PART V
ORBITAL EVOLUTION AND FRAGMENTATION OF ASTEROIDS

1

THE EVOLUTION OF ASTEROIDS AS METEORITE PARENT-BODIES

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The hypothesis that the asteroid belt is the source region for nearly all meteorite remains viable and there is no compelling reason to ascribe any meteorites to cometary origin. On the other hand, uncertainties about the true composition of the larger S type asteroids and difficulties in finding plausible main-belt source-bodies for the ordinary chondrites leave room open for further speculation on this question. The scenario for the evolution of asteroids, based on collisional models of two distinct populations of different physical properties, is being criticized and refined. It remains uncertain whether this approach will ultimately prove to be the correct interpretation of the collisional evolution of asteroids.

INTRODUCTION

The growth in observational data on asteroids during the past six years has been almost explosive. Inevitably, the synthesis and understanding of these data has lagged behind. In a recent paper (Chapman 1976), I established the observational groundwork that links asteroids with meteorites and portrayed a preliminary scenario for the collisional and geochemical evolution of the asteroids. In the short time since the publication of that paper, the data base has expanded and the first bias-corrected statistical analyses since the Chapman (*et al.* 1975) study have been carried out by Zellner and Bowell (1977). It is now evident that at least some modifications in the proposed scenario are necessary, although too brief a time has elapsed for me to fashion a satisfying synthesis.

In the spirit of this interdisciplinary colloquium, I will describe my recent fragmentary ideas about how the new data may be interpreted. I will address some fundamental questions, relevant to the theme of this meeting, concerning the links between asteroids, meteorites, and comets as viewed from the perspective of asteroid astronomy. The background for most of my discussion, including a lengthy bibliography, is given by Chapman (1976).

I wish to emphasize from the outset my flexibility concerning the model I propose. While many elements of the model seem consistent with the major facts of meteoritics, orbital dynamics, and collisional physics, the question of the uniqueness of my perspective remains open. Now that the raw data on statistically large populations of asteroids are appearing in the literature and have

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been assembled in the computer-readable TRIAD data file*, other researchers will have the opportunity to fashion their own syntheses of asteroid data with cosmochemistry and with models for the early evolution of the solar system. We have already seen the beginning of such attempts in papers at this colloquium (*e.g.*, Wasson 1977). Through such continuing synthesis, asteroid science will soon mature.

ARE THE METEORITES FRAGMENTS OF ASTEROIDS?

At least some meteorites must be fragments of the Apollo asteroids. Almost as certainly, at least a few of the others must be from comets and main-belt asteroids. The real question concerns the relative proportions. And in view of the fact that Apollo objects are in relatively short-lived orbits, they too must be fed into Earth-crossing orbits from some source region -- probably the main asteroid belt or the cometary population. Spectral reflectance data suggest that most Apollo objects have compositions akin to the most common meteorite types. Thus the question of the place of origin of meteorites is related to the question about the origin of Apollo asteroids. Wetherill (1976) addresses in detail the question of the relationship between meteorites and Apollo asteroids.

Previously I have argued that the asteroid main belt must be the chief source region for these objects. Briefly, the argument is this: interpretation of asteroid spectral reflectances have shown that the same minerals, and the same mineral assemblages, are present on asteroids as in various meteorites. To be sure, there are differences in the percentages of different asteroid types compared with meteorite types; some meteorite types have yet to be identified in the main belt and others are very rare. Yet our developing understanding of the collisional and dynamical behavior of asteroids, including the role of resonances (see Wetherill 1977), renders the different distributions plausible. Only a relatively small percentage of asteroids is sufficiently near resonances to make them high-yield source bodies. Moreover the present population of stony meteorites, in particular, depends on what major collisions involving stony parent-bodies have occurred in the last 10^7 years. When these facts are considered together with known biases in terrestrial meteorite distributions (*e.g.*, differential survivability during and following passage through the Earth's atmosphere), it seems very plausible that the asteroid and meteorite distributions could be reconciled. A detailed, quantitative model has yet to be developed, however, and our understanding of the importance of various potential source populations (*e.g.*, Mars-crossers and asteroids near the 5:2 Jupiter resonance) is still developing (Wetherill 1977; Scholl and Fröschle 1977).

None of these arguments rules out comets as a major source of Apollo asteroids and meteorites. It has merely seemed that there is little reason to require any major contribution from the comets, and the older cosmochemical objections about comets as meteorite parent-bodies still pertain. Most condensation models place the ordinary chondrites closer to the sun than the presumed outer-solar system formation region of comets. And it is singularly difficult to suppose substantial geochemical differentiation has occurred in comets, necessary for the production of achondrites and metal-rich meteorites. The most plausible cometary meteorites are carbonaceous chondrites, but their cometary origin is hardly required in view of the predominance of C-type asteroids in the main belt.

At this point, without repudiating the above arguments, I wish to sketch some weak points. Let me begin with the compositional interpretation of aster-

**TRIAD = Tucson Revised Index of Asteroid Data. This computer file is resident on a University of Arizona computer and is maintained up-to-date by a consortium of asteroid observers at several institutions. Address inquiries concerning the availability of the data-file to Dr. Ben Zellner, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA.*

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oid spectra. Many asteroids (called the *C* type) have spectra containing some silicates, but dominated by an opaque, black component, just like the carbonaceous chondrites. Others, called *S* type, have spectra dominated by pyroxenes and olivines, plus a reddish component which is probably metallic iron; these seem to be very like the stony-iron meteorites. A few asteroids have been found that apparently have surface mineral assemblages like basaltic achondrites (4 Vesta: McCord *et al.* 1970), enstatite achondrites (44 Nysa and a few others: Zellner 1975), and several additional types. Asteroids of ordinary chondritic composition seem to be very rare or absent in the main belt.

But the art of interpreting asteroid spectral reflectances in terms of composition is not wholly secure. While we can be quite certain of our identification of certain silicates from some of the higher quality astronomical spectra, the identification of certain other materials (*e.g.*, enstatite, carbonaceous material, and metallic iron) from the spectra of some asteroids is subject to serious qualifications. For instance, several scientists have expressed reservations about the interpretation of McCord and Gaffey (1974) that the metallic iron is a major component (*e.g.*, order 50%) in the main-belt S-type asteroids. Zellner has suggested in some of his recent publications that the S-type objects may in fact be similar to, or identical with, the H-type ordinary chondritic meteorites. Others have worried that space weathering and/or regolith formation on moderate-to-large asteroids might modify spectral characteristics of mineral assemblages from those measured in the laboratory. I will not repeat the earlier answers to these doubts (cf. Chapman and Salisbury 1973; Pieters *et al.* 1976). But even taking account of new evidence adduced from infrared photometry of asteroids by Veeder *et al.* (1977) and Matson *et al.* (1977) interpreted as supporting the metallic iron hypothesis, I think it prudent to be somewhat cautious about the compositional interpretation of S-type objects.

If the S-objects really are of stony-iron composition, and not ordinary chondritic, a distinct problem is developing in understanding how the chondritic meteorites (and Apollo and Amor asteroids) can be coming from the main belt. The one case of a main belt asteroid of ordinary chondritic composition that seemed to be secure, namely 349 Dembowska (McCord and Chapman 1975), is now in doubt. Gaffey (1976) now doubts evidence for the presence of pyroxene in Dembowska's spectrum and suspects it may be more nearly similar to the chassignites (meteorites or predominant olivine) than the ordinary chondrites. More seriously, the infrared photometry of Veeder *et al.* (1977) suggests a higher-than-chondritic metal content for Dembowska. Thus, it may be that there are no candidate source bodies for the chondritic meteorites in the main belt. As the observational programs continue, the sampling of moderate sized asteroids becomes more and more complete and the difficulty in accounting for the appreciable population of chondritic objects in Earth-approaching orbits becomes more serious.

There are other meteorite types (especially including some achondritic types) for which a main belt source-object has not yet been found. Since these meteorite types are much rarer than ordinary chondrites, and as yet have no identified large Earth-approaching analog, the ordinary chondrites present a more serious potential incompatibility with the hypotheses that meteorites chiefly originate in the main belt.

To summarize, the hypothesis that the asteroid belt is the source region for nearly all meteorites remains a viable one and there is no compelling reason to ascribe any meteorites to cometary origin. On the other hand, uncertainties about the true composition of the larger S-type asteroids and difficulties in finding plausible main-belt source-bodies for the ordinary chondrites leave room open for further speculation on this question.

If the hypothesis of asteroidal origin is correct, there are several important conclusions for meteoritics: (1) The meteorites originated in the 2 to 4 A.U. zone from the sun. Since C-type asteroids predominate in all but the innermost parts of the main belt, there was a relatively steep temperature gradient in the solar nebula. (2) The scatter of asteroid types over a few tenths of an A.U., rather than a perfect correlation between composition and semi-major axis, suggests that dynamical and/or collisional mixing processes stirred up early planetesimals over several tenths of an A.U. (cf. Zellner, Andersson, and Gradie 1977). (3) The presence of at least half a dozen different oxygen-isotope groupings (Clayton, Onuma, and Mayeda 1976) among the known meteorites, which are here hypothesized to originate in the 2 to 4 A.U. zone, implies a surprisingly small amount of nebular mixing in a rather small portion of the early solar system. Alternatively, some materials formed elsewhere in the solar system may now reside in the asteroidal zone. (4) Some asteroids retain a primitive character while others were subject to a rather high degree of geochemical differentiation, which raises questions about the process that heated some small bodies, but not others, in this zone.

COLLISIONAL EVOLUTION OF THE ASTEROIDS

In my earlier paper (Chapman 1976), I outlined a scenario for the evolution of the asteroids as meteorite parent-bodies based to a large degree on collisional models developed by myself and my colleague Don David (Chapman 1974; Chapman and Davis 1975). These studies, in turn, were predicated on bias-corrected statistics of asteroid spectrophotometric data given by Chapman *et al.* (1975) from an analysis of 100 asteroids.

Zellner and Bowell (1977) have prepared new biased-corrected statistics from a sample more than three times larger than the earlier sample. The new distributions of asteroids of several compositional types with respect to semi-major axis and with respect to diameter differ in several important respects from the previously derived distributions. These differences remove some of the major underpinnings of the earlier interpretations. The reader is referred to Chapman (1976) for a concise description of the earlier model; here I describe the implications of the new distributions for the earlier assumptions and conclusions.

One major assumption is that the large main -belt S-type objects are the stony-iron cores of geochemically differentiated objects whose rocky mantles and crusts have been largely stripped by numerous inter-asteroidal collisions. While that hypothesis remains a viable one, in my opinion, and no compelling arguments have been raised against it, two of the strongest arguments for the hypothesis are weakened by Zellner and Bowell's analysis. First, I had argued that the size-frequency distribution of S-type objects compared with C-type objects implied that S-type objects were *not* highly collisionally evolved while C-type objects were; this could be explained for the two intermingling groups of objects only if S-type objects were much stronger and resistant to fragmentation than C-type objects (*i.e.*, S-type objects are mainly metallic, while C-type objects are of weak rock). As discussed below, the new diameter-frequency distributions for S- and C-type objects are more nearly the same; while the shape of the distribution remains unchanged and would still seem to imply high strength for S-type bodies, an explanation must now be advanced as to why the C-type distribution shows many of the same features. Some progress has been made in developing models that account for the new distributions, but the uniqueness of the earlier interpretation has certainly suffered.

A second argument for major differences in strength between C- and S-type objects rested on the apparent greater degree of avoidance of Kirkwood gaps by C objects compared with S objects (cf. Table 4 in Chapman 1976). While some evidence for this effect still remains for the larger asteroids (Morrison 1977), Zellner and Bowell have now demonstrated that the effect shown in my earlier Table 4 is due chiefly to a heretofore unrecognized tendency of larger asteroids (of whatever composition) to avoid Kirkwood gaps more than smaller ones do combined with the fact that my sample was not bias-corrected. Although my original

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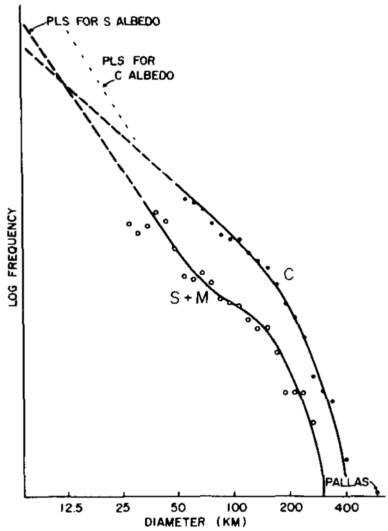

Figure 1. Log-log plot of asteroid frequencies versus diameter. C-type asteroids (solid dots) and S plus M asteroids (open circles) are reproduced from the bias-corrected data of Zellner and Bowell (1977). The Palomar-Leiden Survey constraints on the frequency relation of small asteroids, depending upon whether they are of C or S composition, are also indicated. The frequency relations shown in thick solid and dashed lines are adopted as a working model, but are not the only possible fits to the data. See Zellner and Bowell (1977) for plots giving numerical values for the ordinate.

observation of correlations between asteroid composition and proximity to Kirkwood gaps must now be viewed in a different light, there remain indications in the data of both Morrison and of Zellner and Bowell that there are some compositional correlations. Since most dynamicists now believe that the existence of Kirkwood gaps must be due in part to collisions, although a satisfactory model has not yet been developed, the Kirkwood gaps may yet provide insight to the collisional behavior and relative strengths of asteroids.

The new bias-corrected diameter-frequency data are shown on a log-log plot in Fig. 1, separately for C objects and for S & M objects (filled and open points, respectively). Zellner and Bowell (1977; cf. their Fig. 4) correctly note that the data for both groups of asteroids can be fitted adequately by the *same* frequency relation (two straight lines with a break near 160 km diameter), except that the C types are roughly 3.5 times as numerous at all sizes. Alternative fits to the same data are drawn in Fig. 1. An additional constraint on the true frequency relation of smaller asteroids is given by the Palomar-Leiden Survey (PLS) data. Depending upon whether these objects are predominantly S- or C-types, either the S population or the C population or both must follow the steeper-sloped curve at smaller sizes; that is, a linear extrapolation to smaller sizes of the frequency relations given by Zellner and Bowell for the 25 to 160 km diameter asteroids will not satisfy the PLS data.

As a working hypothesis, I will assume that the true size distributions for the two kinds of asteroids are as given by the solid and thicker-dashed lines in Fig. 1; that is, I will assume that most smaller asteroids are of the S type. Zellner (private communication) finds some further observational support for this assumption; see also discussion by Harris (1977). The S-type frequency relation so depicted may be readily interpreted as an incompletely fragmented population of relatively strong objects. An excess of unfragmented stony-iron cores (in the terminology of Chapman 1974) may be discerned at larger sizes, compared with the straight-line power-law distribution of supposed S-type fragments at smaller diameters.

The problem now is interpreting the shape of the C distribution. The C population had previously been interpreted as a highly collisionally evolved population when it seemed to follow a linear power law throughout the entire observable diameter range, but now it shows a "hump" or inflection near 150 km diameter similar to the S distribution. The slope of the C distribution at diameters less than about 150 km diameter (~ -2.3 for an incremental frequency distribution) is much too shallow for steady-state collisional fragmentation, which should be in the range of -3 to -3.5 according to a host of theoretical and experimental investigations by numerous researchers (*e.g.*, Dohnanyi 1969). But elementary particle-in-a-box collision frequency calculations performed by Chapman and Davis (1975) yield the inescapable conclusion that small C objects must be collisional fragments. There are simply too many C objects moving around the confined volume of the asteroid belt with a relative velocity of roughly 5 km sec^{-1} to avoid numerous catastrophic collisions over solar system history, given anv plausible physical strength.

At the time of the Lyon Colloquium, shortly after Zellner and Bowell (1977) produced their new distributions, I speculated on several possible explanations for the seeming paradox that a population of asteroids known to be collisionally evolved should exhibit such a shallow-sloped frequency relation. One speculation, although unsupported by any experimental or theoretical treatments of which I am aware, was that C objects were so weak that the physical process of collisional fragmentation yielded very few small fragments, resulting in a shallow-sloped frequency relation.

A more satisfying interpretation of the size distributions has been developed subsequent to the Lyon Colloquium by Davis and Chapman (1977). At the outset, it should be pointed out that an attempt was made to retain some of the major assumptions of the earlier interpretation, including the supposition that S objects are stronger than C objects. It remains uncertain whether this approach will ultimately prove to be a unique and correct interpretation of the collisional evolution of the asteroids (see Fig. 2).

Davis and Chapman have augmented their earlier (1975) model in two chief ways. First, the computerized model considers the simultaneous collisional interactions of two distinct populations of asteroids of different physical properites (*e.g.*, a population of strong S objects colliding with both itself and with a population of self-interacting, weak C objects). Secondly a physically more realistic approach has been developed for determining the size of the largest fragment in a catastrophic collision.

The new models demonstrate that even a collisionally evolved population of weak C objects must exhibit a size distribution like that observed, which is not linear on a log-log diameter frequency plot. Gravitational self-cohesion protects a large C object from being dispersed into fragments by the numerous collisions which are more than sufficiently energetic to break the cohesive bonds due to material strength. Thus a weak object evolves into a collection of fragments held together solely by gravity. Eventually the object suffers a sufficiently energetic collision to overcome gravity, and the body is dispersed as a collection of *small* fragments. Very much smaller C objects have no appreciable gravity so they are dispersed by the first collision of sufficient energy to overcome the material strength of the body. In most of the latter cases, the collision will involve a body having only marginally sufficient energy to shatter the body; thus the largest fragments created may be a reasonable fraction of the size of the original small body. Such behavior will provide for the colli-

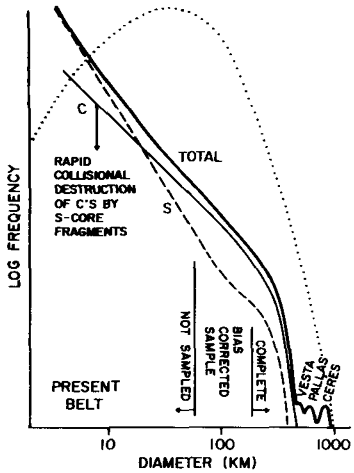

Figure 2. A possible scenario for the collisional evolution of asteroids, depicted on a log-log diameter-frequency plot. Some very large original distribution of carbonaceous asteroids is indicated schematically by the dotted line. Some portion of these asteroids melted and formed cores. Although these cores cannot be as strong as iron metal, they are sufficiently strong that most have failed to collisionally fragment, consisting of the larger S-type asteroids. Those which have fragmented contribute to the steeply-sloped tail of small S-type asteroids. The C-type asteroids, through rapid self-fragmentation, have been reduced greatly in numbers over the aeons. Today collisions between the S-cores and C-type asteroids substantially deplete the latter in addition to self-fragmentation of C's. Gravitational cohesion of highly-fractured large C objects results in the excess of C's near 200 km diameter. Vesta, Pallas, and Ceres are anomalous members of the asteroid population.

sional creation of 10 km fragments (from breakup of both 30 km asteroids and 300 km asteroids), but will rarely yield 50 to 100 km fragments, thus yielding the observed relative dearth of 50 to 100 km asteroids. (The similarity in shape of the S-type and C-type distributions is regarded as a coincidence in this model, if S types have the strength of metallic iron, because such strength dominates gravity even for the largest S asteroid).

Davis and Chapman also report preliminary conclusions from their two-component studies. It appears difficult to maintain the observed population of C asteroids against depletion by S types, if the latter have metallic strengths. The model generates frequency relations that are similar to the observed C and S & M populations only if the S objects are less than about two orders of magnitude stronger than the C objects. Chapman and Davis' (1975) arguments that the asteroid belt may well be a remnant of a much larger population of proto-asteroids is unchanged by the new studies, but their estimate that the belt was ~300 times as populous as now at one early epoch depended on the assumption -- now uncertain -- that the main-belt S asteroids are strong remnant cores of differentiated asteroids.

DISCUSSION

It is apparent from the previous sections that the interpretation of the collisional evolution of the asteroids is still undergoing revision as a result of the astronomical data acquired about the asteroids during the past two years.

This is as it should be. Prior to eight years ago, very little at all was known about asteroids that might link them to the meteorites. The links began to be established following McCord *et al.*'s (1970) discussion of Vesta. The systematic review by Chapman *et al.* (1975) of data concerning a statistically significant sample of asteroids paved the way for my first attempt (Chapman 1976) to fashion a sensible scenario for the evolution of asteroids, consistent with both the meteoritical and astronomical evidence. We should not be surprised that the picture must be modified in some substantial ways now that the asteroid data have been augmented by a factor of 3. By the end of 1978, another 200 asteroids may have been added to the TRIAD data file, permitting yet another analysis of asteroid distributions.

Meanwhile, through meetings such as this one, real discussions are developing between the asteroid observers and the meteoriticists who are presumably studying real asteroid fragments. Such interactions raise many important questions concerning the evolution of asteroids as meteorite parent-bodies. Let me list some of the important questions, as I perceive them. I proceed from the specific to the general.

(1) Vesta has a surface composition unique among medium to large asteroids. As recently argued by Consolmagno and Drake (1977), it is logical to conclude that the basaltic achondrites have come from Vesta. But through what physical process are fragments from the surface of Vesta delivered to the Earth?

(2) As shown schematically in Fig. 2, Ceres and Pallas do not seem to belong to either of the major populations of asteroids (C, S, or M); that is, they seem "too large" compared with an extrapolation of the C population to large diameters. Yet the spectral reflectance of Ceres, and to some degree that of Pallas, resemble C-type asteroids. Can it be that these two largest bodies in the asteroid belt are really of primitive composition, or is it possible that they have been melted just like Vesta and that their surfaces are in fact composed of opaque-rich basalts?

(3) What constraints do the Hirayama families place on scenarios for the collisional evolution of asteroids of various compositions? Chapman (1976), who considered the Eunomia family, and Zellner *et al.* (1977), who considered the Nysa-Hertha families, have encountered some difficulties in constructing plausible collisional scenarios that can account for the compositions of the major members of the resulting families. Other families can be reasonably well accounted for in terms of the collisional breakup of a compositionally homogeneous body (Gradie and Zellner 1977). Shortly it should be possible to determine whether the observed compositions of Hirayama families are consistent with our understanding of geochemical mass-balance, asteroid collision probabilities, and fragmentation physics.

(4) How is the physical nature of asteroid interiors and of asteroid surfaces affected by collisional evolution and is there consistency with the brecciated and gas-rich nature of many meteorites? I argued earlier (Chapman 1976) that asteroid regoliths contain too little volume to be a plausible source region for most gas-rich brecciated meteorites and suggested that these characteristics must pertain to asteroid interiors resulting from the early stage of asteroid accretion. The improved collisional models of Davis and Chapman (1977) show, however, that large C-type asteroids should become highly fragmented and brecciated well before they are catastrophically disrupted. It remains to be demonstrated, however, that such a "megaregolith" provides an appropriate place of origin for the gas-rich meteorites.

(5) What was the source of heat that apparently melted some, but not all, of the larger asteroids or asteroid-precursors? Is it consistent with the relatively primitive state of other asteroids in the main belt and is it consistent with meteorite chronologies?

(6) How can numerous oxygen-isotope groups be accommodated on source bodies in the relatively confined volume of the asteroid belt? Through what dynamical

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processes could material from more widely dispersed portions of the early solar system have come to rest in the asteroid belt?

(7) Perhaps the most fundamental problem of all concerns the origin of the present 5 km sec^{-1} relative velocities among asteroids. It is this velocity which is responsible for the collisional evolution that I have discussed above. At some earlier epoch, when the asteroids were accreting, the relative velocity must have been much lower. What initial size distribution then pertained? Can plausible dynamical processes responsible for the augmentation have occurred during a timespan compatible with meteorite chronologies?

The solution to many of these questions may be relatively near at hand. The meteorite data base is very large indeed and important new measurements with a bearing on the chronology and circumstances of parent-body origins and collisions continue to be developed. Meanwhile the asteroid data base, once very small, is becoming very extensive. Provided the hypothesis is valid that most or all meteorites come from the main asteroid belt, the synthesis of meteoritics and asteroid astronomy should be very fruitful indeed.

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DISCUSSION

WHIPPLE: I have proposed the possibility that a cloud of cometary material developed within Jupiter's orbit and persisted for 10^7 to 10^8 yr after the origin of the solar system. This cloud may have made possible the re-assembly of asteroid fragments. Whether it could have contributed carbonaceous material to the surfaces of the asteroid I am uncertain, possibly yes. Also I should like to emphasize that the source of craters on the Moon and Mercury could have been comets as well as asteroids. The crater will not distinguish the source.

CHAPMAN: I agree that comets or comet-like planetesimals may have played an important role in the early solar system history. I call "asteroidal" those objects--at least now largely devolatilized--in the regions presently occupied by asteroids. The distinction seems blurry to me between the larger early asteroid population I have hypothesized and Prof. Whipple's comet cloud inside Jupiter's orbit. I would point out that it is my interpretation not only that C asteroids have carbonaceous material on their surfaces but that they are actually carbonaceous throughout. Although the source(s) of the objects that cratered the terrestrial planets have not been uniquely distinguished, some researchers have argued that there are subtle properties of craters that may in the future prove to be diagnostic.

ANDERS: There exists a weak constraint on the initial mass of the asteroid belt: the total mass of meteoritic material that has fallen on the Moon between 4.5 and 3.7 AE ago. From trace element studies on lunar samples, it appears that the total amount of carbonaceous material that fell on the moon between 4.5 and 3.7 AE ago was no more than 10 - 100 times higher than the entire amount between 3.7 and 0 AE.

GROSSMAN: Is there some reason why the outer part of the asteroid belt could become a dumping ground for burnt out comets?

CHAPMAN: There are two interpretations of your question. If you mean to ask whether or not C-type asteroids in the outer belt are *burnt-out comets one must imagine comets to have diameters of hundreds of km and were dynamically converted into roughly circular orbits. This seems most unlikely.*

Perhaps, instead, you mean that comets might preferentially disintegrate in such a way that their debris preferentially "coats" outer-belt asteroid surfaces. I see no reason to expect such behavior for comets, but perhaps someone else would care to comment. I have already described my doubts that any but the very largest asteroids could accumulate any significant amount of material derived from elsewhere on their surfaces because of the rapid net erosion by impacts.

MILLMAN: I would like to comment on the identification of cometary material. The only particles we deal with at close quarters, that are incontrovertably of cometary origin, are the meteoroids of the meteor streams that have a known, associated comet. From this point we have a series of possibilities by analogy through lower and lower probabilities. I should like to be shown a meteorite with greater than 95% probability of originating in a comet. Yet we have large masses entering the atmosphere that never reach the earth's surface as objects larger than dust. (i.e., *Prairie Network fireballs and the Tunguska event). I* *agree with Chapman that, at the moment, there is no reason to assume that some fractions of the meteorites in our museums must have an origin in a comet.*

ZELLNER: Considerable discussion has been stimulated by the conclusion that type 0 *or ordinary-chondrite objects are quite rare in the main belt. They are fairly common among Mars-crossers, but still a supply of Mars-crossers has to be found.*

Let me emphasize that most of the analysis presented by Chapman, Gaffey, Matson, Morrison, and myself for the main belt refers to diameters above 50 km only. We do have UBV data for about a dozen objects in the 5 - 20 km diameter range. It is difficult to distinguish between types S *and* 0 *in UBV colors alone, but the smaller objects do often look very much like the Mars-crossers.*

Also, I do not believe that H-chondritic compositions can be ruled out for many of the S *asteroids.*

CHAPMAN: The location of the ordinary chondrite parent-bodies in the main asteroid belt becomes increasingly problematical as our surveys fail to reveal many, if any at all. It is uncertain how big these bodies must be in order to supply the meteorites themselves and their larger siblings , the majority of Earth-approaching asteroids that seem to be of ordinary chondritic composition.

Our lower limit of sampling completeness for bodies of such reasonably high albedos is descending toward 50 km diameter. This sample includes a few candidate chondrites, the most promising one being 349 Dembowska, a 145 km-diameter body near 2.9 A.U. (Data reported earlier today by Matson, however, casts some doubt on the identification of Dembowska as an LL chondritic body). If bodies of several dozen km diameters can be the parent-bodies for the L and H chondrites, them many of them could still be awaiting discovery.

I admit to some slight degree of uncertainty about my belief that S-type asteroids cannot in general be of H-type composition. I refer to the thorough discussion of this possibility by Pieters et al. (Icarus *1975) in our paper on Eros, where we conclude that Eros can be interpreted as an H chondrite only because it has properties atypical of S-type asteroids. But the distinctive observational traits of Eros that distinguish it from other S-types are relatively subtle. It is not at all possible, however, to identify S-type asteroids with L or LL-type chondrites.*

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