3

FRAGMENTATION OF ASTEROIDS AND
DELIVERY OF FRAGMENTS TO EARTH

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    Earth-impacting meteoroids are derived from both comets and asteroids, and
some uncertainty still exists regarding with which of these bodies some stone
meteorites should be identified. In contrast, the long cosmic ray exposure
ages of iron meteorites strongly suggest a long-lived asteroidal source capable
of providing ~10^8 g/yr of this material to the earth's surface over at least
much of solar system history. Spectrophotometric data show that differentiated
asteroids are concentrated in the inner portion of the asteroid belt. The
orbital histories of fragments of inner belt asteroids are investigated, con-
sidering the combined effects of close planetary encounters, secular perturba-
tions, and secular resonances. Particular attention is given to the low inclina-
tion (≤$15°$) objects with small semimajor axis (2.1 to 2.6 A.U.), which can make
fairly close approaches to Mars (≤0.1 A.U.). It is found that the annual yield
and dynamical lifetime of collision fragments of these asteroids is in agreement
with the observed impact rate and exposure age of iron meteorites. A smaller
yield of stone meteorites (~10^7 g/yr) is expected, because elimination of these
objects by collision is probable on the long dynamical time scale. Achondrites
could be produced in this way; the yield is probably too low to account for
chondrites. Chondrites could possibly be derived indirectly from these bodies
insofar as these asteroids are also sources of Apollo and Amor objects.

    Understanding the history of the solar system requires the discovery of
the qualitative principles which govern its long-term dynamical evolution.
Thereby one may rise above the severe limitations imposed by mere numerical
extrapolation of present orbits into the past. Furthermore, it is also necessary
that these principles be at least approximately quantified to permit comparison
of theory with observation. Our understanding of these principles began with
the work of Copernicus and Kepler who showed that the heliocentric trajectories
of bodies in the solar system can be approximated as ellipses, the parameters
and orientation of which change only slowly with time. Further developments
include the demonstration by Jacobi of the approximate constancy of the param-
eter in the 3-body problem which bears his name. More recently, Öpik (1951)
emphasized the dominant effect of close encounter in the long-term evolution of
planet-crossing bodies. Even though such close encounters are rare enough to be
neglected on the ~10^4 year time scale imposed by practical limitations of numeri-
cal integration, on the real ~10^9 year time scale of the solar system, rather
than being improbable or *ad hoc*, these encounters are inevitable. Arnold (1964,
1965) extended Öpik's work by development of a stochastic simulation of the

solar system, the evolution of which was determined by close encounters as
described by Öpik. This work has been subsequently further elaborated (Wetherill
and Williams 1968, Wetherill 1968a,b, 1969, 1971, 1975). Of similar importance
has been the development of general theories of the long range planetary per-
turbations, which, subject to specific assumptions, are valid for all time
(Brouwer 1951; Williams 1969).

Discussion of possible sources of meteorites and meteoroids in the solar
system requires development of these principles. Cosmic ray exposure ages show
that the time interval between fragmentation of the source and impact of the
fragment with the earth is typically millions of years and, in the case of iron
meteorites, may be more than 1000 m.y. The general problem has been reviewed
(Wetherill 1974) and the reader may refer to this earlier article for a more com-
plete discussion with references. In this review it was concluded that major
quantities of non-volatile fragments ≥ 1 Kg in mass from both comets and aster-
oids impact the earth. Any of this material which survives passage through the
atmosphere will be a meteorite. Although much conjecture is possible, under-
standing of the details of the internal structure of either comets or asteroids
is too poor to permit any certainty in statements regarding so subtle a property
as the mechanical strength of material in their interior. A difficult task
therefore remains, that of identifying the various classes of meteorites with
the various classes of comets and asteroids.

Derivation of massive meteoroids from comets presents no serious dynamical
problem, as comets are observed to be in earth-crossing orbits, and non-volatile
material ejected from comets or remaining after loss of volatile ices will re-
main for a time in very similar orbits. This is not the case for main belt
asteroids, as velocity changes of ~6 Km/sec are necessary to effect earth-cross-
ing. Any plausible equilibration of this kinetic energy of 2×10^{11} ergs/g will
result in fragmentation, melting, and other shock effects far beyond those
observed in meteorites. Therefore derivation of meteorites from asteroids has
required understanding the mechanisms whereby asteroidal fragments can be gently
transferred into earth-crossing orbits. These mechanisms are necessarily inef-
ficient, as the annual flux of meteorites is only ~10^{-5} of the meteorite-sized
fragmentation debris produced in the asteroid belt per year. Anders (1964) and
Arnold (1964, 1965) discussed the role of gravitation perturbations by Mars of
mars-crossing fragments. Further work on this mechanism is the principal sub-
ject of the present article.

It has also been shown (Zimmerman and Wetherill 1973) that a series of
probable events involving resonant acceleration and libration in the 2:1 Kirk-
wood gap can also gravitationally deflect a significant quantity (~10^8 g/yr) of
asteroidal fragments to earth-crossing, although the quantitative yield from
this source is difficult to calculate with any high degree of certainty. This
mechanism has the property that the resulting orbits first become earth-crossing
with perihelion very near 1 A.U. and aphelion beyond 4 A.U. This type of initial
earth-crossing orbit has previously been shown to be the only kind which will
yield the observed distribution of time of fall and radiant chondritic meteorites
(Wetherill 1968b, 1971), and which will lead to the observed orbital distribution
of Prairie Network fireballs. At this meeting Ceplecha (1976) presented evidence
tentatively associating about 1/3 of these fireballs (type I) with ordinary
chondrites and another 1/3 (type II) with carbonaceous chondrites on the basis
of their ablation and fragmentation in the atmosphere (Ceplecha and McCrosky
1976). Although their orbital distributions overlap considerably, probably
significant differences are found in the distribution of semi-major axes of
these two types of fireballs. The discovery by Scholl and Froeschlé (1976)
that resonant acceleration in the 5:2 Kirkwood gap may be even more important
than that in the 2:1 gap naturally gives rise to the speculation that Ceplecha's
two fireball classes may be related to these two Kirkwood gap sources. However,

much detailed work is required before this possibility should be taken very seriously.

There remain the Apollo and Amor objects, earth-crossing of which must contribute to the terrestrial meteoroid flux. The role of these bodies as terrestrial meteoroid sources has recently been discussed (Wetherill 1976) and was also a principal subject of two papers (Simonenko 1976; Levin 1976) presented at this meeting. In many ways these objects, themselves of uncertain origin are attractive chondrite sources. However, serious problems with the predicted orbital distributions of their fragments remain to be resolved, hopefully not in an *ad hoc* way, before these bodies can be regarded as the principal sources of chondritic meteorites.

In this paper attention is directed to a particular group of meteorites the irons, the long exposure ages of which strongly suggest an asteroidal origin, inasmuch as any other plausible solar system source would impose a shorter ($\leq 10^8$ year) dynamical lifetime on the fragment.

In this discussion the effects of close planetary encounters and the long-term "secular" perturbations will be combined to investigate the orbital evolution of collision fragments derived from asteroidal bodies with semi-major axes in the range 2.1 to 2.6 A.U. This problem has been previously studied by Arnold (1965) who assumed that only planetary encounters were important. The subsequent discovery by Williams (1969) of strong secular resonances in this region showed that neglect of secular perturbations is likely to lead to an unrealistic solar system model and possibly to incorrect conclusions. It will be seen from the following discussion that although significant resemblance between these results and those of Arnold remain, there are important differences as well.
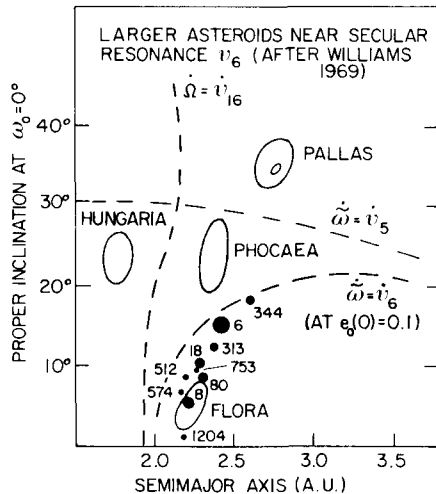

Figure 1. *Inner region of the asteroid belt showing the secular resonances and the asteroids most productive of earth-crossing fragments.*

The portion of the asteroid belt most demanding consideration is the densely population region below the resonant surface $\dot{\tilde{\omega}} = \dot{v}$ (Figure 1), where large asteroids such as 4 Vesta, 6 Hebe, 8 Flora, 18 Melpomene, and 313 Chaldaea are found, as well as the expected accompanying mass spectrum of smaller bodies. Above this resonant surface are located two regions in which high inclination objects are found: the Phocaea and Hungaria regions. The largest

body in the Hungaria region, 434 Hungaria, is only about 8 Km in radius, which severely limits the importance of these bodies as major meteorite sources. Larger bodies are found in the Phocaea region, fragments of which could become Mars-crossers. The high inclination of these bodies and the large ejection veloicty required to place them in the resonant region suggest that these fragments would be too long-lived to represent a major meteorite class. Although these asteroids merit further investigation, attention in this paper will be directed to the region below the resonant surface.

Most of these low inclination bodies are also of sufficiently low eccentricity to preclude close encounters with Mars, and as far as in known are entirely stable on the 4.5×10^9 year time scale of the solar system. A few objects, *e.g.*, 512 Taurinensis are in orbits for which Mars encounters are probable. An important parameter in this regard is "ΔMars" defined by Williams (1971) as the minimum possible distance of approach of the body to the orbit of Mars, assuming the most favorable possible combination of orbital elements of both the body and of Mars. Close encounters are possible only for those objects for which ΔMars is negative. This is the case for some of the objects in this region, *e.g.*, 313 Chaldaea for which ΔMars $= -.039$ A.U. However even though close encounters with Mars are in principle possible for this body, it can be shown that the precisely required combination of secular perturbation phases occur so infrequently that for practical purposes the orbit can be considered almost as stable as, for example, 8 Flora for which ΔMars $= +.024$ A.U.

This stability does not necessarily apply to the orbits of fragments ejected following collisions between these bodies. For some of these asteroids, ejection at velocities of ~300 m/sec can place fragments into orbits for which ΔMars is sufficiently negative (*i.e.* $\leq -.05$ A.U.) to lead to rapid instability. This can arise as a consequence of changes in semi-major axes (a) and eccentricity (e) resulting directly from the collision. More important, proximity to the resonant surface $\dot{\tilde{\omega}} = \dot{\nu}_6$ will cause changes in (a) (and to lesser extent in inclination) to lead to large increases in (e) and hence to negative values of ΔMars.

This effect has been quantitatively evaluated by calculation of the orbits of random ejecta from all known bodies in the region under consideration for which ΔMars $< +.10$ A.U. as given by Williams (private communication 1975), as well as several other bodies particularly close to the resonant surface $\dot{\tilde{\omega}} = \dot{\nu}_6$. It is assumed that ejection is isotropic in the reference frame of the target body and takes place at random positions in the orbit of this body, and at random values of the phases of the forced oscillations of secular perturbation theory (Brouwer and Van Woerkom 1950; Williams 1969). The mass yield from collisions is estimated by combining asteroid collision dynamics (Wetherill 1967) with the results of cratering studies (Gault *et al.* 1963, O'Keefe and Ahrens 1976); these cratering studies are also used to obtain the velocity distribution of the ejected fragments. When available, radii based on measured albedos (Morrison 1974, Morrison and Chapman 1976) were used in calculating yields. Otherwise it was assumed that the objects were "S" type asteroids (Chapman 1976) and the expression:

$$\log r = 3.30 - 0.2 \, g_B \tag{1}$$

was used to calculate r, the radius in kilometers, from the absolute blue magnitude, g_B. When appropriate, this distribution is modified by the effect of the non-zero escape velocity of the target asteroid. The effect of the $\dot{\nu}_6$ resonance is included by use of the expressions

$$e_o \sin\tilde{\omega}_o = e\sin\tilde{\omega} - M_6\sin\nu_6 \tag{2}$$

$$e_o \cos\tilde{\omega}_o = e\cos\tilde{\omega} - M_6\cos\nu_6 \; .$$

In these expressions e and $\tilde{\omega}$ are defined by the orbit of the target aster-
oid and the velocity vector of ejection, ν_6 by the randomly selected phase of
forced oscillation. The forced oscillation amplitude in the vicinity of the
resonance, M_6 is obtained from calculations of Williams (private communication
1976). These equations can then be solved for the proper eccentricity e_0,
which then permits calculation of the maximum eccentricity of the fragment
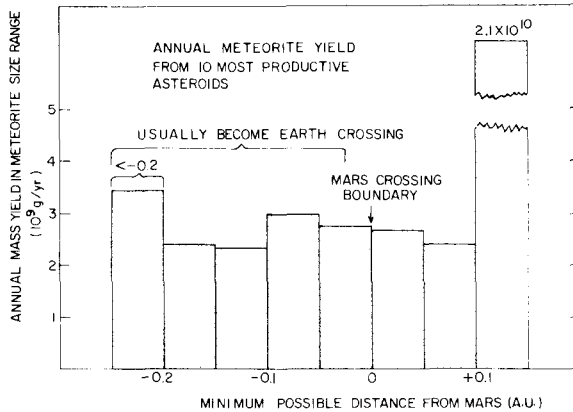$(e_0 + |\Delta M_6|)$ and the new value of ΔMars.

Figure 2. *Calculated annual yield of meteoritic fragments from the asteroids
shown in Figure 1, as a function of the minimum possible encounter
distance from Mars (ΔMars).*

The results of these calculations are shown in Figure 2. It is found that
the yield of fragments with negative ΔMars is dominated by a few bodies (those
marked on Figure 1), and that the total yield of such fragments in the meteorite
size range (100 g to 10^6 g) is ~10^{10} g/yr. The principal uncertainty in this
calculation probably arises from uncertainties in the cratering data employed.
Although no essential difference is found between use of the experimental data
of Gault *et al.* (1963) and the theoretical results of O'Keefe and Ahrens (1976)
this agreement could well be fortuitous. Inclusion of the resonance increases
the yield by a factor of about 20 over that calculated otherwise.

The subsequent evolution of the orbits of these fragments was followed by
use of the stochastic "Monte Carlo" approach previously employed, now modified
to include new calculation of e_0 and M_6 by use of equations (2) following each
planetary encounter. The ease with which Mars can perturb the semi-major axis
of the fragment into the vicinity of the ν_6 resonance and the consequent in-
crease in its maximum eccentricity results in earth-crossing frequently taking
place within 100 million years (Figure 3). Earlier calculations, in which the
effects of the resonance were not included, gave the result that a 500 to 1000
m.y. interval was required for the random-walk reorientation of the orbit into
an earth-crossing configuration.

Nevertheless this rapid achievement of earth-crossing does not decrease
the time scale for earth impacts to the extent that might be expected. Earth-
crossing occurs only at the maxima of the large amplitude forced oscillations in
eccentricity; most of the time the object is only a Mars-crosser. In addition
to the decrease in earth-impact probability resulting from earth-crossing
occurring but a fraction of the time, it also turns out the continual Mars-
crossing frequently permits Mars to perturb the semi-major axis away from the
resonance and at least temporarily terminate earth-crossing. Quasi-
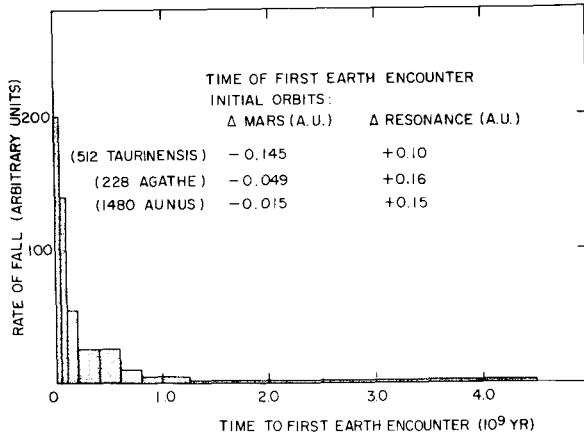permanent earth-crossing and a high probability of earth-impact requires a

Figure 3. Time interval required for the first close encounter with earth for fragments ejected into typical orbits with values of ΔMars in the range indicated in Figure 1 as usually becoming earth-crossing.

"run" of earth-perturbations wherein the sign of the change in semi-major axis is predominantly positive or negative, removing the object from the influence of the resonance and "freezing in" the large (~0.6) eccentricity characteristic of initial earth-crossing orbits. The time required for the occurrence of such runs may be long, ~0.5 x 10^9 years. Calculations of the times for earth impact for objects with initial negative values of ΔMars are given in Figure 4. Although the number of Monte Carlo runs calculated was not sufficient to provide high-quality statistics, the general result is clear: earth impact is most likely to occur between 100 m.y. and 1000 m.y. after the asteroidal collision which produced the fragment.
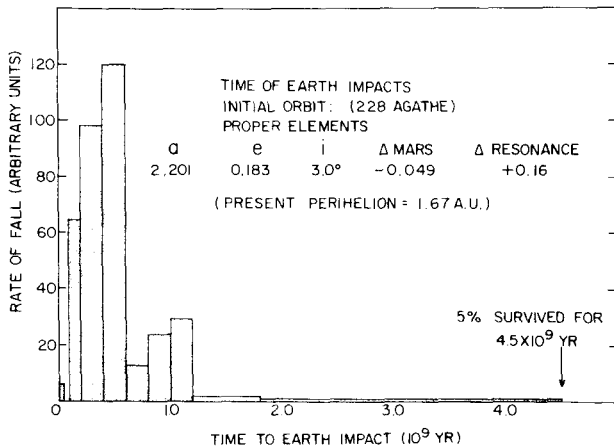

Figure 4. Time intervals required for earth impact for a typical starting orbit.

This time scale is that actually found for iron meteorites, as indicated by their exposure ages (Voshage 1967). However a component with the short (<100 m.y.) exposure ages found for some irons is also compatible with this

288

source, as a consequence of the rapidity with which initial earth-crossing can occur. These same Monte-Carlo calculations give an earth-impact efficienty of 5 to 10 percent. If it is assumed that 10% of the initial fragments are iron objects, this leads to a terrestrial impact rate of $\sim 10^8$ g/yr, in agreement with observation.

Of course, it is not known whether or not the asteroids under consideration contain the necessary quantity of massive metallic iron. Spectrophotometric data suggests that differentiated bodies are predominantly located in this inner region of the asteroid belt. Iron meteorites must come from somewhere, and if the plausible assumption is made that they come from asteroids there doesn't seem to be a better place in the asteroid belt to seek their source.

The long time required for earth impact greatly reduces the earth impact yield expected for the silicate fragments produced in these asteroidal collisions, as a consequence of the vulnerability of the rock fragments to further collisional destruction. A yield of $\sim 10^7$ g/yr of fragments on the $\le 50 \times 10^7$ year time scale corresponding to stone meteorite exposure ages might be obtained. This could represent an important supply of achondrites but is probably inadequate as a source of chondrites, sources of which may be sought elsewhere (*e.g.,* Wetherill 1976, Zimmerman and Wetherill 1973). The distribution of radiants and time of fall expected for these orbits will probably turn out to be quite different from those found for chondritic meteorites (Wetherill 1968b); the smaller quantity of data for differentiated meteorites can be more easily reconciled with a wide range of predictions.

This discussion has been cast in the framework of the problem of identification of meteorite sources. The combined effect of the ν_6 resonance and Mars perturbations has also been considered in the contexts of impact cratering on Mars and of the production rates and orbits of the small Amor and Apollo objects, from which chondrites may be derived (Levin *et al.* 1976, Wetherill 1976). These results will be presented elsewhere at a later time.

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DISCUSSION

BILD: If a group of meteorites originates in the asteroid belt, would all group members have been transferred to earth crossing orbit at once, or would they make the transfer one at a time?

WETHERILL: A group originating from a single collision would be transferred individually, one at a time, into earth-crossing. Some would never achieve earth-crossing before striking Mars or being ejected into interstellar orbits by Jupiter.

GROSSMAN: From your talk, I gather there is no easy way to get ordinary chondrites from the asteroid belt on the required short time-scale and, from other talks, I gather there are not many there anyway.

WETHERILL: If S-asteroids such as 6 Hebe and 8 Flora turn out to contain chondrites, in spite of their present identification as mesosiderites, then there may be a chance to derive ordinary chondrites from this portion of the asteroid belt, but I would have to press a number of parameters to the limit of uncertainty, and also might get into problems with simultaneously maintaining an adequate variety of iron meteorite parents. I think it most likely ordinary chondrites come from Apollo objects, but of course the source of Apollos is still poorly understood. The Kirkwood gap mechanism discussed by Zimmerman and myself could be important, as a meteorite source, but insofar as it is based on the 2:1 commensurability it seems more promising as a source of carbonaceous material if the spectrophotometric identifications are valid.

ANDERS: Do any of these objects have orbits resembling those of the Apollo or Amor asteroids?

WETHERILL: Yes, a large number of them do, but a high percentage evolve into very small orbits, frequently with aphelion near Venus. No such objects are known but they would be harder to discover than Apollos or Amors, which are already difficult.

WASSON: It is important to bear in mind that there are a number of different chondrite groups, but about 90% of the mass flux consists of ordinary chondrites.

WETHERILL: Yes, and the problem is that if we accept the spectrophotometric

meteorite class identifications, the mechanism discussed here does not provide an adequate mass yield of ordinary chondrites.

WASSON: Chondrite cosmic ray ages are all short (≤ 40 Myr), independent of groups. Since it seems reasonable that the parent bodies of these groups are at different solar system locations, it seems unlikely that the cosmic ray ages are of dynamic origin, and more likely that they are determined by erosional or fragmentation processes.

WETHERILL: I think it is open question whether the chondrite exposure ages are primarily controlled by collisions or by dynamics. The observed ages are very similar to the dynamic lifetime for a wide variety of earth-crossing orbits. Hence any mechanism which achieves earth-crossing on a shorter time scale will result in dynamic control. Apollo asteroids and cometary sources, Kirkwood gap resonances, and direct injection into ν_6 or ν_5 resonances have this property. The problem is to plausibly associate an adequate mass of ordinary chondrite parents with these mechanisms. The longer (up to 100 M.Y.) exposure ages of enstatite achondrites also suggest to me that the collisional lifetime of inter-planetary stones is longer than the typical chondrite exposure age, but I would not insist on this.