INTERRELATIONS AMONG ASTEROIDS, COMETS AND METEOROIDS

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If we investigate the interrelations among different classes of small solar system bodies, we must be aware that we deal with nonrepresentative and practically noncomparable data samples consisting of bodies differing either in size, or in orbits, or in their nature. So, practically, all our knowledge about small bodies - from kilometer-sized Apollo asteroids (including Atens) and Amor asteroids (designated below as AA bodies) to fine dust particles - refer to bodies on orbits intersecting the ecliptic plane at a heliocentric distance $\simeq$ 1 A.U. To solve the problem of origin of this ensemble it would be advantageous if analogous data could be obtained at least for one more heliocentric distance. Since planetary atmospheres are excellent detectors for small cosmic objects, the necessary data could be obtained with the aid of artificial satellites orbiting a planet, e.g. Mars or Venus. Thus the source for the ensemble of Earth-crossing objects may not be correctly pictured. Are comets or asteroids the general supplier? We know the answer to this question only in two cases: (1) meteor streams such as the Leonids originate from comets, (2) meteorites originate from asteroids. But these two categories represent a minute part of the considered ensemble by mass. As to its other members the selection of the source is a matter of tradition rather than a logic conclusion.

The problem of the source for the Earth-crossers, which is incitement to the general problem of migration of solid matter in the solar system, did not appear (or more accurately, was not realized) until we encountered a need to explain the origin of the AA-population near the Earth. Öpik (1963) was the first who drew attention to the problem of their source. He came to the conclusion that the replenishment rate of short-lived AA bodies from the asteroid belt under the action of planetary perturbations is too low to preserve their population. The cometary source seemed the only possible alternative, and Öpik put forward the idea that most AA objects are extinct comets. This idea is still popular.

Most main belt asteroids are moving on so stable orbits that it is difficult to understand how these asteroids might be easily transported to the vicinity of the Earth's orbit. The structure of the belt is indi-

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cated in Fig. 1, where the numbered asteroids are placed in quasi-three-dimensional (a, e, i) space. It is obvious that the asteroids concentrate in several compact zones. The wide gaps between these zones are the Kirkwood gaps. The width of such a gap is usually incorrectly determined by the smallest clear space which corresponds to quasi-circular orbits. It increases markedly with increasing eccentricity and inclination of the orbits (Simonenko 1979a, Dermott and Murray 1981). For quasi-circular orbits the width of the gap is mainly determined by the eccentricity of the Jovian orbit. In each section in Fig. 1, corresponding to a particular e-interval, one notices horizontal gaps determined by the secular resonances ν_5 and ν_6.

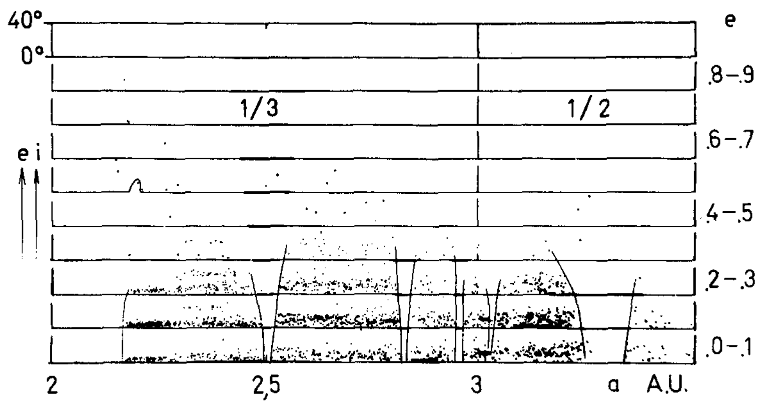

Fig. 1. Osculating orbital elements of main belt asteroids from "Ephem. Minor Planets, 1982". Each strip corresponds to a given excentricity range (right scale). Within each strip the ordinate is inclination (left scale) and the full drawn sections of abscissae denote the width of gaps based on model calculations for low inclination orbits.

It is cosmogonically acceptable to consider the present asteroid belt as a remnant of a more abundant and more uniformly distributed primordial population which has suffered a "clean-up" by the perturbing action of the planets, primarily by Jupiter. The space outside the compact zones is that where rapid transformation of orbits occurs. There are now few asteroids in this space (both inside and outside the asteroid belt, including AA asteroids; see Fig. 2), but practically all short-period comets (Fig. 3), and smaller bodies detected by meteor and fireball observations are found there. The numbers, lifetimes and migration of these bodies have been extensively discussed in the literature but cannot be explained until the mechanisms and tendencies of orbital evolution for bodies outside the compact zones are understood. For papers on this subject see "Comets, Asteroids, Meteorites" (1977), "Asteroids" (1979), "Comets" (1981) and "Sun and Planetary System" (1982).

A peculiarity of larger bodies ($\gtrsim$ 1 km in size) outside the compact zones is the resonant character of motion of most of them. Motion in resonance with Jupiter is well known for the Trojans, for Thule, for

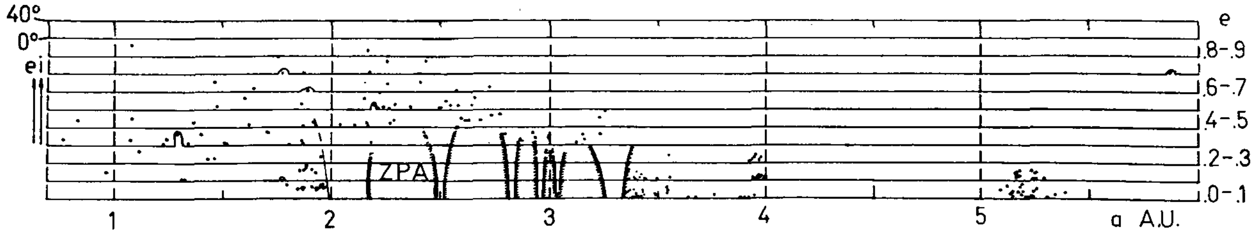

Fig. 2. The same plot as in Fig. 1 for numbered asteroids outside the densely populated zones (ZPA). Some asteroids near the borders of these zones are also shown. In addition, AA objects with preliminary designations are included.

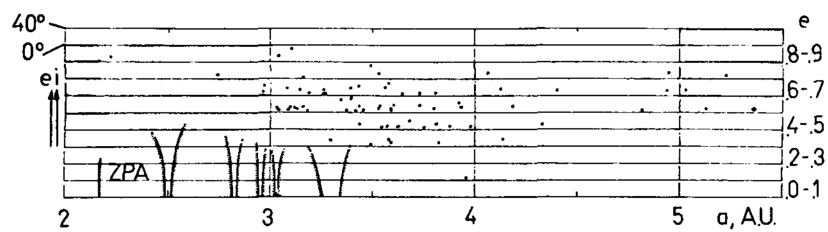

Fig. 3. Comets on orbits with a < 5.5 AU as listed by Marsden (1975), plotted in the same manner as the asteroids in Figs. 1 and 2.

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members of the Hilda group and also for objects inside the Kirkwood gaps (see e.g. Franklin et al. 1975). Many numbered AA objects move in simultaneous resonance with several planets (e.g. Janiczek et al. 1972). A resonant character of the motion is revealed also for some comets (Franklin et al. 1975, Kresák 1974). But false ideas about the width and form of the Kirkwood gaps hinders us as yet to study the resonant bodies and to understand that basically no difference exists between the behaviour of bodies inside the Kirkwood gaps and outside the outer boundary of the asteroid belt (Trojans, members of the Hilda group, etc.).

Theoretical reasons (Froeschlé and Scholl 1977) and model calculations (Simonenko et al. 1980) have made it plausible that bodies from the edges of a gap could be carried into resonance (libration) but afterwards re-appear on the same (or the other) edge of the gap (circulation). It is conceivable that asteroid 2257 (1939 QB) is such an object temporarily circulating in the 1:3 gap. Nongravitational forces will favor both the beginning and termination of libration. It should be noted that error accumulation in the course of a model calculation may play the same role as the nongravitational forces. For the asteroid population fragmentation and chaotic perturbations by other asteroids seem to play such a role.

In recent work on the origin of the structure of the asteroid belt particular attention has been attached to resonant zones. The Themis family turned out to be divided by deep gaps (Dermott and Murray 1981). Zones of secular resonances isolate the Hungaria and Phocaea groups from the rest of the belt (Gradie et al. 1979). But the shape of the resonant zones and even the dimensionality of the space in which they are situated, is unclear and therefore the possibility of transition from one resonant zone to another is unclear as well. A particular problem is the following: Is it possible that secular resonances producing eccentric orbits (Wasson and Wetherill 1979) could supply asteroids to the 1:3 gap?

There are only rare objects outside both resonant and compact zones because of the even shorter lifetimes of these objects. There are small cometary nuclei and asteroids (of size 0.1 to 1 km) on orbits of larger eccentricities and inclinations. But comets are located in the zone of large a, where encounters with Jupiter are possible, and their number drops abruptly near the inner edge of the 1:2 gap. In contrast asteroids are placed in the zone of small a, where encounters are possible only with the terrestrial planets, and their number drops abruptly near the outer edge of the 1:3 gap. There is a remarkable gap between comets and asteroids in the region of $2.7 < a < 3.0$ A.U., which appears to account for the deficiency of comets with small perihelion distances. It is therefore difficult for us to agree with Gehrels (1981) that observation of more faint comets (up to 22^m) could change the situation.

A well known peculiarity of cometary orbits, resulting from their young ages, is that most of them cross the orbit of Jupiter. Comets on such orbits, during the periods between catastrophic perturbations, can

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hardly be assumed to be effective in producing dense meteor streams (cf. Kresáková 1980). The same applies to comets librating in the 1:2 gap. It is not accidental that all meteor streams attributed to cometary origin are produced by comets on stable long-period orbits with regrograde motion.

We cannot exclude, of course, the possibility that cometary nuclei do not disintegrate entirely but are instead transformed into inactive ex-comets, or false asteroids. Inside such bodies ices can be preserved for an indefinitely long time. So an extinct comet might contain the same mixture of volatile and nonvolatile substances in its interior as active nuclei do, but it could have taken on an asteroid-like appearance. False asteroids might be transported in the same way as genuine asteroids, into any region as well as into the AA group.

Collisions of such a fragile ex-comet with another body must result in its total disruption (through fragmentation followed by evaporation of icy fragments from the interior) and the formation of dense compact meteor streams. This mechanism could explain the origin of streams like the Geminids.

However, the number of ex-comets among AA objects appears to be insignificant. By whatever mechanism the initially large cometary orbits would be contracted, the number of objects might be expected to increase with increasing size of the orbits. The AA objects do not show any such tendency.

Small bodies, producing fireballs and meteorites, help us to draw further conclusions. Much data on these bodies has been obtained by fireball networks. The bodies producing fireballs are divided into three classes consistent with (1) ordinary chondrites, (2) carbonaceous chondrites and (3) cometary nuclei (Ceplecha and McCrosky 1976, Ceplecha 1977). The first group shows the greatest strength. Members of the last group are so fragile that, even with masses of $10^2 - 10^3$ kg, they are unable to penetrate the Earth's atmosphere below heights of 50-60 km.

Observational selection is most favourable for fireball objects in large, eccentric orbits. "Cometary" material dominates in these orbits, but it is surprising that it is represented by the smallest objects. When passing to smaller orbits, "cometary" material gradually becomes less abundant (as in the comets themselves). Instead "ordinary chondritic" and "carbonaceous" material becomes more and more abundant. It is often represented by large objects. Detailed analysis of fireball data published by McCrosky et al. (1978, 1979), Ceplecha (1978) and Babadzhanov and Getman (1980) shows "ordinary chondritic" material to appear abruptly near the outer edge of the 1:3 gap, reach a sharp maximum inside the gap and slowly decrease near 1 A.U. "Carbonaceous" material shows a more uniform distribution with the main maximum near 2.3 A.U. and a second maximum near 1.3 A.U. (whereas the minimum is close to the Martian orbit).

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"Cometary" material is practically absent among bodies of decimeter and larger size. One exception is to be noted in particular. Several large, very fragile fireball bodies were revealed on similar orbits. Their mean orbit is close to the orbit of P/Encke, or that of the Taurid and χ-Orionid meteor streams. We may assume that we have one single stream of cometary origin which includes both small and large bodies. This stream produces day-time fireballs. Such a fireball has produced the Tunguska event. The orbital elements (Simonenko 1975), when extrapolated up to a velocity of 26 km/s (the assumed velocity of entry into the Earth's atmosphere for objects of the stream) appear to correspond to the same orbit. The stream may have originated as a result of the splitting of an old comet, rather than from an ex-comet. Preservation in the stream up to the present of such large icy (or dusty-icy) objects as the Tunguska object, 10^2 m in size (Petrov and Stulov 1975) is evidence of a recent origin of the stream.

Thus we see, on the one hand, that comets do not supply "carbonaceous" and "ordinary chondritic" material, and that on the other hand, AA asteroids do not supply fragile "cometary" material, at least in quantity. Meanwhile, there are good reasons to regard the AA population as the supplier of meteorites. Omitting lengthy arguments for this proposal, discussed by many authors on the basis of orbital as well as physico-chemical data (see e.g. Simonenko 1979b, Levin and Simonenko 1981), we call attention to one result (Simonenko 1977), which shows that Amor asteroids account for almost 2/3 of the source of meteorites, Apollo asteroids for 1/3, and Aten asteroids for about 10 per cent. These numbers are roughly proportional to the relative numbers of asteroids in each group.

The revision of lifetimes of 20 known Apollo objects, 3 Aten objects and 2 Amor objects (Shoemaker et al. 1979) shows that they exist for hundreds of millions of years instead of tens of millions of years, as we have believed until recently. Lifetime estimates of the same order of magnitude have been obtained previously for Amor objects on the basis of model calculations (Wetherill 1975). Therefore, the lifetime of stony meteorites (determined by their cosmic-ray exposure age) turns out to be shorter by one order of magnitude than the lifetime of their parent AA population. Only rare irons have lifetimes of the same order as AA objects. This is additional evidence that meteorites originated by fragmentation of AA asteroids.

Ages of AA asteroids larger than the ages of their debris are evidenced also when orbits of AA objects are compared with orbits of fireball producing bodies. Some years ago, gaps were revealed in the distribution of perihelion distances of AA objects (Simonenko 1977). These gaps were situated at the orbits of the terrestrial planets. The origin of the gaps is beyond question: they were swept out by planetary catch-up and perturbation of the AA population. Fireball producing bodies do not show these gaps, in spite of the fact that their perihelion distance is the most accurately determined element of their orbits. While the region of $q \gtrsim 1$ A.U. is an unobserved one, and the Earth orbit gap must be masked

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by observational selection, the Venus orbit gap should be observable if it exists. It is likely that the planets have had sufficient time to clean up the population of AA bodies but insufficient time for cleaning up the population of AA debris.

The discrepancy in age of AA objects and their debris may indicate that the AA population consists of long-lived members moving in resonant orbits. It could be formed as the result of either capture or expulsion by planets of a more short-lived non-resonant component. Still another mechanism might be postulated: orbits of AA objects have been formed in the course of a not-well-understood mechanism of resonant swing in the 1:3 gap, which could be preceded as well as followed by a chain of transitions from one resonant zone to another. In short we suppose that AA objects start out on resonant orbits and do not survive when moving away.

The resonant character of motion must be disrupted for debris originating in the fragmentation process. This seems to be responsible for the fast catch-up of the debris and, therefore, for the shorter age.

A deficiency of comet nuclei and "cometary" fireball bodies in small orbits ($a \lesssim 3$ A.U.) could indicate a deficiency along these orbits of small "cometary" meteor particles. But in this case, we must connect the origin of many meteor streams with asteroids. Is this possible?

The cometary origin of meteor streams is based on the supposition that the disintegration of a cometary nucleus - but not that of an asteroid - can lead to ejection of particles with small relative velocities. This supposition, in turn, is based on our concept of the cometary nucleus as an evaporating "iceberg" and of the asteroids as hard, monolithic rocks which can fragment only by collisions with other bodies. However, recent studies indicate that the asteroids were formed as porous bodies of nearly zero strength (Wood 1979). If contraction and hardening has occurred at all, asteroids would later fragment by repeated collisions (Weidenschilling 1981). This implies that the present-day asteroids are units of loosely bonded blocks barely holding each other together by weak gravitational forces. Such a structure is favorable to the formation of numerous fragments thrown away with small relative velocities and to the formation of a meteor stream. It is possible that the so-called "ecliptical" meteor streams are of asteroidal origin. It is interesting to note that their orbits show a tendency to concentrate to the 1:3 gap.

So, in spite of the inconclusiveness of the arguments presented above, it seems most promising to regard the asteroid belt as the primary supplier of Apollo and Amor type objects. Their numerous fragments of all sizes can produce meteorites. It is possible that the asteroid belt is the supplier of short period meteor streams. Cometary nuclei, if they at all convert into false asteroids, can hardly be encountered among the AA population. They supply small particles, although among them there may exist a few large, extremely porous and fragile bodies.

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