EVOLUTION OF COMETS INTO ASTEROIDS?

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There has long been speculation as to whether comets evolve into asteroidal objects. On the one hand, in the original version of the Oort (1950) hypothesis, the cometary cloud was supposed to have formed initially from the same material that produced the minor planets; and an obvious corollary was that the main physical difference between comets and minor planets would be that the latter had long since lost their icy surfaces on account of persistent exposure to strong solar radiation (Öpik, 1963). However, following a suggestion by Kuiper (1951), it is now quite widely believed that, whereas the terrestrial planets and minor planets condensed in the inner regions of the primordial solar nebula, icy objects such as comets would have formed more naturally in the outer parts, perhaps even beyond the orbit of Neptune (Cameron, 1962; Whipple, 1964*a*). Furthermore, recent studies of the evolution of the short-period comets indicate that it is not possible to produce the observed orbital distribution from the Oort cloud, even when multiple encounters with Jupiter are considered (Havnes, 1970). We must now seriously entertain the possibility that most of the short-period orbits evolved directly from low-inclination, low-eccentricity orbits with perihelia initially in the region between, say, the orbits of Saturn and Neptune, and that these comets have never been in the traditional cloud at great distances from the Sun.

On the other hand, there is also the extreme point of view that comets completely disintegrate after only a few passages near the Sun. This feature was present in the original Whipple (1950) icy-conglomerate comet model, principally on account of the widespread assumption that the frequent and complete disappearance of comets was an observed fact. Twenty yr ago, 44 comets were known to have been observed at more than one perihelion passage, but 10 of these (i.e., 23 percent) were regarded as lost, having failed to appear at several of their recent returns. The number of more-than-one-appearance comets has now risen to 59; and 5, if not 6, of those lost have been found, reducing the proportion of those lost to only 7 or 8 percent. Two of the comets were found by accident, but the reduced percentage is mainly a demonstration of what can be done when modern computational and observational techniques are applied to the problem (Klemola, 1965; Kowal, 1970*a,b;* Marsden, 1963; Roemer, 1964, 1968; Schubart, 1965); and there is every expectation of our being able to reduce the percentage of lost comets even further.

Closely related to this is the question of secular brightness decrease. Straightforward use of the observational data cataloged by Vsekhsvyatskij (1958), and the assumption that a decrease in the total brightness of a comet is accompanied by one in the radius of the nucleus, reveals the startling possibility that 60 percent of the known periodic comets will cease to exist by the end of the present century (Whipple, 1964*b;* Whipple and Douglas-Hamilton, 1966). Because of changing observational methods, it is extremely difficult to correlate estimates of cometary brightness by different observers at different times in history. Periodic fluctuations in brightness, sometimes rendering a comet systematically brighter or fainter for a whole apparition, further confuse the issue. In any case, variation in the total brightness of a comet does not necessarily give any information about variation in nuclear brightness, which is what we need to know.

The most reliable information about cometary decay is probably that furnished by the modern investigations on the nongravitational anomalies in the motions of periodic comets (Marsden, 1969, 1970*a;* Yeomans, 1971). There is some uncertainty concerning the effective velocity of the escaping matter, but the mass loss rates obtained (Sekanina, 1969), less than 0.1 to about 1 percent per revolution, are quite consistent with the values derived from theoretical studies on the sublimation of the ice (Huebner, 1967).

Thus a comet should survive at least 100 passages within 1 AU of the Sun, and 1000 passages or more might be more typical. Decay takes place; but the point at issue is whether the sublimation results in shrinkage of the nucleus and complete dispersal of the comet's meteoric material or whether, as the nucleus loses its volatiles, it evolves into an object that, to all outward appearances, is indistinguishable from a minor planet. Some comets are often remarkably asteroidal in appearance. In particular, P/Arend-Rigaux and P/Neujmin 1 have consistently appeared asteroidal—except during their discovery apparitions when they were relatively close to Earth and careful scrutiny revealed very slight, but definite cometary activity. It has not been possible to detect nongravitational effects in the motions of these two comets, which means that the effects must be at least two orders of magnitude smaller than those for more typical comets. Furthermore, it is observed that the nongravitational effects on several comets, very notably P/Encke, are systematically diminishing with time, strongly suggesting reduction in the rate of mass loss and evolution toward objects like P/Arend-Rigaux and P/Neujmin 1. A cometary nucleus whose radius is decreasing linearly with time, on the other hand, should in its later stages show a progressive *increase* in these nongravitational effects (Sekanina, 1969).

A certain amount of insight into the relationship between comets and minor planets is provided by a comparison of their orbits. Criteria have been developed (Kresák, 1967; Whipple, 1954) for distinguishing asteroidal and cometary orbits; however, we feel that the single most important factor is the aphelion distance Q. Because no comet has $Q < 4.1$ AU, we shall restrict ourselves to those minor planets with $Q > 3.9$ AU, or about 5 percent of all the numbered objects. Among the comets, we shall consider just those of more than one appearance and $Q < 15$ AU. The outstanding difference between the comets and the minor planets is that the former are continually passing near Jupiter–half of them have been within half an astronomical unit at some time during the past half century–whereas the latter do not. The 32 minor planets having a large Q and perihelion distances q of less than 2.4 AU are listed in table I in order of decreasing Q. There are also 63 minor planets with $q > 2.4$ AU, of which 60 percent belong to the Trojan and Hilda groups (and none of the other 40 percent has $Q > 4.1$ AU). The Trojan and Hilda minor planets are prevented from approaching Jupiter on account of libratory situations. The same is true of 279 Thule (which has a nearly circular orbit at 4.3 AU from the Sun), the second and third entries in the table (1373 Cincinnati and 1362 Griqua), and the final entry (887 Alinda). Appropriate interaction of orbital eccentricity, inclination, and sometimes mean distance also seems to keep the other minor planets, except for 944 Hidalgo, away from Jupiter. For a detailed discussion, see Marsden (1970*b*).

With this single exception, and so far as we can tell, the numbered minor planets are unable to pass within 1.1 AU of Jupiter; and in the absence of any nongravitational effects, their orbits are essentially stable for an interval that can very conservatively be taken as within 10 000 yr of the present time. As for Hidalgo, soon after its discovery it passed only 0.9 AU from Jupiter and in 1673 it passed less than 0.4 AU away. Among the comets, all but two have

TABLE I.–*Numbered Minor Planets With* $q \leqslant 2.4$ *AU and* $Q \geqslant 3.9$ *AU*

Minor planet	q, AU	Q, AU	Minor planet	q, AU	Q, AU
944 Hidalgo	2.0	9.6	965 Angelica	2.3	4.0
1373 Cincinnati	2.3	[a]4.5	880 Herba	2.0	4.0
1362 Griqua	2.2	[b]4.4	612 Veronika	2.3	4.0
225 Henrietta	2.4	4.3	1317 Silvretta	2.4	4.0
1006 Lagrangea	2.0	4.3	719 Albert	1.2	4.0
814 Tauris	2.2	4.1	1537 1940 QA	2.1	4.0
1036 Ganymed	1.2	4.1	717 Wisibada	2.3	4.0
1477 Bonsdorffia	2.3	4.1	372 Palma	2.4	4.0
1099 Figneria	2.2	4.1	1093 Freda	2.3	4.0
1474 Beira	1.4	4.1	882 Swetlana	2.3	4.0
1672 1935 BD	2.3	4.1	1625 The NORC	2.4	3.9
680 Genoveva	2.2	4.1	664 Judith	2.4	3.9
886 Washingtonia	2.2	4.0	931 Whittemora	2.4	3.9
794 Irenaea	2.2	4.0	1508 1938 UO	1.6	3.9
778 Theobalda	2.3	4.0	1134 Kepler	1.4	3.9
747 Winchester	2.0	4.0	887 Alinda	1.1	3.9

[a]Because of libration, extremes are 4.4 and 5.2.
[b]Because of libration, extremes are 4.0 and 4.4.

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passed within 0.9 AU of Jupiter during the past 200 years. The two exceptions are the asteroidal comets P/Arend-Rigaux and P/Neujmin 1, neither of which has passed near Jupiter for about 1000 years. The relative stability of their orbits, in particular the fact that the perihelion distances cannot for at least a millennium have had significantly larger values than now, means that these two comets have long been subject to strong solar radiation, and considerable aging should certainly have taken place. Many of the other comets not unreasonably had larger perihelion distances only a few centuries ago, and until these distances dropped below 2.5 to 3.0 AU there would have been little deterioration. One cannot exclude the possibility that Hidalgo is an ordinary minor planet ejected recently into its rather unstable orbit through collision with some other minor planet, but there is at least as much justification for supposing that it is physically an object very similar to the two exceptional comets. It certainly will be very desirable to have appropriate physical observations made of Hidalgo at its next return to perihelion in 1976-77.

Although P/Arend-Rigaux and P/Neujmin 1 (and probably Hidalgo) may look and behave very much like conventional minor planets, it does not seem probable that they will continue to survive indefinitely. If the future lifetime of a defunct cometary nucleus were as long as that of a typical stony or iron asteroid, we should expect to find very many more asteroidal objects with only relatively stable, or even completely unstable, orbits. The Palomar-Leiden survey (van Houten et al., 1970) did not reveal any. The only minor planets having $Q > 4.1$ AU were intrinsically fainter members of the Trojan and Hilda groups, and their orbits are presumably stable.

Sekanina (1969, 1971*a*) has attempted to explain the decrease and accelerated rate of decrease of the nongravitational effects on P/Encke in terms of a nuclear model consisting of a porous meteoric matrix with ices embedded uniformly inside it. During each revolution about the Sun the ices in the surface layer are sublimated out; the remaining volatiles then diffuse throughout the nucleus and restore the uniform distribution without any reduction in the total volume. This model describes the observed history of P/Encke very well and suggests that the comet will evolve into an asteroidal object about 60 yr from now. Extrapolation into the past, however, yields an unacceptably small proportion of meteoric material for the time, at least 700 revolutions ago, when the comet's aphelion distance would have been large enough for Jupiter to perturb the comet into something like its present orbit. Sekanina has therefore proposed a core-mantle model for the nucleus, the porous, ice-embedded matrix being surrounded by an envelope of free ices and loose dust particles. He supposes that the mantle of P/Encke finally evaporated during the two centuries or so before discovery; until shortly before then, the comet would have behaved much like a pure icy nucleus, with the nongravitational effects constant or *increasing* very slightly in magnitude. With this model, capture by Jupiter can be pushed back to at least 1200 revolutions ago, more in line with data on the evolution of the associated Taurid meteor streams (Whipple and Hamid, 1952).

Our more recent investigations have revealed a few cases where the nongravitational effects on comets do seem to be increasing slightly with time, or indeed to change sign. We have tended to regard this as an apparent effect, incidental to the real systematic decrease in the magnitude of the force, and arising merely on account of long-term changes in the inclination of a comet's equator to its orbit (Marsden, 1971*a*) or as a consequence of precession of the nucleus (Sekanina, 1971*b*).

It could be, however, that the increases are real. Sekanina[1] envisages newly captured comets as generally having nuclei that, at least in their outer regions, have a great deal of free ice. Some of them would evolve as we have discussed. Others, lacking significant cores, would show increases and perhaps even sudden changes in their nongravitational parameters; eventually they would completely disperse.

It is hard to judge which, if either, of these courses represents the "main sequence." There is certainly something unusual about the two almost defunct comets P/Arend-Rigaux and P/Neujmin 1. They were last in the vicinity of Jupiter 900 and 1200 yr ago, respectively. Just as we wonder what has become of those short-period comets that were last near Jupiter 2000 and 5000 yr ago and more, we must question the absence of comets that last passed within the critical distance of 0.9 AU between 200 and 900 yr ago. This indicates either that the cores of these comets (and Hidalgo) are unusually large or that the majority of comets are coreless. As already noted, however, recent experience shows that lost comets have an excellent recovery rate, suggesting that most cometary nuclei do have small cores. P/Biela, one of the comets that Sekanina supposes has completely disintegrated, is, of course, one of the four, or possibly five, comets of more than one appearance that are still lost. P/Brorsen may also be a coreless comet that has disintegrated. No searches have been made for either comet since the 19th century, and observers should certainly not be discouraged from trying to recover a small asteroidal remnant of P/Biela at its favorable return later this year (Marsden, 1971*b*). P/Tempel-Swift is still lost, but the possibility of recovering it is now hampered by the fact that its perihelion distance—and thus its minimum apparent magnitude—has significantly increased. Searches have been made in recent months for P/Neujmin 2; it was not found, which suggests that it was within 2 days of the prediction, but more than 2 mag fainter than predicted, or up to 5 days from the prediction but more than 1 mag fainter (E. Roemer, Z. M. Pereyra, and C. Kowal, personal communications). The fifth comet, P/Tempel 1, may possibly have been recovered in 1967 (Roemer, 1968), but confirmation will not be possible until it returns again next year.

The indication that the cores of most cometary nuclei are small naturally leads us to discuss the Apollo group, tiny asteroidal objects with $q < 1$ AU and discovered only because they pass close to Earth. By estimating the probabilities of their collisions with Earth and other inner planets, Öpik (1963)

[1] See p. 423.

concluded that they could not have existed in their present state since the origin of the solar system. Deflection of ordinary minor planets by collision or through perturbations by Mars appears to be insufficient for producing them, so he supposed that they were ex-comets whose aphelion distances had been decreased to their present values by the nongravitational effects that once would have been acting. There is the problem, however, that all the Apollos have aphelion distances smaller than that of P/Encke (and presumably that of P/Encke will not be decreasing much further). This is certainly a severe difficulty in the case of the objects with $Q < 3.5$ AU, although coordination of the nongravitational effects with the systematic perturbations by Jupiter when the comets pass through mean motion resonances can be of assistance (Sekanina, 1971*c*).

In table II we list, in order of decreasing Q, the Apollo objects and also the so-called Amor objects (having perihelion distances slightly greater than 1 AU). Except for two very uncertain objects, the table is complete for numbered and unnumbered minor planets currently found to have $q \leqslant 1.15$ AU. Only the first two objects, each of which is kept away from Jupiter because of a libration, have Q in the range included in table I. In addition to q, Q, the orbital eccentricity e, the orbital period P, the orbital inclination i, and the absolute magnitude $B(1, 0)$, we have noted whether there seem to be associated meteors (Sekanina, 1970) and short-term light variations (Gehrels et al., 1970; E. Roemer, K. Tomita, and T. Gehrels, personal communications). Large light variation can almost certainly be regarded as indicating a deflected, conventional minor planet; a small variation and, to a lesser extent, associated meteors might be considered as indications of cometary origin.

We conclude that 433 Eros and 1620 Geographos are very probably planetary, and this is also rather probable for 1968 AA. If any of the objects are of cometary origin, they are most likely to be among the first five entries in the list, although there also exists the enigmatic possibility of cometary origin for 1566 Icarus, small though its aphelion distance may be. Deflection of ordinary minor planets into Apollo orbits is perhaps not as much of a problem as it was thought to be: consider the enormous number of planets of the Hungaria group, on the inner fringe of the main belt (with mean distances of 1.95 AU), indicated by the Palomar-Leiden survey (van Houten et al., 1970). Accurate photometric studies of all the Apollo and Amor minor planets are much to be encouraged. Among the unnumbered objects, only 1968 AA has been observed at two approaches to Earth, although there will be a good opportunity for recovering Apollo itself later this year. Adonis will come within 0.20 AU of the Earth in 1977. Past searches for 1953 EA, 1948 EA, and 1960 UA have not been adequate; and these objects should be pursued more extensively on appropriate occasions in the future. The orbits of the remaining four objects are more uncertain.

Příbram, one of the two meteorites with well-determined orbits, had the surprisingly large aphelion distance of 4.1 AU, which might be suggestive of

TABLE II.—*Apollo and Amor Objects* ($q \leqslant 1.15$ *AU*)[a]

Objects	q, AU	Q, AU	e	P, yr	i	$B(1,0)$	Meteors	Light variation
1953 EA	1.03	4.0	0.59	4.0	21°	19.6		
887 Alinda	1.15	3.9	0.54	4.0	9	16.3		Small
1948 EA	0.89	3.6	0.60	3.4	18	16.6		
1960 UA	1.05	3.5	0.54	3.4	4	18.1		
1936 CA Adonis	0.44	3.3	0.76	2.6	1	18.6	Yes	
1580 Betulia	1.11	3.3	0.49	3.2	52	15.7		
1968 AA	1.06	3.2	0.51	3.2	24	16.6	Maybe	Large
1221 Amor	1.08	2.8	0.44	2.7	12	19.2		
1937 UB Hermes	0.62	2.7	0.62	2.1	6	18.1	Maybe	
1627 Ivar	1.12	2.6	0.40	2.6	8	14.2		
1950 DA	0.84	2.5	0.50	2.2	12	16.1		
1971 FA	0.56	2.4	0.62	1.8	22	16.3		Large
1932 HA Apollo	0.65	2.3	0.56	1.8	6	15.6	Maybe	
1950 LA	1.08	2.3	0.36	2.2	26	14		
1566 Icarus	0.19	2.0	0.83	1.1	23	17.6	Maybe	Small
1685 Toro	0.77	2.0	0.44	1.6	9	16.3		
1959 LM	0.83	1.9	0.38	1.6	3	14		
433 Eros	1.13	1.8	0.22	1.8	11	12.4		Large
1620 Geographos	0.83	1.7	0.34	1.4	13	16.0		Large

[a]See table I of Roemer (p. 644) for current observational status.

cometary origin. This meteorite, a crystalline chondrite (Tuček, 1961), passed only 1.3 AU from Jupiter 6 yr before it collided with Earth, and similar approaches occurred previously at intervals of about 70 yr.

We cannot exclude the possibility of cometary origin for some of the large-Q objects listed in table I. The three librating objects, for example, could be ex-comets that were trapped in libration when the nongravitational forces ceased. (This same explanation is not likely for the Hildas, Thule, and the Trojans because their perihelion distances are too large for the nongravitational effects to have been significant.) Photometric and other physical studies are most desirable, particularly for these three and the objects with q significantly smaller than 2 AU (719 Albert is lost, unfortunately; but we may add the single-apparition object 1963 UA, which has $q = 1.2$ AU and $Q = 4.0$ AU, and should be recoverable in 1976). If we decrease the limiting Q to 3.6 AU, the following interesting objects may be included: 132 Aethra ($q = 1.6$, $Q = 3.6$), 475 Ocllo (1.6, 3.6), 699 Hela (1.5, 3.7), 898 Hildegard (1.7, 3.7), and 1009 Sirene (1.4, 3.8; lost).

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