Obs. arc (days)	ρ(AU)	Libr. around
1979 VA	3.08	4.29	0.98	2.8	49	88	1.16	
1981 FD	2.99	4.79	1.69	2.6	18	40	3.14	2/1
1981 VA	2.96	4.29	0.63	22.0	23	49	1.54	
1982 TA	3.09	4.07	0.53	12.1	46	213	1.19	
1982 YA	2.38	6.29	1.12	34.6	11	27	1.02	5/3
1983 LC	2.98	4.50	0.77	1.5	12	19	0.91	
1983 SA	2.31	7.25	1.21	30.8	54	174	0.51	4/3
1983 VA	2.98	4.36	0.80	16.2	6	68	0.85	
1983 XF	2.98	4.78	1.45	4.2	35	100	0.01	2/1
1984 BC	2.78	5.30	1.55	22.5	7	32	0.30	

Approach distances to Jupiter significantly smaller than 1 AU have been found for all the five objects discovered in 1983 and 1984 (see Table I). Thus Hidalgo is no longer unique in this respect. We have three new first-rank candidates for being asteroids of cometary origin (1983 SA, 1983 XF and 1984 BC) and three more, only somewhat less certain cases (1982 YA, 1983 LC and 1983 VA). Of the other asteroids, we remark that 1981 FD appears to add to the Griqua group (see Franklin et al. 1975; Kresák 1979; Schubart 1979), as indicated already by Bowell and Marsden (1981).

Recently another Apollo asteroid was also discovered using the IRAS satellite, providing even more clearcut evidence for a cometary association from the dynamical point of view. This is 1983 TB, the asteroid of the Geminid meteors (Whipple 1983c; see also Hughes 1983). The idea of possible associations of asteroids with meteor streams is an old one (see Sekanina 1973b, 1976; Kresák 1977), and recently Drummond (1982) suggested several such associations, the most likely cases involving asteroids 2101 Adonis and 2201 Oljato.

However, for 1983 TB there can be no reasonable doubt about its association with the Geminid stream. Although no parent comet was known for this stream, it was considered highly probable that such a comet had earlier existed, being now extinct (e.g. Kresák 1973). Thus 1983 TB could be this extinct comet, but one important problem still remains to be solved: how can an active comet be transferred into the orbit of the Geminid stream having the very high value of T = 4.27 and the low aphelion distance Q = 2.6 AU? There is not yet any satisfactory answer to this often posed question except for, possibly, the simple observation that P/Encke seems somehow to have managed at least part of the required evolution (T = 3.00; Q = 4.10 AU). Certainly, nongravitational forces may be involved (Sekanina 1971), and the stable, favourable orientation of the spin axis found for P/Encke in the past (Whipple and Sekanina 1979) may indeed have been essential for reducing Q to its present value. However, it must also be noted that this orientation is changing dramatically in such a way that the evolution of Q will soon be reversed (Whipple and Sekanina 1979). We hence can not be sure that a stable settling into an asteroidal orbit will in fact occur even for comet P/Encke. Furthermore, the value of Q = 2.6 AU for the Geminids appears too small to be produced by nongravitational effects (Sekanina 1971). We must pay attention to the possibility that genuinely asteroidal meteor streams may exist as a result of collisional fragmentation or release of ejecta clouds by minor impacts (Degewij and Tedesco 1982; Drummond 1982).

Let us briefly mention another property expected to reveal possible ex-comets among asteroids (Kresák 1977), i.e., the existence of nongravitational forces affecting the orbital motion. It was recently claimed that such effects may exist for some asteroids (Ziolkowski 1983). However, the true nature of the effects in question has not yet been fully worked out (see e.g. Marsden 1970b, 1984).

Further observational studies of the physical nature of Aten-Apollo-Amor asteroids are obviously needed. In view of the results by Gradie and Veverka (1980), Hartmann et al. (1982) and by Hartmann and Cruikshank (1984), an important indicator of cometary origin would be an RD-type reflectivity spectrum. This has not yet been found (McFadden 1983; McFadden et al. 1984), but many of the above-mentioned candidates for cometary origin remain to be examined. Statistics of rotation rates for Earth-approaching asteroids appears to indicate a bimodal distribution, suggesting the existence of both cometary and asteroidal contributions (Debehogne et al. 1983; Harris 1983). However, to associate rapid spin of a group of Earth-approaching asteroids with an origin in the main belt may not be justified, since a recent analysis by Farinella et al. (1984) indicates no clear difference between the spin rates of comets and small main-belt asteroids. A significant fraction of the Apollo-Amor objects (5 out of 21 observed photometrically; Farinella, priv. comm.) have a highly elongated shape. However, comparison of these statistics with the shape distribution of small main-belt asteroids (Binzel and Mulholland 1983; Binzel 1984; Lagerkvist 1983a,b) or with that of fragments produced in laboratory impact experiments (Capaccioni et al. 1984) is complicated by the likely existence of various selection effects. At present no conclusion regarding the importance of the cometary contribution appears possible from such data.

9. ORIGIN OF THE EARTH-APPROACHING ASTEROIDS

One of the outstanding issues regarding comet-asteroid evolution is the problem of the origin of Earth-approaching asteroids. Reviews of work performed in this field have been given e.g. by Shoemaker et al. (1979) and Wetherill (1979). In brief, the Earth-approaching asteroids often have typically asteroidal orbits as far as the Tisserand invariant is concerned. In principle there are evolutionary tracks of the coplanar Tisserand criterion connecting some orbits of Apollo asteroids with the

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main belt, but the problem is that in the absence of close encounters it appears impossible under most circumstances to produce the necessary increases of eccentricity. Even if gravitational captures by the action of Mars are invoked, any transfer mechanism from the main asteroid belt appears unable to explain the high ratio of Apollo to Amor objects as inferred from observational statistics (Shoemaker et al. 1979). This difficulty adds to the problem of accounting for the required infeed rate of appr. 15 objects per 10^6 yr (Wetherill 1979), derived under the assumption of a steady state for the population of Earth-approaching objects.

Such arguments led Öpik (1963) to suggesting comets as a source for Apollo asteroids, and this idea has remained a popular one, especially since it conforms well to ideas about the evolution of cometary nuclei, as discussed above. Specifically, Wetherill (1976, 1979) found dynamical evidence in favour of a cometary origin for most Apollo asteroids. This cometary source would evidently be identifiable with the Mars-crossing Jupiter family ($q \lesssim 1.5$ AU; $Q \lesssim 8$ AU). However, the dynamical lifetimes of objects in such orbits are limited to $\sim 10^3$ yr due to Jovian perturbations, mostly at close encounters (e.g. Froeschlé and Rickman 1981; Carusi et al. 1979). This interval may be shorter than the typical one during which the object is observable as a comet. This observable lifetime is estimated to be several hundred revolutions for the cometary orbits in question (Kresák 1981a,b; Fernández 1981) as derived from observational and orbital statistics, and even longer (Weissman 1980b) if standard models for the sublimation from cometary nuclei are to be trusted. Processes decreasing Q and increasing T are needed in order to capture comets from the source in question into typical Apollo asteroid orbits as described above, and evidently they must work rapidly in order not to be disturbed by Jovian perturbations of the cometary orbit.

One possibility is that active comets are transferred into Encke-type orbits by nongravitational forces whereafter their activity may terminate, and the extinct nuclei appear as Apollo asteroids (Kresák 1979). The likelihood of occurrence of this process needs to be further investigated. The other alternative is that extinct comets moving in unstable orbits ($Q \gtrsim 4.5$ AU) are gravitationally captured by the terrestrial planets at near-collisions, so that Q is suddenly decreased by a large amount. At least in the second case it would be justified to compare the observed vs. expected numbers of both Apollo-Amor asteroids with: ($q < 1.3$ AU; $Q \lesssim 4$ AU) and corresponding extinct comets with: ($q < 1.3$ AU; $Q \gtrsim 4.2$ AU). Such a comparison was carried out by Rickman and Froeschlé (1980) on the basis of a Monte Carlo simulation of the distribution of extinct comet orbits. The absence, at the time of writing of that paper, of any observed Apollo-Amor asteroid with a safely determined Q well in excess of 4 AU, combined with a large number of expected extinct comets, led these authors to the conclusion that most extinct comets are non-existent, i.e., that no more than several percent of the Jupiter family comets may develop into sizeable asteroidal bodies at the end of their activity (cf. Kresák 1980; Whipple 1981). By using a similar argument for high-inclination comets, Nakamura (1983) arrived at the same estimate.

We may now add two comments to this discussion. Firstly, the conclusion by Rickman and Froeschlé (1980) holds under the assumption that the majority of observed Apollo-Amor asteroids are indeed extinct comet nuclei. On the other hand, if these objects should be mainly collisional fragments of main-belt asteroids, they might have a much higher albedo than the extinct nuclei of the Jupiter family, and the lack of observations of such nuclei might to some extent result from this albedo difference. Secondly, Table I shows that the number of zero observed Apollo-Amor asteroids with $Q \gtrsim 4.2$ AU used by Rickman and Froeschlé has now increased to six! In fact, four of these belong to the above-mentioned group of candidates for cometary origin judging from their orbital evolutions. The conclusion by Rickman and Froeschlé would now be changed into an estimate that almost 10% of the short-period comet nuclei develop into sizeable asteroidal objects, and by the albedo effect just mentioned this could in fact be taken as a lower limit. However, it must be emphasized that the statistical material underlying these estimates is still extremely poor, and that further serious sources of uncertainty exist in the necessary estimates of the steady-state number of extinct comets and the discovery probability of such an object.

Evidently, the question of the cometary vs. asteroidal origin of the usual Earth-approaching asteroids with $Q \lesssim 4$ AU is still far from being satisfactorily answered. The above arguments give some evidence against a major cometary contribution. Another piece of evidence pointing in the same direction is the difficulty in identifying Apollo objects both as extinct comets and as the source of stony meteorites (Levin and Simonenko 1981).

Unfortunately, the orbital inclinations (i) of Earth-approaching asteroids do not yet appear to provide any clearcut evidence regarding their origin. Four known objects have $i > 50^{\circ}$, and three of these belong to the Apollo group. This might possibly be indicative of a cometary origin for these asteroids, but it must be noted that as yet there is no statistically significant difference between the i-distributions of Apollos and Amors. Furthermore, it is not yet clear to what extent a dynamical transfer from the main asteroid belt would lead to smaller inclinations than a transfer from the Jupiter family of comets.

In this connection one should also note the recent work by Wisdom (1982, 1983). By application of an algebraic mapping of phase space onto itself, motions near the 3/1 resonance with Jupiter could be tracked over very long time intervals, and large sudden increases in eccentricity were often found. These eccentricity jumps are similar to those earlier found by Scholl and Froeschlé (1977) at the 3/1, 5/2 and 2/1 resonances by numerical integration using Schubart's (1964) averaging method. However, by extension to a longer time span this phenomenon now appears more wide-spread for near-resonant orbits. Thus Mars-crossers and perhaps even Earth-approachers may result from the 3/1 resonance, and this possibility appears to increase considerably the efficiency of gravitational transfer from the main belt into Apollo-Amor orbits, as compared with existing estimates. The orbit of the recently discovered asteroid 1984 AB ($a = 1.58$ AU, $e = 0.076$, $i = 14^{\circ}.8$ computed by Marsden using an identification with 1975 XL4 by Bardwell; see MPC 8679) is of great interest in this connection, being quite similar to the orbit of Mars. This kind of orbit is indeed to be expected as an intermediate

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stage in a capture by Mars of an object coming from the main belt, since the Tisserand parameter with respect to Mars has a value near 3 and the encounter speed is thus relatively low. Future studies of the orbital evolution of this object may indicate whether the idea here outlined can be upheld.

Regarding dynamical possibilities for a cometary origin of Apollo-Amor objects, an interesting suggestion by Kresák (1979; see also Carusi et al. 1981) is to follow the T = 3 evolutionary track, perhaps even with T somewhat above 3, via a quasi-Hilda type motion whereby Q reaches relatively low values at an early stage of capture, and possibly further so that low enough perihelion distances may be reached for an efficient action of nongravitational forces. This kind of evolution should be studied further. Some attention has already been paid to it since it is closely connected with temporary satellite captures by Jupiter (Carusi and Valsecchi 1981, 1983). Indeed, two of the three above-mentioned quasi-Hilda type comets (P/Oterma and P/Gehrels 3) have experienced such satellite captures lasting for short but significant time intervals (Chebotarev 1967; Carusi and Valsecchi 1979, 1981, 1982; Rickman 1979; Rickman and Malmort 1981).

In conclusion, the problem of the origin of Earth-approaching asteroids is not yet solved. It appears at present that there are some indications of a mixture of two disparate populations among the 'usual' Apollo-Amor asteroids ($Q \lesssim 4$ AU), corresponding perhaps to the two sources classically considered. The recent discovery of a number of Apollo-Amor and Mars-crossing asteroids in 'unusual', cometary orbits ($Q \gtrsim 4.2$ AU) strengthens the evidence for evolution of Jupiter-family comets into asteroidal objects. However, much work remains to be done in order to clarify the dynamical transfer mechanisms from both the asteroidal and cometary sources.

J.A. FERNANDEZ: For the estimate of the conversion rate of short-period comets into Apollo-Amor asteroids it is necessary to know the dynamical lifetime, t_{dyn}, of AA objects. Have you considered any particular value of t_{dyn} in your study?

H. RICKMAN: For estimating that a certain fraction (at least 10% according to my discussion) of short-period comets with $q < 1.3$ AU develop into Apollo-Amor asteroids, no knowledge of t_{dyn} is required. When it comes to estimating what fraction of such objects may be stabilized from Jovian perturbations by reduction of the aphelion distance, too little is known at present to give any quantitative figure. Assuming that the majority of AA asteroids do come from the cometary source, we would require a conversion rate supplying $\gtrsim 10$ new objects per 10^6 yr, and this corresponds to an estimate of $\sim 10^8$ yr for t_{dyn}, where collisions as well as dynamical ejections are taken into account.

P.R. WEISSMAN: I would be very cautious about accepting Cruikshank and Brown's radius for P/Schwassmann-Wachmann 1. They base their estimate on the magnitude of the comet when it is quiescent at around m = 18, assu-

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ming there is no coma at that time. But IRAS has looked at Schwassmann-Wachmann 1 and found that it is very bright in the infrared even during quiescent periods, indicating that there is always a very substantial coma. Thus the estimate of the radius by Cruikshank and Brown is likely too large.

H. RICKMAN: I fully agree that one should not take it for granted that the 20-μm observations by Cruikshank and Brown pertain to the solid nucleus without any coma. Hence it might indeed be preferable to consider their estimate of the nuclear diameter as an upper limit. However, the existence of a visual brightness threshold during quiescent periods, below which the comet appears never to fall, speaks against the presence of an optically thick dust coma on such occasions.

P.R. WEISSMAN: Another example of an Apollo asteroid that is likely an extinct comet is 2201 Oljato. Chris Russel at UCLA has detected disturbances in the solar wind associated with close approaches of this asteroid to Venus, using the Pioneer-Venus spacecraft. He interprets this as some sort of outgassing debris stream in the asteroid's orbit. Also, Lucy McFadden has found a brightening of this object in the ultraviolet which she interprets as Rayleigh scattering from a cloud of fine particles around the asteroid. Thus, Oljato may be another extinct cometary nucleus like 1983 TB.

H. RICKMAN: Indeed Oljato is one of the most promising candidates for being an extinct comet. Another piece of evidence in support of this is its possible meteor stream association suggested by Drummond.

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