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DYNAMICAL EVIDENCE REGARDING THE RELATIONSHIP BETWEEN ASTEROIDS AND METEORITES

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Meteorites are fragments of small solar system bodies (comets, asteroids and Apollo objects). Therefore they may be expected to provide valuable information regarding these bodies. However, the identification of particular classes of meteorites with particular small bodies or classes of small bodies is at present uncertain. It is very unlikely that any significant quantity of meteoritic material is obtained from typical active comets. Relatively well-studied dynamical mechanisms exist for transferring material into the vicinity of the Earth from the inner edge of the asteroid belt on an $\sim 10^{8-9}$ year time scale. It seems likely that most iron meteorites are obtained in this way, and a significant yield of complementary differentiated meteoritic silicate material may be expected to accompany these differentiated iron meteorites. Insofar as data exist, photometric measurements support an association between Apollo objects and chondritic meteorites. Because Apollo objects are in orbits which come close to the Earth, and also must be fragmented as they traverse the asteroid belt near aphelion, there also must be a component of the meteorite flux derived from Apollo objects. Dynamical arguments favor the hypothesis that most Apollo objects are devolatilized comet residues. However, plausible dynamical, petrographic, and cosmogonical reasons are known which argue against the simple conclusion of this syllogism, *viz.*, that chondrites are of cometary origin. Suggestions are given for future theoretical, observational, experimental investigations directed toward improving our understanding of this puzzling situation.

INTRODUCTION

The Earth, Moon, and terrestrial planets are impacted by solid interplanetary bodies ranging in mass from $\sim 10^{-15}$ g to 10^{19} g. The total mass flux is ~ 100 g/km^2/yr, of which ~ 1 g is in the mass range from 100 to 10^7 g. About 10% of the material (*meteoroids*) in this mass range survives entry and passage through the atmosphere. Of this 10%, $\sim 0.1\%$ is collected from the Earth's surface and constitutes the collections of *meteorites* housed in museums.

Petrological and trace element investigations are interpreted as implying that prior to the recent onset of their cosmic ray exposure, meteorites were in the interior of bodies ranging from 10 to 500 km in diameter. The chemical and mineralogical differences between the various classes of meteorites are principally a consequence of differences in the composition of these *parent bodies*.

The identification of the parent bodies among various small bodies of the solar system is not definitive at present. Candidate objects include comets, asteroids, the Apollo-Amor objects with perihelia near Earth's orbit, and possibly undiscovered classes of bodies as suggested by the recently discovered Saturn and Uranus-crossing object, Chiron (1977UB). Discussion of evidence for and against the association of particular meteoritic classes with these various candidate objects is the principal topic of this review.

Progress toward more positive identification is essential if we are to make full use of the abundant data relevant to the pre-history, the origin, and the history of the solar system being obtained from laboratory studies of meteorites. Only in this way will it be possible to place these small samples of solar system matter in their appropriate geological and astronomical context. Achieving this goal will require a significant and continuing program of interactive laboratory, observational, and theoretical investigations, and is a major argument in support of space missions to these bodies.

Meteorites are of varied chemical and mineralogical composition, and there is no particular reason why all of them should be derived from the same type of parent body. They can be divided fairly well into two classes: the undifferentiated and the differentiated meteorites. Undifferentiated meteorites are also termed *chondrites*, because they usually contain small (0.1 to 1 mm diameter) spherules called *chondrules*, which are primarily of silicate composition. In the undifferentiated meteorites the relative abundances of the refractory elements (*e.g.*, Mg, Fe, Si, [illegible], etc.) to one another are very similar to those found in the Sun and in averaged solar system material. The more volatile elements are systematically depleted (Ganapathy and Anders, 1974). These volatile elements are least depleted in the carbonaceous chondrites in which the S/Si ratio is nearly the same as in the Sun, and even more volatile elements such as C and N are depleted by only a factor of ∿10. Greater depletions of volatiles are found in the most abundant classes of chondrites, the *ordinary chondrites*. The differentiated meteorites have been even more chemically fractionated relative to average solar system composition. They include objects consisting nearly entirely of nickel-iron, silicate objects which appear to have formed by partial melting processes similar to those which form terrestrial and lunar basalts, silicate objects intruded by veins of nickel-iron, and various other mineralogical assemblages (*cf.*, Wasson, 1974).

Identification of appropriate parent bodies for meteorites of these various classes requires a plausible correspondence between the chemical, mineralogical, and physical nature of the parent body and the meteorite, and cannot be accomplished entirely on the basis of dynamical arguments. The characteristics of possible parent bodies are briefly discussed in the following section.

CANDIDATE SOURCES OF METEORITES

It is conventional to distinguish between comets and asteroids on the operational basis of whether or not they possess a visible coma. Although this definition may sometimes be useful, it also ignores the most important point at issue, namely the ultimate origin of the large and small bodies in the solar system. This discussion will therefore make use of a genetic classification, wherein an object, however gas-free, which was derived from a more typical volatile-rich comet, is considered to be cometary.

Typical comets are small (∿1 to 10 km) objects containing more or less equal quantities of volatile compounds of H, C, N, and O and more refractory compounds, *e.g.*, silicates and metal. The success of the "dirty snowball" model of a comet (Whipple, 1950) has probably accidentally led to a misconception in the minds of some workers, particularly those in related fields of study. This is that comets are principally composed of ice, and can be visualized more or less as a glacier or snowbank. In fact, the material emitted by a comet contains as much dirt as snow (Delsemme, 1977). Furthermore, only the smaller nonvolatile particles can be "blown off" with the volatiles, and presence of larger bodies (*e.g.*, ∿25 cm) in comets cause the fraction of ice to be even smaller. As the ice is volatilized, the fraction of rocky material will increase and will tend to accumulate as residual material.

Fireball studies show that the more massive nonvolatile cometary material is abundant and this conclusion is strengthened by the evidence for nearly-extinct and extinct cometary nuclei. Thus at least half, and possibly 90% of even an active comet may be nonvolatile dust and rocky matter. It is possible that a comet may be more like a breccia than an iceberg, and that pieces of ice may be clasts in this breccia, as a consequence of H_2O and CO_2 being as solid as anything else at the low temperatures which prevailed in the region in which comets were formed. At present, most (and probably all) comets are derived from the outermost regions of the solar system, the Oort cloud at a distance of 10^4-10^5 AU (0.1 to 1 light-year) (Marsden, 1977). They become observable only when they are gravitationally perturbed by passing stars into the inner solar system. The volatilization of their H, C, N and O compounds produces a *coma* $\sim 10^4$ km in diameter, and an ionized tail (up to $\sim 10^7$ km in length), which renders the comet visible.

Comets are definitely associated with much of the interplanetary flux of bodies impacting the Earth, including those in the mass range (100 to 10^7 g) under discussion. This has been established by photographic studies of the orbits of these bodies as they enter the atmosphere (Ceplecha and McCrosky, 1976), and comparison of these orbits with those of known comets. Positive identification with particular comets is possible in many cases. In many additional cases similarity of both orbits and physical properties (as indicated by their ablation or fragmentation in the atmosphere), to objects associated with known comets demonstrates their cometary association. However, only three meteorite falls (the undifferentiated ordinary chondrites Pribram, Lost City and Innisfree) are contained among these photographic meteoroids. As will be discussed further subsequently, their orbits and physical properties, although well-determined, do not define at all well whether or not they are also of cometary origin.

Asteroids are bodies ranging up to 1000 km in diameter which are almost entirely confined to the wide region between Mars and Jupiter. They exhibit no coma of volatile compounds, and most likely consist of mixtures of silicates and metal. Spectrophotometric studies (Chapman, 1976) are interpreted as indicating that different asteroids are of different composition. They primarily fall into two classes: the most abundant C type, presumably containing an admixture of carbonaceous composition, and the S type, probably mixtures of silicates and metal. Unlike the comets, direct association of photographic meteoroids with an asteroidal source is not possible, as the orbits of asteroids do not intersect the orbit of the Earth. However, there are mechanisms by which the orbits of asteroidal bodies can evolve into Earth-intersecting orbits. These will be discussed in the following section.

Apollo-Amor objects are small bodies (typically ~ 1 km diameter, but ranging up to ~ 30 km) with perihelia less than a rather arbitrary value of 1.3 AU, and usually with aphelion in the asteroid belt. These orbits are dynamically unstable on the time scale of the solar system, and like the meteorites they must be derived from sources elsewhere in the solar system, which probably include both comets and asteroids (Anders and Arnold, 1965; Wetherill, 1976). Their Earth-crossing or near Earth-crossing nature identifies them as prime candidate meteoroid and meteorite sources (Anders, 1964; Levin *et al.*, 1976; Wetherill, 1976). However, up to the present no clear-cut orbital identifications have been made, although tentative identification of a few Apollos with known small meteoroid streams has been proposed (Sekanina, 1973). Physical measurements show that all but one (1580 Betulia) of the Apollo-Amor objects studied using these techniques resemble the S-type asteroids more than they do the C-type (McCord, 1978). These statistics are certainly biased in favor of the higher albedo S-type objects. In any case, it is of interest to note that they are not all of the same composition, and this range of compositions includes high albedo, silicate objects resembling differentiated and undifferentiated silicate meteorites.

It is hard to rule out the possibility that more than a negligible fraction of the meteoroid flux is derived from unknown classes of objects, as small, nonvolatile objects are very difficult to observe telescopically. The recent discovery of Chiron is evidence that we have not yet learned even all the more qualitative facts concerning the distribution of small bodies in the solar system. It is possible that there are small bodies stably stored in inner solar system orbits (*cf.*, Weissman and Wetherill, 1973), possibly in resonances, which resemble those in which 1685 Toro is currently trapped (Danielsson and Ip, 1972; Williams and Wetherill, 1973) but which, unlike Toro, are not destabilized by Mars' perturbations. Even an interstellar contribution cannot be entirely ruled out, although orbits of photographic meteors show their proportions must be very small ($\lesssim 0.1\%$).

During the last century opinion has shifted to and fro regarding with which of these classes of candidate bodies one should associate meteorites. Until the last decade or two, the prevailing opinion was primarily determined by stochastic fluctuations arising from the small number of "experts," rather than from an abundance of relevant data. However, during the last few years there has been a great increase in the quantity of experimental, observational, and theoretical data concerning meteorites, meteors, and their candidate sources. In spite of this, serious problems of identification of Earth-impacting bodies with their solar system sources remain.

It might be thought that the gross difference between typical cometary and asteroidal orbits would make it relatively easy to distinguish between cometary and asteroidal sources once the orbits of meteorites are known. This is not the case. In order for asteroidal material to impact the Earth as a meteorite, it is necessary that it be placed into a more eccentric orbit with perihelion within the orbit of the Earth. On the other hand, comets or cometary residua will have short dynamical lifetimes in the inner solar system unless their orbits evolve into orbits with aphelia inside Jupiter's orbit, *i.e.*, become similar to the orbit of Encke's comet (aphelion = 4.1 AU). Thus asteroidal and cometary meteorites will have similar orbits, with Earth-crossing perihelia and aphelia in the asteroid belt. The distinction will be further blurred as a consequence of perturbations by Earth and Venus which will tend to "equilibrate" the distribution of Earth-crossing orbits. It is known from radiant and time-of-fall statistics (Wetherill, 1971) that at least ordinary chondritic meteorites must evolve from initial Earth-crossing orbits with perihelia near Earth and aphelia near Jupiter. Both asteroidal and cometary sources can have this general characteristic. However, more subtle differences exist which in the future may be helpful in identification of candidate sources.

DYNAMICAL ARGUMENTS FOR AND AGAINST PARTICULAR IDENTIFICATIONS, CONSIDERED IN THE LIGHT OF OTHER EVIDENCE

Asteroids

Purely dynamical considerations. Asteroids are strong *prima facie* candidates because it is known that collisions among the asteroids must provide a quantity of small debris (10^{13}-10^{15} g annually) which would be more than adequate to supply the present flux of Earth-impacting matter, *provided* that there exist mechanisms able to place a sufficient fraction ($\sim 10^{-4}$) of this material into Earth-crossing orbits on the short time scale ($\sim 10^{6}$ yr) defined by the cosmic-ray exposure history of meteorites. It is also necessary that the shock damage associated with this transfer mechanism usually be limited to that associated with low shock pressures (10-100 Kb).

Difficulties in finding such mechanisms have been a problem in the past. Suitable mechanisms must be primarily gravitational in nature, as collisional shock associated with more than small ($\lesssim .1$ AU) changes in semimajor axis is probably excessive. Gravitational perturbations of Mars-crossing and Mars-grazing asteroidal fragments by Mars have been suggested as such a gravitational mechanism (Arnold, 1965; Anders, 1964) but until recently it appeared that, except for iron meteorites, this mechanism required transit times too long to be reconciled with cosmic-ray exposure histories.

Production of relatively low velocity ($\lesssim 200$ m/sec) fragments in proximity to various regions in the asteroid belt in which the motion of fragments is in resonance with the motion of the giant planets has now been semi-quantitatively shown to be an adequate source.

Fairly large ($\sim$100 m) fragments will be produced by collisions in the vicinity of the Kirkwood 2:1 gaps at 3.28 AU, in which the orbital period is commensurable with the period of Jupiter. The resulting resonant motion will at times cause these fragments to be in highly eccentric orbits with aphelia beyond 4 AU and perihelia $\sim$2 AU. These orbits will be stabilized by librational relationships which preclude close encounters to Jupiter. However, statistically probable collisions of these $\sim$100 m bodies with smaller asteroidal debris will produce low-velocity meteorite-size fragments which will escape the libration region and undergo strong perturbations by Jupiter near their aphelion, which can cause their perihelion to random walk into Earth-crossing on a short ($\sim 10^6$ yr) time scale, and hence become meteorites when they impact the Earth (Zimmerman and Wetherill, 1973). This chain of events has been criticized on the grounds that requiring two collisions, close approaches to Jupiter, etc., renders it too complex and by inference *ad hoc* to be taken seriously. Such reasoning is fallacious, as there is no reason to suppose that nature provides meteorites to Earth by mechanisms which are simple for us to describe to one another in preference to those which are probable. The mechanisms described are real phenomena of significant and estimable probability which cannot fail to occur.

The principal problem is a quantitative one, as best estimates of the meteorite yield on Earth from this source are 10^7-10^8 g per year, and this estimate is uncertain by at least an additional order of magnitude. Thus it is not clear if a major or only a minor part of the Earth's meteorites are produced in this way. Scholl and Froeschlé (1977) have presented evidence that the mechanism described above may be more effective for the 5:2 Kirkwood gap than for the 2:1 case. Large asteroids in proximity to these Kirkwood gaps are listed in Tables 1 and 2.

Table 1. Large Asteroids with Semimajor Axis
within 0.1 AU of 2:1 Kirkwood Gap (3.28 AU)

Asteroid	a	e	i	B(1,0)	Class	Diameter (km)
106 Dione	3.17	.18	5	8.8	C	139
511 Davida	3.18	.18	16	7.4	C	323
154 Bertha	3.18	.10	21	8.5	C	191
92 Undina	3.19	.07	10	7.9	C	244
702 Alauda	3.19	.03	21	8.3	C	205
758 Mancunia	3.20	.13	6	9.6	C	119
175 Andromache	3.21	.20	3	9.6	C	113
530 Turandot	3.21	.20	8	10.3	C	81
381 Myrrha	3.21	.12	13	9.7	C	126
108 Hecuba	3.22	.09	4	9.7	S	61
122 Gerda	3.22	.06	2	9.2	C	139
895 Helio	3.22	.14	26	9.5	?	
745 Mauritia	3.24	.07	14	11.0	?	
903 Nealley	3.24	.05	12	10.9	?	

Classifications and diameters from Morrison (1977) and Zellner and Bowell (1977), Bowell *et al.*, (1978), and Bowell (private communication, 1978). Absolute magnitudes from Gehrels and Gehrels (1978).

Williams (1973) showed that collision fragments produced at low velocity in the vicinity of certain secular resonant surfaces in (a,e,i) space (Williams, 1969, 1971) can be perturbed directly into Earth-crossing on the necessary short time scale. Again, the quantitative yield is difficult to estimate with certainty.

Table 2. Large Asteroids with Semimajor Axis within 0.1 AU of 5:2 Kirkwood Gap (2.82 AU)

Asteroid	a	e	i	B(1,0)	Class	Diameter (km)
146 Lucina	2.72	.07	13	9.2	C	141
45 Eugenia	2.72	.08	7	8.3	C	226
410 Chloris	2.72	.24	11	9.5	C	134
156 Xanthippe	2.73	.23	10	9.8	C	104
140 Siwa	2.73	.21	3	9.6	C	103
110 Lydia	2.73	.08	6	8.7	C	170
200 Dynamene	2.74	.13	7	9.5	C	123
185 Eunike	2.74	.13	23	8.7	C	169
247 Eukrate	2.74	.24	25	9.3	C	142
387 Acquitania	2.74	.24	18	8.4	S	112
173 Ino	2.74	.21	14	9.1	C	142
308 Polyxo	2.75	.04	4	9.3	U	138
128 Nemesis	2.75	.12	6	8.8	C	164
71 Niobe	2.76	.17	23	8.3	S	115
93 Minerva	2.76	.14	9	8.7	C	168
356 Liguria	2.76	.24	8	9.3	C	150
41 Daphne	2.76	.27	16	8.1	C	204
1 Ceres	2.77	.07	11	4.5	C	1003
88 Thisbe	2.77	.17	5	8.1	C	210
39 Laetitia	2.77	.11	10	7.4	S	163
2 Pallas	2.77	.23	35	5.2	U	608
148 Gallia	2.77	.19	25	8.5	S	106
532 Herculina	2.77	.17	16	8.0	S	150
393 Lampetia	2.77	.33	15	9.2	C	129
28 Bellona	2.78	.15	9	8.2	S	126
68 Leto	2.78	.18	8	8.2	S	126
139 Juewa	2.78	.17	11	9.2	C	163
446 Aeternitas	2.79	.07	11	10.2	0	40
216 Kleopatra	2.79	.25	13	8.1	M	128
354 Eleonora	2.80	.12	18	7.5	S	153
346 Hermentaria	2.80	.10	9	8.9	S	84
236 Honoria	2.80	.19	8	9.5	S	65
441 Bathilde	2.81	.08	8	9.5	M	66
804 Hispania	2.84	.14	15	8.9	C	141
385 Ilmatar	2.85	.13	14	8.8	?	?
81 Terpsichore	2.85	.21	8	9.6	C	112
129 Antigone	2.87	.21	12	7.9	M	115
47 Aglaja	2.88	.14	5	9.2	C	158
471 Papagena	2.89	.24	15	7.9	S	143
386 Siegena	2.90	.17	20	8.4	C	191
238 Hypatia	2.91	.09	12	9.2	C	154
22 Kalliope	2.91	.10	14	7.3	M	177
16 Psyche	2.92	.13	3	6.9	M	250
674 Rachele	2.92	.20	14	8.5	S	102
349 Dembowska	2.92	.09	8	7.2	0	144

Data from same sources as Table 1.

Wetherill (1974, 1977) and Wetherill and Williams (1977) have proposed a "synergistic" mechanism by which the nonlinear interaction of secular resonance and Mars' perturbations can perturb a rather large yield ($\sim 10^{10}$ g/yr) of meteorite-size asteroidal fragments into Earth-crossing. The typical time required for this material to impact the Earth is $\sim 5 \times 10^8$ years, but a significant fraction (∿1%) can impact within 50 million years. The mechanism is proposed as the most probable source of iron meteorites, and of some minor portion of the silicate meteorites, *e.g.*, the differentiated basaltic achondrites. The asteroids which supply this material are those with semimajor axis ∿2.25 AU, low inclinations, and with eccentricities which permit the parent objects to come within ∿.05 to .1 AU of Mars' aphelion for favorable combinations of the long-period "secular" variations in the orbits of both the asteroids and Mars (Figure 1). Most of these asteroids are S type, which have been suggested to be most likely of "mesosiderite" (mixed iron and basaltic silicate) composition. The massive nickel-iron meteorites must come from somewhere, and the combination of appropriate calculated exposure age, yield, and plausib [illegible] emical composition argues strongly in support of this being the most likely place. [illegible] r, this identification also reduces somewhat the plausibility of obtaining the most [illegible] nt classes of chondrites from this source, as this identification of S asteroids witn [illegible] tic silicates argues against their being also of undifferentiated chondritic composit... [illegible] however, the largest object of this group (313 Chaldaea, 160 km diameter) is of carbonaceous composition (Chapman, 1977, private communication) and may be expected to produce a small quantity of carbonaceous meteorites, constrained by the association of small yields with short transit times for this source.

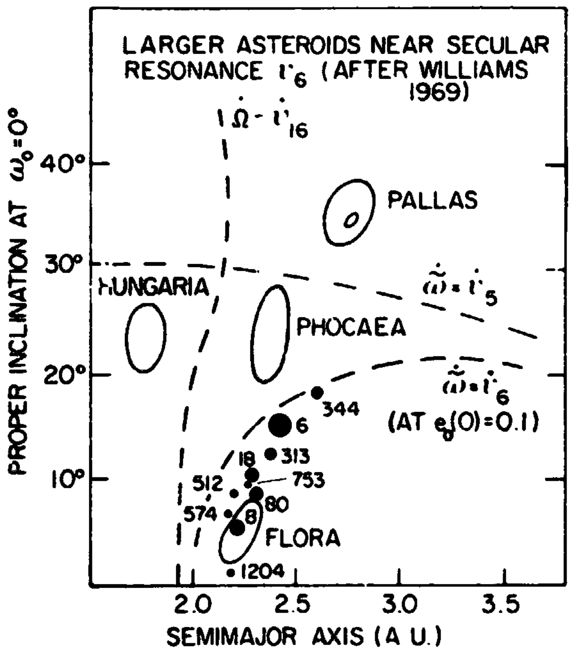

Fig. 1. Observed distribution of large asteroids in the inner portion of the asteroid belt and in the vicinity of the ν_6 resonance. The large open "circles" approximately define the limits of the Hungaria, Flora, Phocaea, and Pallas regions of the asteroid belt.

Recognition of the evidence for meteorites being asteroidal regoliths. A small but significant fraction of silicate meteorites of all classes are rich in inert gases similar in chemical and isotopic composition to the solar wind, contain solar flare cosmic-ray charged particle tracks, in some cases grains exhibiting microcraters, and glassy agglutinates. All of these meteorites are highly brecciated, and the combination of these features strongly suggests an origin similar to that of the lunar regolith (Rajan, 1974). Anders (1975) has carried this argument further and has used the ratio of implanted solar wind and galactic cosmic-ray exposure to infer the heliocentric distance at which this regolithic material was produced. This distance turns out to be 4 to 8 AU, but is model-dependent in a number of ways. Rajan *et al.* (1978) and Schultze and Signer (1977) have identified breccia clasts within both chondritic and differentiated gas-rich meteorites which have radiogenic argon ages markedly younger than the more typical ∼4.5 billion year age of other clasts from the same breccia. From this it is plausibly inferred that the breccia was assembled subsequent to the younger of these ages, which in one case is as recent as 1350 million years.

In addition, Turner (1969), Turner and Cadogan (1973), and Bogard *et al.* (1976) have interpreted disturbed radiometric age patterns in relatively highly shocked meteorites as indicating that their parent body was involved in a major impact event 500 million years ago (Heymann, 1967). However, it can also be argued that these events are not well-dated, and could represent a very recent event, associated with the collision which established the recent onset of cosmic-ray exposure, in combination with a small (∼3%) retention of radiogenic argon from its previous history. Recent theoretical studies of the evolution of Apollo-Amor objects of either cometary or asteroidal origins shows that when secular resonance is included, an asteroidal parent body cannot necessarily be inferred from these ages even if they are interpreted literally (Wetherill, 1978). It turns out that a significant fraction (∼15%) of Apollos are transferred into the Amor and Mars-crossing region for times as long as 2000 million years, and then returned to Earth-crossing. Thus an Apollo object of cometary origin can have been in the inner solar system 500 million years ago, and have developed some sort of a regolith. However, a small, 1 km Apollo object would seem unlikely to develop a full-fledged lunar-style regolith.

Since there are strong arguments against meteorites being derivable from the regolith of one of the terrestrial planets, and studies of lunar material show they are not from the Moon, the most plausible place to suggest for their source are the surfaces of large (*e.g.*, ≥100 km diameter) bodies in the asteroid region. If so, this regolith cannot be a surficial layer only a few meters deep, as asteroid collision calculations show that the mass yield from asteroidal fragmentation is dominated by deep and even totally destructive impacts (Wetherill, 1967; Dohnanyi, 1969). Whether or not a body with the low surface gravity of an asteroid can be expected to possess such a deep regolith is not clear. Many workers have argued against anything but a very surficial regolith, whereas Anders (1975) has concluded that it is possible that almost the entire asteroid has had a regolithic history. Combined theoretical and experimental work directed toward a detailed understanding of the probable nature of an asteroidal regolith is badly needed. A start in this direction has been made (Housen *et al.*, 1977; Chapman, 1978). Until this is done it cannot be said whether or not the effects observed are compatible with this plausible but undemonstrated association.

The full set of these regolith features are observed in only a few of the gas-rich meteorites. The most clear-cut case is that of the highly brecciated basaltic differentiated meteorites, the howardites (*e.g.*, Kapoeta), for which the "synergistic" mechanism of derivation from the inner asteroid belt is proposed in the previous section. Less complete effects, such as presence of inert gas of solar composition, is less definitive, as unfractionated gas of this type was available over all of solar system history and even earlier. It is probable that formation of a regolith at a well-defined heliocentric distance is not the only way for incorporation of this gas into interplanetary material.

Chemical and mineralogical evidence from meteorites. Even the undifferentiated chondritic meteorites have had a complex chemical history. The volatile-poor ordinary chondrites have in many cases been heated and metamorphosed at temperatures as high as $\sim$900°C (Van Schumus and Wood, 1967). Subsequent cooling histories several hundred million years in length have been inferred from the extent to which Ni diffuses in the solid state from Ni-poor α-Fe to Ni-rich γ-Fe in the small bits of metallic Fe found in chondrites, as well as in the differentiated iron meteorites. It is not clear how a small asteroidal body could have experienced an early thermal history this extreme. However, the evidence for an asteroidal origin is most strong for basaltic differentiated meteorites, and it has been *demonstrated* that these objects experienced a melting event $\sim 4.5 \times 10^9$ years ago. Therefore, it does not seem extreme to suppose that other asteroids underwent the less severe heating required to explain the textures and mineralogy found in chondrites. If the only alternative source turns out to be comets, it must be remembered that there is no evidence to support a claim that the interior of a comet ever went through such a high temperature stage, or was massive enough to require the long cooling times observed.

Another class of chemical arguments is based upon a presumably known relationship between the temperatures at which meteorites were formed (as deduced from their mineralogy, trace element, and oxygen isotopic composition), and the heliocentric distance at which these temperatures would be found (Larimer and Anders, 1967). However, these calculations require that the present state of knowledge concerning the processes and conditions of star and planetary system origin is more secure than there is any reason to suppose it to be. Such condensation theories also fail to explain how such different classes of asteroids, as inferred from spectrophotometric and polarimetric data, are found at the same heliocentric distance. The variations in oxygen isotopic composition of pre-solar origin found between the different meteorite classes (Clayton *et al.*, 1976; Clayton, 1978) is even more difficult to explain. These phenomena appear to require that asteroids which were originally formed at significantly different heliocentric distance were subsequently mixed by an unknown physical mechanism. This may well have occurred. However, inasmuch as asteroids may have moved since formation this weakens the identification of an asteroidal origin based on an inferred "asteroidal belt" distance of origin.

Relationship of spectrophotometric observations of asteroids to the dynamical evidence. During the last five years a large body of spectral reflection data for asteroidal surfaces has been obtained (Gaffey and McCord, 1977; McCord, 1978). This permits at least tentative identification of the mineralogical nature of these surfaces, particularly the presence of opaque materials such as amorphous carbon, pyroxene and olivine (Fe, Mg silicates), and metallic iron. This has led to an asteroidal taxonomy in which the S and C types, previously mentioned, are the most abundant classes. (See papers in this volume by Morrison (1978) and by Zellner (1978).)

At least one large C type asteroid is located near the ν_6 resonant surface (313 Chaldaea) and others are in proximity to the Kirkwood gaps (Tables 1 and 2). Assuming these asteroids are indeed similar to carbonaceous chondrites, they are strong candidate sources for meteorites. The Apollo-Amor object 1580 Betulia is also of presumed carbonaceous compositions. The high geocentric velocity of fragments of Betulia would lead to a very small yield of material from this particular object. However, the existence of one carbonaceous body among this group, together with the observational biases against such low albedo objects, argues that there are likely to be many more, including some in low-velocity orbits.

The S objects near the resonant regions may also be considered to be excellent parent-body candidates for differentiated silicate and iron meteorites. This is particularly true of those near the ν_6 surface, in view of the agreement between their calculated exposure ages and those measured on iron meteorites. The large asteroid 4 Vesta has frequently been proposed as the source of the basaltic achondrite meteorites. Its reflectance spectrum is in accord with this identification. However, its perihelion is so far from Mars' aphelion and its semimajor axis so far from resonant value that there is no dynamical reason to expect a significant yield of meteorites from this asteroid. It seems more likely that differentiated silicate meteorites (achondrites) are derived from the silicate portion of large S asteroids such as 6 Hebe and 8 Flora, their smaller counterparts (some of which are likely to be their fragments), and Apollo-Amors derived from these bodies. Consolmagno and Drake (1977) have questioned the validity of this inference in view of the near absence among differentiated meteorites of the peridotitic residues of basalt formation, and have proposed Vesta as a basaltic achondrite source for which only the surficial basalt layer is exposed. In view of the dynamical problems associated with this identification, it seems premature to consider this line of reasoning definitive; rather it seems best to leave this matter open at present. It is not at all clear that the collisional fragmentation of even Vesta was sufficiently mild to preclude considerable excavation of its "mantle." It might be that the excess of basaltic achondrites relative to their more ultramafic counterparts is a statistical fluctuation associated with most of these meteorites being derived from a single Apollo-Amor fragment from the Flora region, which happened to be a sample of a basaltic portion of a large S asteroid.

If ordinary chondrites do come from asteroids, it is becoming increasingly puzzling why almost none of the asteroids match the reflectance spectrum of a chondrite. In fact, only one main belt asteroid (the Apollo-Amor objects will be discussed separately) has been held to be of ordinary chondritic composition by spectrophotometric observers, 349 Dembowska. Even this identification has been questioned by recent infrared data (Matson *et al.*, 1977). Various explanations of this discrepancy have been proposed: poor sampling of asteroids, observation of only a surficial layer of the asteroid, changes in reflectance caused by solar wind sputtering or microparticle bombardment. However, plausible reasons for rejecting these hypotheses can be given. 349 Dembowska is a large asteroid (144 km diameter) not too distant from the 5:2 Kirkwood gap, from which meteorites could be derived (Scholl and Froeschlé, 1977). However, there are many other large asteroids similarly well situated which don't look like ordinary chondrites, but are largely normal S- and C-type asteroids. No mechanism is known which would preferentially sample Dembowska relative to these others. Statistical fluctuations in the recent impact history appear inadequate to explain the variety of ordinary chondrite classes or their different exposure histories.

Comets

It is practically certain that no meteorites in our collections have been derived from historically observed comets. The shortest known cosmic-ray exposure age is that of the ordinary chondrite Farmington (19,000 years) and this is unique. In contrast, the volatile content of comets is insufficient to continue the observed volatile loss for more than 10^4 years. Furthermore, it is unlikely that most meteorites are derived from comets during the active stage of their history, as they are usually too massive to be swept along by the outflowing gases. Although meteorites could be freed from comets during more violent cometary outbursts, or following disruption while passing close to the Sun, it seems most likely that cometary meteorites, if they exist, are derived from nonvolatile residues of comets which are likely to survive following the active lifetime of a short-period comet. This could be either from a core which was originally mantled with volatile ices, or a loosely aggregated collection of meteoritic fragments originally scattered through the icy material, or from ice-poor portions of a regolithic breccia.

There is good, if not compelling, evidence that nonvolatile residues of comets exist. There is a gradation in activity between highly volatile comets newly arrived from the Oort cloud, and the short period comets. This trend continues down to apparently severely volatile-depleted short period comets, such as Encke (Sekanina, 1971) and barely active comets such as Arend-Rigaux and Neujmin I. The natural end-members of this series are the nonvolatile Apollo-Amor objects, and it has frequently been proposed that some or all of these bodies are extinct comets (Öpik, 1963; Anders and Arnold, 1965; Wetherill and Williams, 1968; Wetherill, 1976).

One short period comet (Encke) is presently in an orbit with aphelion at 4.1 AU, well within the orbit of Jupiter. An orbit of this kind is relatively stable with respect to gravitational perturbations, in contrast to Jupiter-crossing bodies which will be ejected from the solar system in $\sim 10^5$ years. Sekanina (1971) has shown how the "jet effect" (non-gravitational forces which are the reaction to the comet's emitted dust and gas) has reduced Encke's aphelion to its present value during the last $\sim$1000 years. At present these forces are small, implying relatively little emission of gas, which is compatible with Encke being nearly extinct. On this line of reasoning, it can be predicted that during the next few hundred years, Encke will become an Apollo object. Nor does it appear to be alone. A number of meteor streams are in orbits similar to Encke, often with aphelia even much further within the orbit of Jupiter. Meteors in these streams exhibit physical characteristics very much the same as the Taurid meteors, known to be fragments of Encke (Ceplecha and McCrosky, 1976; Ceplecha, 1977a). It is most plausible that these streams have been recently derived from unobserved extinct comets, because the time required for evolution into orbits as small as, for example, that of the Geminids (aphelion = 2.6 AU), is $\sim 10^6$ years (Wetherill, 1976). In contrast the time during which a stream will remain coherent is $\sim 10^4$ years.

Fragments of extinct comets are not confined to the small, and usually weak, small meteors. Large objects, kilograms in mass, are associated with these streams. There is even evidence that very large ($\sim$100 ton) bodies are sometimes found in streams (Table 3).

Table 3. Fireball λ Orionids (Type III)

	a	e	i	ω	Ω	Date
N. λ Orionids	2.22	0.79	2	281	258	12/4-12/15
EN041274 (10^8 g)	1.98 ±.18	0.76 ±.03	3.5	282	252	12/4/74
EN021267 (14 kg)	2.20 ±.02	0.79	3.9	283	250	12/3/67
S. λ Orionids	2.18	0.78	7	101	79	12/7-12/1
PM39469.850 (1 kg)	2.33	0.78	5	93	78	12/10/76

Data from Ceplecha and McCrosky (1976) and Ceplecha (1977b).

So it seems very likely that extinct comets exist and that large meteoroids derived from them impact the Earth. To a large extent the orbits of these meteoroids will be similar to those derived from the asteroid belt by the mechanisms discussed in the previous section. Are these meteoroids ever meteorites, *i.e.*, can they survive passage through the atmosphere and be recovered from the ground? No direct evidence for this exists at present. However, there is circumstantial evidence that this may be the case. Ceplecha and McCrosky (1976) have shown that meteoroids in the 100 g to 10^7 g mass range differ considerably in their physical strength and ability to penetrate deeply into the atmosphere. Although it is possible these differences will prove to be gradational, those observed so far fall into three classes, and can be discussed separately.

Class III, the weakest of all, is associated with a number of well-established cometary meteor streams, and is nearly certain to be of cometary origin. Class II is significantly stronger. Some objects of this class also have definite cometary association (*e.g.*, Taurids and Encke). Ceplecha *et al.* (1977) have obtained a spectrum of one of these bodies which had a terminal mass of 70 g, and hence survived passage through the atmosphere. The spectrum shows strong CN bands and therefore contains carbonaceous matter. It seems most plausible to associate this body with at least some type of carbonaceous meteorite.

The strongest type of fireball meteor is Type I. All three fireballs photographed by fireball networks which have been recovered as meteorites (ordinary ≡ noncarbonaceous chondrites) are of this class. Many fireballs ($\sim 1/3$) fall into this class. There is every reason to believe that any of them could have reached the ground if they had been large enough, or had entered the atmosphere at sufficiently low velocity. Their terminal mass distribution (Figure 2) indicates that it is common for both Type I and Type II meteoroids to survive atmospheric passage. Except for the problem that asteroids don't appear to be of ordinary chondritic composition, there is no particular reason why most of these fireballs could not be of asteroidal origin, accelerated into Earth-crossing by one of the gentle resonance gravitational mechanisms discussed in the previous section. If so, this would oppose the present consensus that most meteors, both large and small, are derived from comets.

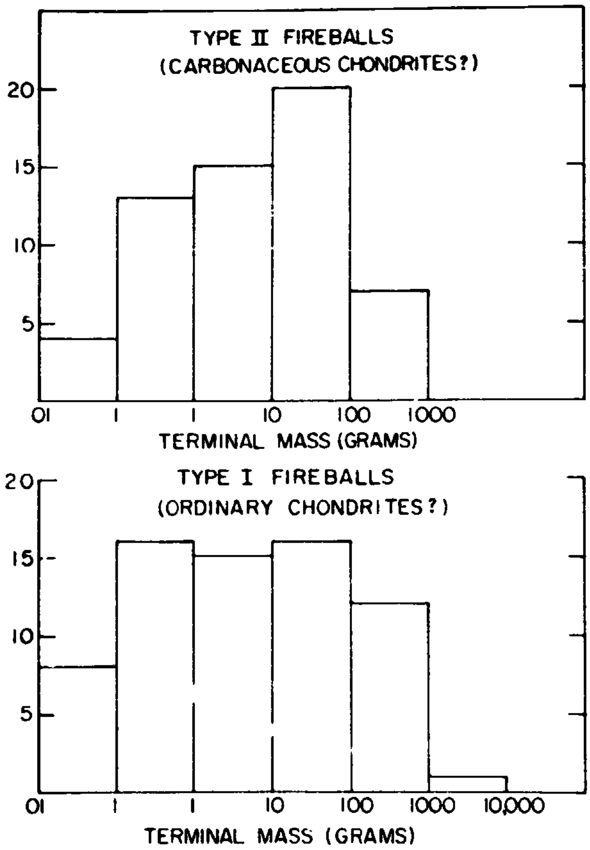

Fig. 2. Observed distribution of Prairie Network fireball terminal masses (Ceplecha and McCrosky, 1976). It is seen that significant terminal masses are found for both Type I and Type II fireballs. Most fireballs belong to these classes.

However, there also seem to be Type I and Type II bodies in *prima facie* cometary orbits, *e.g.*, with aphelia beyond Jupiter or in retrograde motion. Many of these are of high atmospheric entry velocity, >25 km/sec, and scaling to the velocities of the Type I bodies actually recovered as meteorites may have caused them to be erroneously assigned to Type I. But this is not always the case. Six (∼3%) of the Prairie Network fireballs (McCrosky *et al.*, 1977) are low velocity (<20 km/sec) Type I bodies with aphelia (Q) beyond Jupiter (see Table 4). These have low terminal masses consistent with their small initial masses. It is very unlikely that this is asteroidal material which impacted the Earth while in the process of being ejected from the solar system, as their number is a factor of ∼100 larger than the number calculated from studies of the orbital evolution of such material. It is certainly possible that these bodies are similar to recovered meteorites, and if so it is only a matter of time before a sufficiently large one falls and is recovered by a fireball network, provided these networks remain operative. Most probably these bodies are of chondritic composition, but they could be either ordinary or carbonaceous chondrites, as many carbonaceous chondrites are essentially as strong as ordinary chondrites, and would be expected to be observed as Type I fireballs.

Table 4. "Strong" Jupiter-Crossing Fireballs with Low Entry Velocity

Number	a (AU)	e	i	Q (AU)	V_{ENTRY} (km/sec)	$M_{INITIAL}$ (g)	M_T (g)	M_T^* (g)	Type
PN39057	4.2	0.76	0.1	7.3	14.7	1400	40	80	I
PN39820B	3.1	0.69	11	5.3	16.7	1100	19	8	I
PN39972	5.5	0.84	3	10.4	18.1	170	1	0.7	I
PN42357C	3.0	0.67	12	5.0	16.0	360	7	20	I
PN42312	3.0	0.69	14	5.1	17.5	430	2	6	I
PN41282	4.5	0.80	2	8.1	17.5	1900	1	20	II

$M_{INITIAL}$ is the initial photometric mass given by Ceplecha and McCrosky (1976).

M_T is the terminal mass calculated by the formal procedure of Ceplecha and McCrosky (1976). M_T^* is the estimated photometric mass near the end point at ∼8 km/sec.

If it can be shown that identifiable meteorites are associated with these more unusual orbits of cometary affinity, it will be plausible to associate meteorites of the same class in more ordinary orbits with extinct comets.

Apollo-Amor Objects

The fact that Apollo objects are in Earth-crossing orbits and are exposed to asteroidal collisions near aphelion implies that at least some Earth-impacting meteoroids must be derived from these bodies. Although Amor objects are not Earth-crossing at present, it has been shown (Wetherill, 1978) that evolution of Apollos into Amors and vice-versa is so rapid that many Amors must be former or future Apollos. With regard to their role as meteorite sources, the only questions are the quantitative one of yield, and that of their mechanical strength. Calculations of the yield show that this could be large enough to supply the entire flux of chondritic meteorites (∼10^8 g/yr), and is at least high enough to supply ∼1% of this material. No definite information regarding their strength is available.

If some fireballs could be associated with known Apollo objects, such information could be obtained from the end heights of these meteoroids. It is not obvious that such identification will be possible, as the exposure ages of stone meteorites are comparable to the time scale for major orbital evolution of Apollo objects. However, in the case of meteorites with very short exposure ages, this could prove possible (Levin *et al.*, 1976).

One problem with identifying the Apollo-Amor objects with ordinary chondrites is that the radiants of chondrites (Astopovich, 1939; Simonenko, 1975) and time of fall (Wetherill, 1968, 1969) are at least at first sight not in agreement with dynamical calculations of the expected distribution of these quantities. This question needs to be examined in the light of more recent work on the aerodynamics of the entry of fireballs into the atmosphere (ReVelle, 1976) and the orbital evolution of Apollo-Amors (Wetherill, 1978).

As discussed previously, Apollo-Amors are not permanent residents of the inner solar system, but are derived from an asteroidal or cometary source, or more likely, both. Thus they can be thought of as big meteoroids which can fragment into small meteoroids, or impact the Earth before fragmentation, forming craters 1-100 km in diameter. Some of these bodies are probably the extinct comets discussed earlier, whereas others can be derived from the inner asteroid belt (Levin *et al.*, 1976; Wetherill, 1976, 1978). The resulting orbits are similar in either case (Wetherill, 1978). Dynamical considerations suggest that the cometary component should predominate. Interpretation of physical observations leads to an ambiguity. All but one of the Apollos for which there are relevant data appear to be related to either ordinary chondritic material or to S asteroids, rather than to carbonaceous material. On cosmochemical grounds, most workers would interpret this to indicate an asteroidal origin. However, this argument could be turned around to imply a cometary origin, as a consequence of spectrophotometric work showing that ordinary chondritic material is rare or absent in the asteroid belt.

All three types of source bodies discussed will lead to the same general distribution of meteorite and meteoroid orbits. These will predominantly be orbits of low inclination, with perihelia near Earth's orbits, and aphelia in the asteroid belt. Full exploitation of more subtle differences in the distributions is likely to require more detailed observational data and improved theoretical techniques. However, as discussed below, some tentative conclusions are now possible and suggestions for advancing our theoretical understanding can be made.

SUMMARY AND SUGGESTED FUTURE WORK

The evidence is very strong that most differentiated meteorites are derived from the asteroid belt, either directly or through the intermediary of Apollo-Amor objects. Spectrophotometric observations show there is opaque material with low albedo in the asteroid belt. It is likely that this is carbonaceous. Some of these asteroids are adjacent to resonances which can gently accelerate their low velocity collision spectra into Earth-crossing. Except for the unlikely possibility that this material is too weak to survive atmospheric passage (Type III fireballs), there should also be carbonaceous meteorites of asteroidal origin.

It is also quite possible that some of our meteorites are cometary, probably derived from extinct comets, most of which will be in orbits such that they would be identified as Apollo-Amor objects. If so, these are likely to be undifferentiated meteorites. They could be carbonaceous chondrites, ordinary chondrites, or both. It seems unlikely that ordinary chondrites are of both asteroidal and cometary origin. However, carbonaceous meteorites are so close to average nonvolatile solar system composition that their composition does not argue for a unique source region. Some classes of carbonaceous meteorites could be asteroidal, others cometary.

One might think that the abundance of observational, theoretical and experimental evidence relevant to the problem of identification of meteorite sources should permit more clear-cut identifications to be made than seems to be the case. The reason is that the evidence does not lead to an internally consistent solution. Thus, by use of only a portion of the available evidence, it is apparently possible to come to more firm conclusions than when all the evidence is considered.

It is likely that an entirely new source of evidence, *e.g.*, returned samples from asteroids and comets, would really clear up the question. However, at the present stage, it would appear useful to understand which line of evidence is leading us astray. This suggests several lines of investigation.

1. Perhaps the most straightforward problem would be to resolve the question of whether or not the distribution of chondrite radiants and time of falls is or is not compatible with derivation of most of these bodies from Apollo-Amor objects. This will require selection of a plausible range of fragment size distributions making use of available or new hypervelocity impact data. This could then be combined with bias-corrected Apollo-Amor statistics (smoothed by theoretical steady-state considerations) and an improved physical theory for meteorite entry, perhaps along the lines of ReVelle (1976) and Padavet (1977). Comparison of the theoretical radiant and time of fall distribution with that observed should then permit us to know whether or not the discrepancy is as serious as appears at first glance.

2. Spectrophotometric measurements on asteroids has led to the conclusion that ordinary chondrites, especially L and LL chondrites, are rare or absent in the main asteroid belt. On the other hand, there are large asteroids adjacent to the 5:2 Kirkwood gap which probably could supply meteorites with the required radiant and time of fall distributions of chondrites. Could these be ordinary chondritic bodies, the spectral signature of which has been obscured by surface alteration processes? Plausible arguments against this possibility have been advanced, but do not seem to be sufficiently definitive to settle the issue. Further laboratory simulation coupled with theoretical studies of the basic physical processes involved may be expected to be of considerable value. These studies should also shed additional light on the origin of other features, such as the absorption feature at ∿.65 μm seen in many S asteroids, but which is absent in noncarbonaceous meteorites. Several explanations of this feature have been given, but it is not clear that any of them are correct. When understood, this feature could be important in relating the mineralogical composition of meteorites to that of asteroids.

3. On a sufficiently short time scale, *i.e.*, 10^2-10^4 years, the orbital evolution of planet-crossing bodies is deterministic and can be handled by classical methods of celestial mechanics. However, on longer time scales multiple close planetary encounters occur and minor differences in initial orbits result in grossly different final orbits. Under these circumstances the system is best modeled statistically. Although, like a roulette wheel, it is still in principle deterministic, the information required to make deterministic predictions is not available. Nevertheless, in both cases, valid inferences of a probabilistic nature can be made. Discussion of the long-range orbital evolution of planet-crossing bodies has been entirely dependent on these stochastic methods (Öpik, 1951, 1977; Arnold, 1965; Wetherill, 1968, 1977). However, there are a number of assumptions and approximations made in these stochastic methods which have never been critically

examined using the full range of classical or conventional celestial mechanical understanding which is available. It would be trivial to show that the stochastic methods are not rigorous and trite to say "they should be used with great caution." What is needed is a constructively motivated critical study of these techniques, directed toward placing them on a better theoretical foundation. This could allow us to have more confidence in interpreting second-order differences between observed and theoretical orbit distributions and to more quantitative estimates of expected yields from various sources.

4. A principal basis for the inference that there is meteoritic material of cometary origin is obtained from photographic fireball networks, particularly the Prairie Network (McCrosky *et al.*, 1977). However, the efforts of these networks have primarily been directed toward meteorite recovery, and are strongly biased against the most clear-cut occurrences of cometary origin--the shower meteoroids. Meteoroids identified as belonging to the major showers were not reduced in the Prairie Network investigations, and Canadian Network data is not reduced at all unless a meteorite fall is suspected. There are no continuing fireball studies in the U.S. at present. In fact, all of meteor science in the U.S. is in a state of rapid decline, following withdrawal of both the NASA Ames Research Center and the Smithsonian Astrophysical Observatory from this field. The inferences tentatively made previously strongly suggest that serious treatment of fireball data may force revision of our present concepts of the physical nature of comets, but this cannot happen unless some people work in this field.

5. Many of the arguments used to identify meteorites with their sources are based on regolithic analogs. However, there is very little understanding of how regolithic properties may be expected to vary as a function of heliocentric distance or of mass and composition on the body on which they occur. A start in this direction has been made (Housen *et al.*, 1977; Chapman, 1978). Until we understand much more quantitatively just what an asteroidal or cometary regolith should look like, including charged particle tracks, microcraters, agglutinates, etc., we do not really know if meteoritic evidence favors or disfavors particular regolithic identifications.

6. There is at present no theory adequate to explain even qualitatively the origin of the principal features of the asteroid belt, *e.g.*, its small mass content, relative velocity distribution, Kirkwood gaps and mixed chemical composition. Development of a theory of this kind will require a much more quantitative understanding of the origin of stars and planetary systems in general, and the Sun and planets of our solar system in particular. There has been renewed interest in these problems during the last few years, but the goal is still distant.

One can be hopeful that investigations along the lines suggested above would help considerably in constructing an internally consistent framework in which to view the problem of identification of meteorites with their sources.

This short list of suggestions for future work is in no sense intended to be complete. For example, it is obvious that the full set of chemical, petrological, and isotopic laboratory work on meteorites is essential to a correct understanding of the relationship of meteorites to their sources. Much more needs to be done. It is unlikely, however, that such investigations would lead to the qualitatively distinctive revelations which have followed actual spacecraft missions to the Moon and planets. "Ground truth" and sample return may be expected to be the ultimate answer to the identification of meteorites and their source, and to the realization of the geological context in which these small bits of primordial material should be viewed.

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DISCUSSION

ARNOLD: I tend to trust very much the argument that we don't get meteorites from the Moon because of the 2.3 km/sec required ejection velocity.

WETHERILL: I believe that argument, too. It is difficult to quantify because it requires quantitative knowledge of the impacts of large objects on the Moon. It could be that there haven't been any large impacts on the Moon in the last few million years and therefore this mechanism would not be expected to contribute much to the meteorites in our collections. A skeptic could get around this argument in this way. In our thinking on this problem in the last several years we have looked for more gentle methods for transferring material from the asteroid belt to Earth-crossing regions rather than direct impact and high velocity transfer.

CHAPMAN: What would be the yield of chondrites from Earth-approaching objects if you wanted to assume they were all ordinary chondrites?

WETHERILL: About 10^8 g/yr, but this number is uncertain by at least an order of magnitude. There are more serious problems with an Apollo meteorite source. One is that if you wish to believe that Apollos are derived from the asteroid belt, it is necessary to stretch the estimates of their production rates by a factor of ∿10, possibly more.

ARNOLD: Does that problem also extend to the distribution of eccentricities?

WETHERILL: I don't really think so. In your work you had very small semimajor axes and relatively low eccentricities. The ν_6 resonance changes that result a lot. There are slight differences between the orbits of Apollos and orbits derived from the different regions of the asteroid belt or those derived from orbits like Comet Encke. But they are not nearly as extreme as they used to be.