7

RELATIONSHIP BETWEEN METEORITES, ASTEROIDS AND COMETS

B. J. LEVIN

There seem to be no objection any more to regard the asteroid belt as the past and present source of initial and intermediate parent-bodies of meteorites. Initial *parent bodies were of the size of the present-day largest asteroids; the irregular size of medium sized asteroids suggests* intermediate *parent bodies fragmented by collisions. Finally, most of the* terminal *parent bodies can be identified with Earth-crossing or grazing objects. In contrast, icy planetesimals of the outer zone of the primeval nebula underwent almost no thermal evolution, but only a complicated orbital evolution leading to the comets observed now. This does not exclude the possibility that* some *extinct comets end up on asteroid-type orbits, although their nuclei might still contain ices covered by an insulating crust that can preserve them for a very long time. These could be the parent bodies of bolides, as opposed to meteorites.*

About 10 years ago various difficulties led people to doubt the old idea that meteorites are fragments of asteroids. Therefore several authors suggested a cometary origin of some or even most meteorites. However, meanwhile these difficulties have been eliminated. Supporting the asteroidal origin of meteorites, I consider it necessary to define more precisely the concept of meteorite parent bodies.

Already many years ago evidence existed that most meteorites had undergone several collisions and fragmentations in space. This indicates that practically all meteorites had a series of consecutive parent bodies. Unfortunately this evidence has not been duly recognized. People continue to speak about parent bodies in general.

Actually for a typical meteorite one has to distinguish three principal consecutive generations of parent bodies:

a) One *initial* parent body. In its hot interior meteoritic material acquired its initial mineralogical composition and texture.

b) several *intermediate* parent bodies of decreasing size--products of consecutive fragmentation by collisions. A regolith layer on the largest intermediate parent bodies is the place where brecciated and xenolithic meteorites acquired their structure;

c) one *last* parent body. In its interior the meteoritic material continued to be shielded from galactic cosmic rays. Some decimeter or meter-sized

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fragments of these last parent bodies, when hitting the Earth, can survive after ablation in the atmosphere and become meteorites. For such survival the fragment must have sufficient mechanical strength and must enter the atmosphere with a velocity below 22 km/sec.

In its initial form, the idea of an asteroidal origin of meteorites involved the assumption that collisions in the asteroidal belt are a direct source of meteorite-producing bodies. People believed that when asteroid fragments scatter after a collision, some of them, including meteorites-to-be, acquire orbits that cross or approach the Earth's orbit. Subsequent small changes of these orbits by planetary perturbations lead to temporary intersection of orbits and eventually--to a meteorite fall.

But about 20 years ago it was recognized that ejection velocities of fragments are insufficient to change a typical asteroidal orbit to an Earth-crossing or Earth-grazing orbit (Öpik and Singer 1957; Anders 1964). An alternative mechanism, increasing dispersion of orbital elements by *random* planetary perturbations, is very slow for main belt asteroids. The expected number of orbits with small perihelion distances is very low and this leads to difficulties both with the productivity of this source and with radiation ages of meteorites.

Let us begin with a quest for the *last* parent bodies of meteorites. Because the initial orbits of fragments differ only slightly from those of the colliding bodies and because the time intervals since fragmentation, as given by the radiation ages, are relatively short - 10^7 - 10^8 years - most of the *last* parent bodies must have had Earth-crossing or Earth-grazing orbits.

In the sixties, when several Earth-crossing (or Apollo) asteroids, were already known, they were briefly considered as possible meteorite parent bodies. However, according to calculations by Wetherill and Williams (1968), the expected yield of meteorites from the *known* Apollo asteroids seemed to be too small compared to estimates of the meteorite influx on the Earth. But on reconsidering the problem on the basis of the latest data, Wetherill (1976) finds it necessary to decrease by one order of magnitude the estimate of meteorite influx and to increase by at least one order of magnitude the expected mass yield from Apollo asteroids. Thus the discrepancy has all but vanished.

Because the mean life-time of Apollo asteroids is much smaller than the age of the solar system, they must be replenished from some long-lived source. About 10 years ago it seemed that Mars-crossing asteroids were the only possible source. (Öpik 1963; Anders 1964; Anders and Mellick 1969; Anders 1971). But, as it was shown by Öpik (1963), the productivity of this source is too low by about a factor of 5. It was just this difficulty that impelled Öpik to suggest a cometary origin of most Apollo asteroids and thus--of meteorites.

However, further studies by Wehterill and his co-workers revealed the existence of asteroids in the main belt that experience *systematic* perturbations causing a sufficiently rapid evolution of their orbits in the necessary direction - a shift of the perihelion toward the Sun (Williams 1973; Zimmerman and Wetherill 1973; Wetherill 1974).

At present asteroids with small perihelion distance ($q < 1.2 \div 1.4$ A.U.) are divided into Apollo group (Earth-crossing orbits; $q \leq 1$ A.U.) and Amor group ($q > 1.$ A.U.). Because meteorites are bodies that hit the Earth, all of them, by definition, had Earth-intersecting orbits that belong to the Apollo type. However, it is convenient in the forthcoming discussion of meteorite orbits to include shallow Earth crossers ($q > 0.9$ A.U.) into Amor type. Taking into account the necessarily large spacings between isolines on nomograms used to determine approximate orbital elements of meteorites from visual observations (Simonenko and Levin 1974; Simonenko 1975) we will call Apollo-type orbits only those with $q < 0.9$ A.U. while those with $q > 0.9$ A.U. will be called Amor-type orbits.

Of two meteorites with orbits determined from photographic observations

Pribram had an Apollo type orbit while Lost City had an Amor type orbit. Their radiation ages are of the order of 10 million years. Thus their orbits can have been changed somewhat since their separation from their respective last parent bodies. Nevertheless it is likely that the orbits of their last parent bodies were of essentially the same type.

To the Apollo asteroids belonged also the last parent body of the Farmington meteorite. Its extremely short radiation age - 25,000 years - virtually assures that its orbit was not appreciably changed by planetary perturbations since it left its parent body. But all variants of Farmington orbit compatible with visual observations of its atmospheric trajectory are of the Apollo type, as shown recently by Anders, Simonenko and myself (Simonenko *et al.* 1976; Anders *et al.* 1976; Levin *et al.* 1976).

As it was found by Simonenko (1976), about 1/3 of the meteorites falling on Earth were in Apollo type orbits, while about 2/3 were in Amor type orbits. About 10% of meteorites were in very small orbits with semi-major axis less than 1 A.U. and were overtaken by the Earth near the aphelia of their orbits.

Bodies in Earth-*grazing* orbits intersect the Earth's orbit at very small angles. Therefore they have a much larger probability of encountering the Earth than do bodies in Earth-*intersecting* orbits. Besides, bodies in Earth-grazing orbits of small a and i have a small geocentric velocity, as is necessary for the preservation of a meteorite during its flight in the atmosphere. Thus it is easy to see why Amor, rather than Apollo asteroids represent the major class of the *last* parent bodies of meteorites.

The ages of meteorites show that their *initial* parent bodies were formed at a very early stage of the formation of the planetary system. According to various lines of evidence these bodies were no more than a few hundred kilometers in size. The largest of present-day asteroids are of just such size. The already disrupted initial parent bodies of meteorites in our museums undoubtedly belong to the same category.

On the other hand, medium sized asteroids often are angular fragments, and thus are excellent candidates for the intermediate parent bodies.

Thus, if we take into account the recent results by Wetherill and coworkers, at the present time there seem to be no objection to regard the asteroid belt as the past and present source of initial and intermediate parent bodies of meteorites.

Now let us discuss the relationship, if any, between asteroids and cometary nuclei. From the point of view of planetary cosmogony, asteroids are the evolved survivors of stony planetesimals formed in the inner, warm zone of the protoplanetary cloud, while cometary nuclei are survivors of icy planetesimals formed in the outer, cold zone of the cloud.

The population of bodies that accumulated in the asteroidal zone contained in addition to a limited number of large bodies also a multitude of small ones. Initially all were loose aggregates of mineral grains. Later the interiors of larger bodies became heated and mineral grains were sintered or even melted. But the thermal history of smaller ones was inadequate for such thermal metamorphism. Thus, because of their low crushing strength, most planetesimals of moderate and small size were destroyed by collisions. Even if some of their fragments still survive and hit the Earth from time to time, they are totally disrupted in the atmosphere, producing only bolides. On the other hand, some of the consolidated large bodies and a multitude of fragments of the remaining ones that underwent disruptive collisions, survived up to the present time and represent the major part of the asteroidal population that remains in the zone of its formation.

In contrast, icy planetesimals of the outer zone underwent almost no internal thermal evolution but only a complicated orbital evolution. When the accumulation of giant planets was sufficiently advanced these planetesimals were ejected outside the planetary system (Levin 1959; 1963). Most of them

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were lost forever, but some were favourably deflected by stellar perturbations and formed Oort's cloud - the source of presently observed comets.

The origin of most asteroids by agglomeration of non-volatile particles does not exclude the possibility that a few of them are nuclei of extinct comets. The lack of observable outflow of gases does not mean that ices are entirely exhausted in such nuclei. A porous surface layer of non-volatile particles, a few meters thick, is sufficient to prevent heating of the deeper interior. In most comets stony particles are blown away by gases. But larger particles can remain and form a crust that can spread over the whole surface of the nucleus. The recent analysis by Delsemme and Rud (1973) of photometric observations of comet Encke shows that evaporation occurs from only about 10% of the surface of its nucleus. It seems possible that in the near future the whole surface will be covered by an insulating layer. Then comet Encke with its small perihelion distance q = 0.34 A.U. will be indistinguishable from Earth-crossing asteroids. But for an indefinitely long time this quasi-asteroid will contain ices in its interior.

When Öpik put forward the hypothesis of cometary origin of most Apollo asteroids and also elevated them to meteorite parent bodies, he proposed two alternative models of cometary nuclei. According to the first (Öpik 1963, 1966a,b), chunks of meteoritic material - fragments of a short-lived population of primary meteorite parent bodies - were imbedded in icy cometary nuclei before their ejection into Oort's cloud. However the idea of such short-lived primary meteorite parent bodies is in disagreement with all existing data on meteorites.

The second model (Öpik 1963) suggests a stony core surrounded by an icy mantle. It requires an initially hot solar nebula in which accumulation of solids occurred more rapidly than the cooling of gas and condensation of more and more volatile compounds. However, even if we accept such inhomogeneous accumulation, ordinary cometary nuclei of usual size would have a cold core, not a hot core necessary to account for the thermal metamorphism of meteoritic material.

Another two-layer model was proposed by Sekanina (1971) to explain the progressive decrease with time of nongravitational forces observed in some comets (Marsden 1969, 1970). Sekanina regards the core of the nucleus as a porous nonvolatile matrix impregnated with ices. He assumed that nuclei of those comets that show a decrease of nongravitational forces are cores stripped of their mantles. The loss of gases occurs by means of activated diffusion and markedly decreases from one perihelion passage to another, causing a decrease of nongravitational forces. However this expectation is incorrect. When free sublimation of ices is replaced by diffusion through a "dry" porous layer, the mass ejection decreases by several orders of magnitude, practically to zero.

The observed decrease of nongravitational forces can be explained by spreading of a nonvolatile insulating layer over the surface of a "classical" homogeneous icy-conglomerate nucleus.

Thus, from my point of view, the following conclusions can be formulated:

At the present time there are no grounds to doubt the asteroidal origin of meteorites. However, to understand correctly all processes that occurred on the way from a large asteroid to a decimeter or meter-sized fragment that hit the Earth, one has to bear in mind that a typical meteorite had several successive generations of parent bodies.

Cometary nuclei are built according to Whipple's "classical" icy-conglomerate model and represent a separate type of small bodies. In some cases some nuclei of short-period comets probably transform into asteroid-like objects. This can occur when their whole surface becomes covered by an insulating layer a few meters thick preventing sublimation of ices that are still contained in their interior. Due to the very low thermal conductivity of such insulating

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layer, the internal ices sublime extremely slowly and thus can be preserved for an indefinitely long time. But these asteroid-like bodies can be parent bodies only of bolides, not of meteorites.

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DISCUSSION

SEKANINA: Comet Encke (specifically mentioned in the paper) is anomalously faint after perihelion (compared with the same heliocentric distance before perihelion), but anomalously bright near aphelion (see my paper in IAU Coll. No. 25). Levin's insulating layer would have to miraculously vanish far from the sun and reappear near the sun in order to explain the observed brightness behavior. Furthermore, Shul'man's formula indicates that at perihelion chunks up to some 10 meters in size would be blown away from the surface of the nucleus (1 km radius made of water snow). Even when we disregard the possibility that large chunks should be prone to fragmentation (thus assisting in the removal of the material), it is physically impossible to form the proposed insulating layer under any feasible circumstances.

WETHERILL: A good reason for distinguishing between shallow earth crossers and earth-grazing objects, and deeper earth crossers is that only the shallow and grazing objects produce meteorite orbits which agree with the observed distribution of meteorite radiants and fall times. However, the problem is that earth-grazers will evolve into deeper earth-crossers, and it isn't likely that this effect can be offset by the higher earth impact rate associated with shallow crossing. The Amor objects, as defined here, offer very attractive

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possibilities as chondrite sources, but I think this difficulty still requires quantitatively resolution.

HERNDON: The suggestion of multiple generations of parent bodies has a familiar ring to it, reminescent of Harold Urey's "Grandparent Bodies."