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Dynamical Relations between Asteroids, Meteorites and Apollo--Amor Objects [and Discussion]

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Dynamical relations between asteroids, meteorites and Apollo–Amor objects

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A Monte-Carlo technique has been used to investigate the orbital evolution of asteroidal collision debris produced interior to 2.6 AU. It is found that there are two regions primarily responsible for production of Earth-crossing meteoritic material and Apollo objects. The region adjacent to the 3:1 jovian commensurability resonance (2.5 AU) is unique in providing material in the required quantity and orbital distribution of the ordinary chondrites. This region should also supply a comparable preatmospheric flux of carbonaceous meteorites. The innermost asteroid belt (2.17–2.25 AU), via the ν_6 secular resonance, provides a flux *ca.* 9% that of the ordinary chondrites, and appears to be the strongest candidate for the basaltic achondrite source region. It is unlikely that a significant number of meteorites originate beyond 2.6 AU. It is speculated that enstatite achondrites are derived from the Hungaria region, interior to the main belt, and that iron and stony-iron meteorites originate from many main-belt sources interior to 2.6 AU.

1. Introduction

About 2500 years ago an unpleasant Greek named Heraclitus irritated his erudite contemporaries in a number of ways (Russell 1945). One of these was by telling them that their search for the eternal was a waste of effort, because in fact everything was changing all the time. This dialogue concerning the fundamental priority of substance against process has continued ever since. Those of us who try to understand the history of the Universe, Solar System, and the Earth are the intellectual descendants of Heraclitus. Although the Solar System and its inhabitants will not pass this way again, we still want to know where we have been.

Those of us who serve on too many NASA advisory committees have spent much time providing stirring prose to support the view that 'primitive bodies', the real comets and asteroids of our Solar System, will provide the clues to understanding its earliest days. Actually, this is true. It will be worthwhile not to always think of meteorites as samples of hypothetical 'parent bodies' in the solar nebula, but rather simply as rocks broken from outcrops on real asteroids. Increasingly, we have become aware of the dramatic difference between samples of rocks from planetary bodies, even those as small as the moon, and those from asteroidal objects. The hallmark of a planetary rock is its complex geochemical history, extending to times late in Solar System history. Even though the 4500 Ma age of the Solar System can be inferred from terrestrial and lunar rocks, and the probably martian SNC meteorites, this event is heavily veiled by subsequent events. In contrast, as expected from calculations of thermal evolution of small bodies, the radiometric date of *ca.* 4500 Ma dominates the chronology of all other meteorites, even when these objects have undergone igneous differentiation (basaltic achondrites) or late shock metamorphism (hypersthene chondrites).

This paper will describe recent work that seeks to identify distinct portions of the asteroid belt as source regions for the most abundant type of stony meteorite (ordinary chondrites) and the majority of differentiated stony meteorites. Many of the Earth-approaching Apollo–Amor objects of 1 km in diameter are members of the same 'collision hierarchy' of asteroidal debris produced in these same regions. For this reason the distinction between meteorites produced in the asteroid belt and those produced as collision fragments of Apollo objects is not a fundamental one. The question of spectrophotometric identification of belt asteroids with their meteoritic and Apollo-asteroid collision fragments is at present unresolved, however.

With significantly more uncertainty, asteroidal source regions of other types of meteorites can be proposed. The identification of at least most meteor showers with periodic comets is well established. It also seems likely that a large number of the Apollo–Amor objects are related to comets rather than to asteroids. It is much less certain whether any survivable meteorites are of cometary origin, but fireball data suggest that this possibility should be considered. Micrometeorites of both cometary and asteroidal origin must have been collected, but their relative proportions are at present unclear.

2. Production of ordinary chondrites in the vicinity of the 3:1 Kirkwood gap

^{39}Ar–^{40}Ar and Rb–Sr ages of ordinary chondrites provide clear evidence for collisional shocks throughout Solar System history (Bogard 1979). This indicates an asteroidal, rather than a cometary, source region. If this is accepted, one can then turn to the question of identifying the specific region in the asteroid belt from which these meteorites are derived. As discussed in detail elsewhere (Wetherill 1985), the distribution of ordinary chondrite orbits, as inferred from fireball data, is strongly peaked toward bodies with perihelia near 1 AU. As a consequence, it is also observed that their geocentric radiants are concentrated toward the antapex of Earth's heliocentric motion, and about twice as many ordinary chondrites fall in the afternoon as compared with the morning. It has been known for some time (Wetherill 1968) that concentration of meteorite perihelia near 1 AU is associated with meteorite-size bodies that first become Earth-crossing while in orbits with $a \sim 2.5$ AU, $e \sim 0.6$ and moderate (not more than 15°) inclination. For small bodies in initial orbits of this kind, vulnerability to collisional destruction while near aphelion in the asteroid belt and/or perturbation to trans-jovian aphelia preclude extensive evolution into smaller orbits prior to Earth impact. Until recently, however, a quantitatively adequate mechanism for providing sufficient bodies with this initial Earth-crossing orbital distribution was lacking.

This deficiency has been removed by the work of Wisdom (1983, 1985) who showed that most asteroidal collision debris with orbital periods near one third of that of Jupiter ($a = 2.48$–2.52 AU) are in 'chaotic' orbits, i.e. their eccentricity increases in a manner resembling random walk up to values of 0.6 or greater. Previous work (Scholl & Froeschlé 1977) suggested that the effects of resonance with Jupiter's motion were more limited, i.e. eccentricities increased only to *ca.* 0.3 and the long-term orbital evolution was quasi-periodic. Wisdom's discovery provides the long-sought answer to the near-absence of asteroids with these periods (3:1 Kirkwood gap, figure 1), as well as providing a source of meteorites with the required initial Earth-crossing orbital distribution.

Fundamentally the mechanism works as follows. Asteroidal collision debris produced in the vicinity (i.e. within *ca.* ±0.05 AU) of the edges of the Kirkwood gap, collisionally ejected at moderate velocities of 50 to 200 m s^{-1}, will have a reasonably high probability of being placed in the chaotic resonant region. On a time scale of not more than 1 Ma, resonant acceleration will lead to excursions in eccentricity, eventually reaching $e \sim 0.6$ (figure 2). The close proximity of the fragment's perihelion to Earth's orbit will lead to close gravitational encounters with Earth, and the resulting perturbation will remove the semimajor axis from the resonant interval.

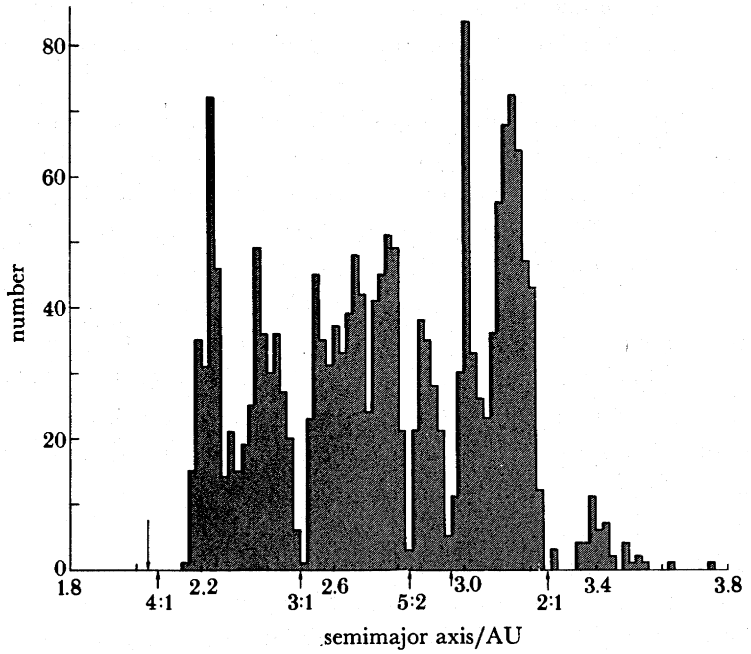

FIGURE 1. Number of catalogued asteroids against semimajor axis (exclusive of Apollo–Amor objects). With the small histogram interval chosen, the nearly complete depletion of the 3:1 resonance is apparent.

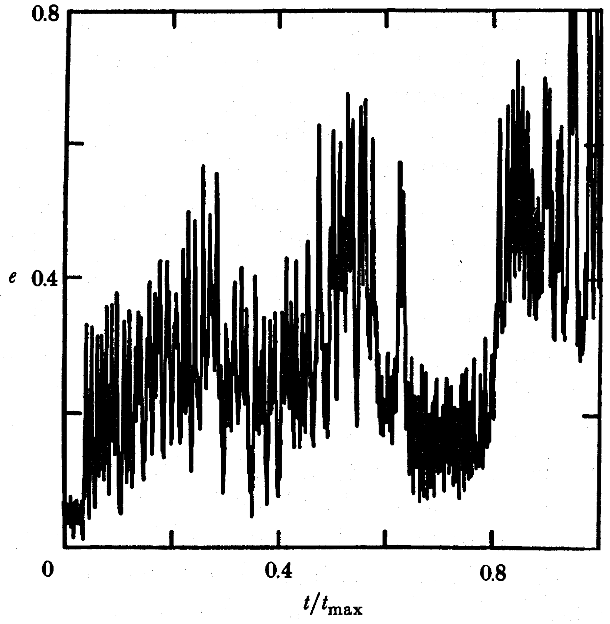

FIGURE 2. Evolution of eccentricity of an asteroid collision fragment in the 3:1 commensurability, as calculated by Wisdom (1983). On this time-scale ($T_{\max} = 2.4$ Ma) the eccentricity becomes large enough (0.6) to cross the orbit of Earth.

The fragment will thus be 'stranded' in an orbit of nearly constant eccentricity *ca.* 0.6 and with perihelion near 1 AU.

The natural unfolding of this situation, described qualitatively above, has been quantitatively studied by a Monte-Carlo technique (Wetherill 1985). Meteorite size (up to 1 m) fragments produced in the vicinity of the 3:1 gap will impact Earth within a few million years, in accordance with observed cosmic ray exposure ages. Quantitatively, the calculated distribution of orbits turns out, at first glance, to be 'too good'. The concentration of perihelia of the impacting bodies is so strong that the ratio of daylight afternoon impacts – total daylight falls is 0.76, even greater than the observed ratio of 0.64 ± 0.02.

At least most of this discrepancy is only apparent, however. The reason for this is that only a portion of the asteroid collision debris injected into the resonant region will be already in the size range of meteorites. The size spectrum of this material will include larger bodies, ranging from those several metres in diameter up to Apollo–Amor size bodies, in the kilometre-size range. These larger bodies will achieve Earth-crossing in just the same way as meteorite-size asteroidal fragments. Their large size, however, will cause them to be less vulnerable to collisional destruction after they become Earth-crossing. On a time scale of *ca.* 10^7 years, the concentration of their perihelia near 1 AU will become blurred and the perihelion distribution will spread well within the orbit of Venus. These larger bodies will be fragmented by collisions while near their aphelia in the asteroid belt, and the resulting secondary (and tertiary, etc.) meteorite-size debris will share the diffused perihelion distribution of the objects from which they are derived.

A proper calculation of the expected distribution of meteorite orbits must therefore include the weighted sum of not only the contribution of meteorite-size fragments produced in the asteroid belt, but those produced by all sizes of asteroidal debris in Earth-crossing orbit as well. A new set of calculations is reported here (table 1), including some improvements over those reported earlier (Wetherill 1985). By combination of steady-state concepts with the observed distribution of small asteroids (Wetherill 1985), determined by the Palomar–Leyden Survey (Van Houten *et al.* 1970), the absolute mass yield of terrestrial meteorite impacts can also be calculated. This yield will be equal to the product of the 'weighted impact yield' for the entire region (last line on table 1) and the steady-state production rate of meteorite size S-asteroid debris (1.97×10^{12} g a^{-1}) in this region (Wetherill 1985). The result, 2.5×10^8 g a^{-1}, agrees with the observed preatmospheric flux (Halliday *et al.* 1984).

In making these new calculations, the range of asteroidal eccentricities and inclinations was chosen in a more realistic way than in Wetherill (1985), i.e. it was based on the observed distribution of asteroids below the ν_6 resonance as a function of semimajor axis, as given by Brown *et al.* (1967). The range of inclinations and eccentricities, together with the weighting factor determined by the number of asteroids in the region are also given in table 1. The impact-ejecta velocity distribution used was that of Gault *et al.* (1963).

It is not clear how much attention should be paid to the difference between calculated fall-time ratio (0.688) and that observed (0.64 ± 0.02). If, instead of making use of observed chondrite falls, the comparison is made with fall-time distributions inferred from orbits of fireballs believed to be ordinary chondrites (Wetherill & ReVelle 1981), and consideration is given in the calculations to the exclusion of twilight fireballs by the astrometric network, the calculated and inferred fall-time ratios agree at 0.64. Furthermore, the calculated fall-times were calculated under the assumption of a complete steady state, whereas there is actual

Table 1. Meteorites ultimately derived from vicinity of 3:1 Kirkwood gap

	asteroidal source regions		
semimajor axis/AU	eccentricity range	inclination range/deg	weighing factor
2.40–2.45	0.05–0.20	2.9–14.9	0.40
2.45–2.48	0.05–0.21	2.9–12.0	0.15
2.52–2.55	0.05–0.30	2.9–14.9	0.14
2.55–2.60	0.05–0.35	2.9–17.8	0.31

	Earth impacts		
source semimajor axis/AU	impact efficiency	weighed impact yield	p.m., total falls
2.40–2.45	2.22×10^{-5}	8.88×10^{-6}	0.699
2.45–2.48	3.73×10^{-4}	5.60×10^{-5}	0.701
2.52–2.55	4.00×10^{-4}	5.60×10^{-5}	0.677
2.55–2.60	3.26×10^{-5}	1.01×10^{-5}	0.675
entire region	—	1.310×10^{-4}	0.688

evidence (e.g. the 6 Ma peak in bronzite chondrite exposure ages (Crabb & Schultz 1981)) that stochastic fluctuations associated with single events are of some importance. Finally, our present understanding of the details of the behaviour of material in the chaotic zone is rudimentary. For example, it was found that Earth was nearly certain to 'pick off' the high-eccentricity fragment during the first set of excursions shown in figure 2. On the other hand, only two such calculations have been presented (Wisdom 1983, 1985) and it is not clear how typical these cases are. For these cases the probability that a Mars perturbation will remove the body from the resonance is 50%. On the other hand, if Earth were less effective in removing the body from resonance, Mars might 'smear' the distributions, and delay Earth-crossing in such a way to favour impacts from larger bodies more. Until these details are better understood, it will not be possible to pursue the question further.

In view of these considerations, it seems best to emphasize the role of the 3:1 resonance as a mechanism for delivering to Earth an adequate number of ordinary chondrites with a pronounced asymmetry in the fall-time distribution. No other asteroidal region shares these properties.

3. Source region of differentiated stony meteorites

It has been proposed (Wetherill 1977; Wetherill & Williams 1979) that the most plausible asteroidal source region for differentiated meteorites is the innermost edge of the asteroid belt ($2.17 < a < 2.25$ AU). Many of the asteroids in this 'Flora' region are 'Mars-grazing', i.e. their perihelia will come within *ca.* 0.05 AU of Mars aphelion for rare, but inevitable, favourable values of the secular variations in the orbital elements of both the asteroid and Mars. Favourably orientated collision ejecta (*ca.* 100 m s^{-1}) will make even closer approaches to Mars, as a result of their smaller semimajor axes and high values of eccentricity. The latter is a consequence of the amplitude of the secular oscillations in eccentricity becoming larger as the semimajor axis approaches the ν_6 resonant value of *ca.* 2.04 AU (Williams 1969) (figure 3). The smaller perihelia of these ejecta fragments can cause them to be occasional Mars crossers.

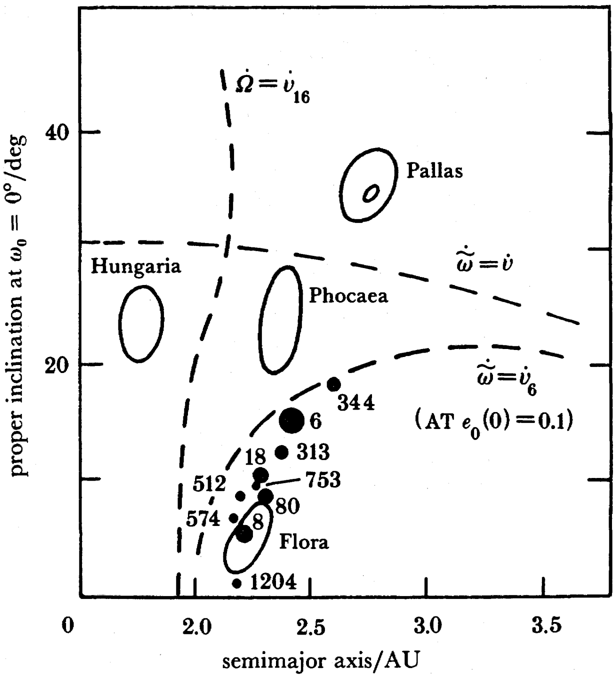

FIGURE 3. Secular resonances and asteroidal regions in the inner asteroid belt, after Williams (1969).

Close encounters to Mars will then lead to a random walk in semimajor axis that will sooner or later cause *a* to become close enough to the ν_6 resonance to cause the eccentricity to become high enough to permit deep Mars-crossing.

The foregoing orbital evolution will thereby accelerate with time, often leading to Earth-crossing on a time scale of *ca.* 10^8 years. Small, meteorite size, stony fragments will be destroyed by collisions before they become Earth-crossing. In contrast, iron fragments and larger (not less than 10 m) stony fragments can become Earth-crossing. While in Earth-crossing orbit these 'large meteorites' and Apollo objects of various sizes will continue to be fragmented while passing through the asteroid belt and will supply Earth-impacting meteorites. This biasing of the size distribution toward larger initial Earth-crossing masses will reduce the tendency of meteorite perihelia to cluster near 1.0 AU and cause the p.m.:a.m. fall-time distribution to be nearly symmetrical.

This meteorite source mechanism has been studied quantitatively (Wetherill & Williams 1979), verifying the qualitative account given above. In this earlier work, however, it was difficult to estimate very well the absolute flux of meteorites from this region, because of uncertain parameters associated with details of cratering mechanics.

By use of both the approach and results of § 2, a much better evaluation of this innermost region of the asteroid belt as a source of stony meteorites has now been made. This improvement is primarily the consequence of several factors.

1. The calculation of the rate of injection of asteroidal debris into the 3:1 gap is now based on the observed distribution of small asteroids and steady-state theory. This is believed to be superior to attempting to estimate the injection rate by use of cratering mechanics. (The result, however, is entirely consistent with cratering mechanical calculations of the injection rate.)

2. The calculated and observed Earth-impact flux of ordinary chondrites from the 3:1 gap agree at *ca*. 10^8 g a^{-1}. Either of these results can then be used to normalize calculations of the Earth-impact rate from other regions of the asteroid belt. In this way, the absolute flux from other regions can be based on the more accurate calculation of the ratio of the yield from a particular region to that from the vicinity of the 3:1 gap.

3. In the earlier work on the source region of differentiated meteorites, the yield from specific asteroids in the Flora region was used to estimate the total yield from this region. A new approach is now used (Wetherill 1985) based on the entire collision hierarchy of asteroidal bodies. This provides a better observational basis for the calculations, and further reduces their sensitivity to details of cratering mechanics.

4. In this work, consideration was taken of the secular perturbations in the orbit of Mars. When this is done, the calculated populated stable region of the innermost asteroid belt agrees well with the observed distribution of asteroids in the vicinity of the ν_6 resonance. If only the present orbit of Mars is considered, the calculated stable region extends well inside that observed. The present correction of this discrepancy should improve the reliability of the calculations. This effect was not included in Wetherill (1985), nor in earlier work.

5. Unlike the results reported by Wetherill & Williams (1979), in this approach the effect of atmospheric ablation of meteorites is explicitly induced in the calculations, and the time of fall distribution explicitly calculated, rather than only estimated.

In this way an entirely new set of calculations has been made of the Earth-impact efficiency of random asteroid ejecta in eight source intervals between the innermost edge of the asteroid belt (2.17 AU) and 2.60 AU and lying below the ν_6 resonance (figure 3). For each of these regions, the source asteroid eccentricity and inclination distributions reported by Brown *et al.*

TABLE 2. METEORITES ULTIMATELY DERIVED FROM THE INNERMOST ASTEROID BELT

asteroidal source regions

semimajor axis/AU	eccentricity range	inclination range/deg	weighing factor
2.17–2.25	0.10–0.17	2.9–7.0	0.27
2.25–2.30	0.10–0.20	2.9–8.0	0.29
2.30–2.35	0.05–0.20	4.0–9.7	0.22
2.35–2.40	0.05–0.21	2.9–11.5	0.21

Earth impacts

source semimajor axis/AU	impact efficiency	weighed impact yield	p.m., total falls
2.17–2.25	4.40×10^{-5}	1.19×10^{-5}	0.52
2.25–2.30	3.85×10^{-6}	1.12×10^{-6}	0.55
2.30–2.35	3.18×10^{-7}	7.00×10^{-8}	0.53
2.35–2.40	2.93×10^{-6}	6.15×10^{-7}	0.72

(1967) were approximated (tables 1 and 2). Three values of ejection velocity (50, 150 and 300 m s^{-1}) are shown. These efficiencies include the contribution from meteorite-size fragments produced directly in the asteroid belt from bodies of all sizes, as well as meteorite-size fragments produced from bodies after they have been transferred into Earth-crossing orbit.

It may be seen (figure 4) that in the velocity range that includes *ca*. 98 % of the collision

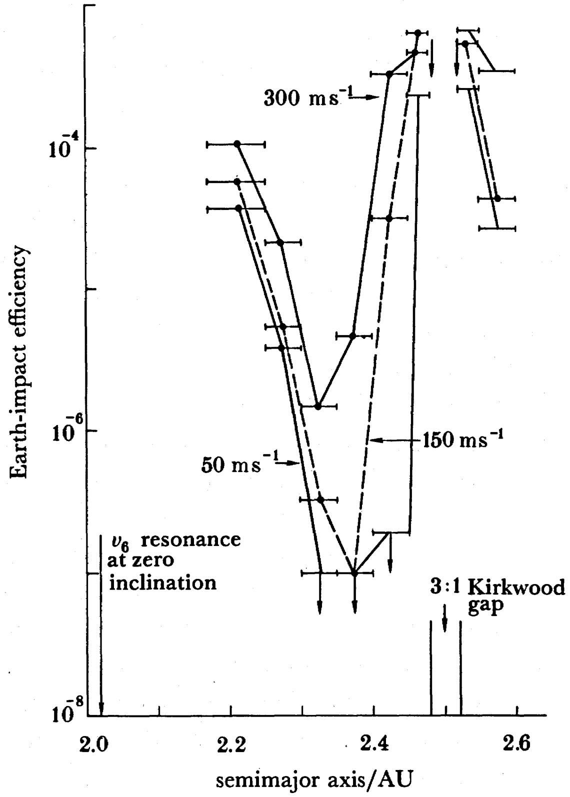

FIGURE 4. Earth impact efficiency for asteroidal collision ejecta as a function of semimajor axis and ejection velocity.

ejecta (Gault *et al.* 1963), the Earth impact efficiency is very dependent on semimajor axis. Efficiencies are very high in the vicinity of the 3:1 Kirkwood gap at 2.5 AU, and moderately high in the innermost edge of the belt. The latter is caused by proximity to the ν_6 resonance. Much higher efficiencies have been calculated for smaller values of semimajor axis in immediate proximity to the ν_6 resonance (and the 4:1 commensurability resonance at 2.06 AU). However, this region is of no relevance to the question of meteorite sources because the number of asteroids in long-lived stable orbits in this region is negligible.

Very low Earth-impact efficiencies are found for material ejected between 2.25 and 2.40 AU in the range of proper inclination and eccentricity considered. The range of proper eccentricities and proper inclinations for each semimajor axis interval encompasses almost all the asteroids in these regions that lie beneath the ν_6 resonance. In addition, there are a few asteroids within higher eccentricities and inclinations that lie closer to the ν_6 resonance. These have higher Earth-impact efficiencies. Insofar as this region of the asteroid belt is a potential source of meteorites, the objects in these orbits are those that should be considered. Calculations for the largest such object, that of the *ca.* 80 km diameter C-asteroid 313 Chaldaea, together with several other specific orbits, are given in table 2. The relatively high efficiency found for this orbit is attributable to its minimum perihelion already being slightly inside the maximum aphelion of Mars (Williams 1979). Therefore, in this sense, this object (and any retinue of smaller collisional debris) is already a Mars-crosser, and some of even its lowest velocity collision ejecta will be even deeper Mars-crossers. Only at higher velocities (*ca.* 1 km s^{-1}) does this yield from more typical asteroids in this region approach that found between 2.17 and 2.25 AU, but only *ca.* 10^{-3} of the ejecta will have velocities this high. Therefore, assuming these calculations to be valid, meteorites from asteroids in this intermediate region (including 4 Vesta at 2.36 AU) should be absent or at most very poorly represented in meteorite collections.

Earth-impact efficiencies have been calculated for the entire range of impact velocities that make a significant contribution for each region of the inner asteroid belt. The yield of each velocity interval was weighted in accordance with the mass against velocity distribution of Gault *et al.* (1963), in accordance with the data used for 'solid rock' by Greenberg & Chapman (1983), and then weighted by the number of asteroids in each semi-major axis interval as given by the Palomar–Leiden survey. The results of this calculation are given in table 2.

TABLE 3. EARTH IMPACT EFFICIENCIES AND FALL TIMES FOR SPECIFIC ASTEROIDAL ORBITS IN THE INNER ASTEROID BELT

		proper elements (Williams 1979)		ejection velocities		
asteroid	a	e	i	m s^{-1}	impact efficiency	fall-time ratios
313 Chaldaea	2.38	0.23	12.4°	50	3.9×10^{-5}	0.53
				100	4.8×10^{-5}	0.54
				150	2.7×10^{-5}	0.52
				200	4.6×10^{-5}	0.56
4 Vesta	2.36	0.22	6.4°	400	$< 10^{-7}$	—
				450	3.7×10^{-5}	0.71
				500	1.3×10^{-4}	0.71
8 Flora	2.20	0.14	5°	25	9.3×10^{-6}	0.50
				50	1.4×10^{-5}	0.52
				100	2.2×10^{-5}	0.53
				150	3.9×10^{-5}	0.55
				200	6.0×10^{-5}	0.51
				300	1.2×10^{-4}	0.52
6 Hebe	2.42	0.15	15°	150	$< 10^{-7}$	—
				200	3.9×10^{-5}	0.59
				300	4.6×10^{-4}	0.62

The total yield from the region between 2.17 and 2.25 AU is found to be about 9% that from the vicinity of the 3:1 Kirkwood gap. The time of fall distribution is markedly different, morning and afternoon falls being more nearly equal in number. If both the asteroids in this region as well as those near the 3:1 resonance are of ordinary chondritic composition, admixture of meteorites from this region with those ultimately derived from the 3:1 resonance will reduce the expected afternoon fall ratio of ordinary chondrites only to about 0.67. Therefore there is no strong observational reason for excluding the possibility that the *entire* inner asteroid belt is the source region of ordinary chondrites. In this case, the 3:1 gap would simply be the primary source, because of the greater impact efficiency of asteroidal debris produced in that region.

On the other hand, the achondritic meteorites must come from somewhere, and their observed total p.m./total fall ratio of 0.53 is definitely inconsistent with that expected for the 3:1 resonance region. Because observational bias must discriminate against recovery during night-time a.m. hours, the actual ratio should be even less. Although the data are meagre, from the work of Simonenko (1975) it seems unlikely that achondritic perihelia are as concentrated near 1 AU nearly as strong as those of the ordinary chondrites (figure 5). Achondrites, exclusive of SNCs (probably of Martian origin) and the enstatite achondrites, comprise 8% of the observed stone meteorite falls. The basaltic achondrites represent 6% of the observed falls, and have a 24 h fall-time ratio of 0.51. The relatively high proportion of these achondrites among meteorite falls implies that they must be derived from a prolific source. This region of the asteroid belt between 2.17 and 2.25 AU is the only candidate known now for a source region that provides the appropriate orbital distribution and impact rate. Very few of these meteorites will be direct collision ejecta from belt asteroids. Rather, they will be secondary (and tertiary etc.) fragments of larger fragments, ranging up to the largest Apollo–Amor objects, such as 433 Eros (20 km diameter). The expected Earth impact rate of these *large objects* is similar to that from the 3:1 region, in agreement with the observation (Kyte & Brownlee 1985) that melt rock data (see, for example, Palme *et al.* 1981) suggest chondritic bodies may not dominate the Earth impact flux of crater-producing bodies.

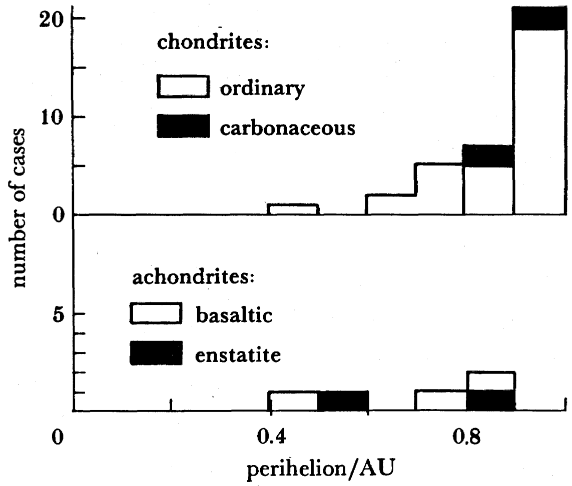

FIGURE 5. Observed distribution of achondrite perihelia, based on Simonenko (1975).

Because of its basaltic reflectance spectrum, the 400 km diameter asteroid 4 Vesta is often suggested as the primary source of basaltic achondrites (e.g. Drake 1979). The principal problem with this otherwise attractive suggestion is that Vesta ($a = 2.36$ AU) not only lies within the region (2.30–2.40 AU) for which the yield is lowest, but its rather low eccentricity (0.09) and inclination (7°) cause it to be in an unproductive portion of this region. For this orbit, a minimum ejection velocity of *ca.* 450 m s^{-1} is required before a statistically significant Earth-impact efficiency (more than 10^{-7}) is found (figure 4). Even if as much as 10% of the asteroidal material in this region of the belt were Vesta-derived (for which there is no spectrophotometric evidence), the yield from this 'Vesta Source region' would be only 10^{-3} that of the 3:1 gap. Therefore only *ca.* 10^5 g a^{-1} of this material should impact the Earth, when normalized to the *ca.* 10^8 g a^{-1} flux of ordinary chondrites. If instead of considering the Vesta material to be this entire collision hierarchy, only meteorite-size fragments from Vesta itself are considered, the yield is much lower, *ca.* 1 kg a^{-1}. This is similar to the mass of basaltic achondrites added annually to museum collections, thereby requiring 100% efficiency in collection of this material, including that falling in the ocean.

4. Other source regions and other types of meteorites

The regions between 2.17 and 2.60 AU below the ν_6 resonance, contain most of the asteroidal mass in the inner asteroid belt. The high inclination Phocaea and Pallas regions (figure 3), above the ν_6 resonance are sparsely populated (*ca.* 4% as many bodies as the region studied). The Monte-Carlo techniques used in the low-inclination region are probably not applicable in this high-inclination region because of nonlinear mixing of the free and forced oscillations of the secular perturbations. Therefore in this case only qualitative considerations are possible now. In this context, it may be expected that the ν_5 resonance may be expected to behave qualitatively similar to ν_6 in expediting the evolution of Mars-crossing orbits, but because of the smaller mass injected into this region, its effects should be more minor. There is no theoretical requirement that asteroids in this region need to be represented in meteorite collections at all, but a small contribution is possible.

The outer asteroid belt, beyond 2.60 AU, can be expected to contribute a significant number of meteorites only if the outer resonances at the 5:2 (2.82 AU), 7:3 (2.96 AU) and 2:1 (3.28 AU) commensurabilities can avoid excessive transfer of asteroidal debris to the vicinity (i.e. within *ca.* 0.5 AU) of Jupiter before it is Earth-crossing. If these resonances are as effective as the 3:1 resonance in increasing eccentricity, it is likely that Jupiter will remove this material from the Solar System so effectively that the contribution of the outer belt to the terrestrial meteorite flux will be negligible. Murray (1986) has studied chaotic orbits associated with the 2:1 resonance and found that eccentricities as high as 0.8 could be achieved, sufficient to cause the aphelion of the fragment to reach 5.9 AU, i.e. deep Jupiter-crossing. Mars perturbations and/or collisions would then remove the asteroidal fragment from the resonance, destroy the liberation condition, and expose the body to very strong Jupiter perturbations, leading to ejection from the Solar System.

On the other hand, the extent of this chaotic zone appears to be more limited than the 3:1 resonance. Because of this, it is conceivable that the mechanism proposed earlier (Zimmerman & Wetherill 1973) could permit a small amout of material to undergo more modest eccentricity increases and become Mars-crossing before it is Jupiter-crossing. The semimajor axis could then be perturbed inside the resonance, and combined Jupiter and Mars perturbations could random-walk the perihelion toward Earth-crossing. The nearly bimodal nature of the 'maximum-eccentricity' map in Murray (1986) makes this possibility seem very unlikely.

The Hungaria region at 1.95 AU (figure 3) deserves investigation as a possible meteorite source. Most of the asteroids in this region, including the largest (434 Hungaria, 23 km diameter), display the rare, high-albedo, featureless, reddish reflectance spectra of the E-asteroids that are similar to laboratory data on enstatite achondrites. Monte-Carlo techniques available now do not permit quantitative calculations for high-inclination orbits of this kind, particularly considering the proximity of Mars, the ν_{16}, ν_6 and 3:1 resonances. Qualitatively, however, it seems that this source region could be unique by producing fragments with aphelia initially inside the main asteroid belt, and thereby relatively immune to collisional destruction. This could be the reason why enstatite achondrites have remarkably old exposure ages (Schultz & Kruse 1978). Despite the small mass of its largest asteroid, the Palomar–Leyden survey appears to indicate the presence of a surprisingly large number of smaller bodies in this region. If combined with a sufficiently high Earth-impact efficiency, this region would be a strong candidate for the source region of the enstatite achondrites.

Turning to meteorite classes that have not been considered, the region adjacent to the 3:1 gap contains approximately equal numbers of C-asteroids and S-asteroids. If the usual identification of carbonaceous meteorites with C-asteroids is made, then the expected pre-atmospheric terrestrial flux of carbonaceous meteorites should be comparable to that of ordinary chondrites. The conventional explanation of why the observed fall rate is only 6% that of the ordinary chondrites, greater ablation and fragmentation during passage through the atmosphere, is likely to be correct. The fall-time ratio of these meteorites (*ca.* 0.8) is probably consistent with a 3:1 resonance source, but of little statistical significance. There is also evidence that some Earth-impacting meteoroids from cometary orbits could be recoverable (Wetherill & ReVelle 1982). If so, these are likely to be carbonaceous. For a cometary source (either live comets or cometary Apollo objects), no fall-time asymmetry is expected. The important possibility that large samples of cometary material may be available in the form of meteorites should be pursued, but there is no strong reason to believe they are contained in our present meteorite collections.

A similar treatment of iron and stony-iron sources would be difficult, because of large uncertainties in fracturing and cratering mechanics, asteroidal identification, and fall statistics for meteorites of these kinds. Based on fall rates, a total source at least as productive as that of the achondrites, and possibly that of the ordinary chondrites, is required. Qualitatively, an inner asteroid belt source region (less than 2.60 AU) appears very probably, simply because of the apparent absence of productive regions in the outer belt. It is quite possible, however, that iron fragments can be accelerated to higher velocities without destruction. Therefore proximity to the 3:1 or ν_6 resonance may be less critical, and a broader sample of metallic sources in the inner asteroid belt may be present in meteorite collections. Although fall-time statistics are inadequate to be useful, the fact that all five hexahedrite falls occurred in the morning is curious and, if not a fluke, would be difficult to explain.

The matter of identification of S-asteroid spectra in the 3:1 resonance and the Flora region with the most abundant classes of chondrites and achondrites is still unresolved. Gaffey (1984) presents cogent reasons for believing that 8 Flora is a differentiated asteroid, rather than being chondritic, and at least tentatively extends these arguments to S-asteroids as a whole. Dermott *et al.* (1985) present UBV data indicating a difference in spectroflectance of S-asteroids interior to 2.4 AU relative to those with larger semimajor axes. Qualitatively, a difference would be expected if the achondrite sources are S-asteroids in the Flora region and the ordinary chondrite sources are S-asteroids near the 3:1 resonance. Feierberg *et al.* (1982) present data and arguments to support their position that typical S-asteroids are of ordinary chondritic composition and mineralogy.

One strong conclusion from quantitative studies of asteroid dynamics is that the ordinary chondrites require a major asteroidal source region, such as half the asteroids within ±0.05 AU of the 3:1 resonance. Although it is true that meteorite collections represent a biased sample of the asteroid population, the extent of these selective effects is limited. The natural length scale on which selection can operate is that imposed by collision ejection velocities of several hundred metres per second, i.e. ±*ca.* 0.05 AU. This precludes the exquisitely precise sampling that would be required to deliver to Earth only the material from a nearly unobservable population of asteroids. Stochastic effects associated with single large collisional events are undoubtedly present, but completely fail as a quantitative explanation of the dominance of the meteorite flux by ordinary chondrites.

One possibility that merits further attention is the relation between asteroidal size and spectral reflectance. The meteorite-size fragments in our collections are nearly the end members of a collisional hierarchy that extends through 'Apollo-size' asteroids of 0.1–10 km up to much larger bodies. The immediate parent bodies of most meteorites are concentrated toward the small mass end of this hierarchy. It is conceivable that for some presently unknown reason the detailed mineralogical composition of smaller asteroids differs from the large bodies on which the most precise spectral reflectance data is available, perhaps because these large bodies are collisional residues, or because of some winnowing process that occurs as material passes down the collisional hierarchy. The tendency of small Earth-approaching objects to more often resemble meteorites (McFadden *et al.* 1985) may be relevant to this question. If the relation between chondrite-like Apollo objects and ordinary chondrites is more than a coincidence there must also be an appropriate asteroidal source for these Apollo objects. For both, the quest for an ordinary chondritic source leads back to at least intermediate size (*ca.* 50 km diameter) bodies in the main asteroid belt.

5. SUMMARY AND CONCLUSIONS

1. Combination of observational data on meteorite orbits and dynamical theory strongly suggest that the ultimate source region of ordinary chondrites and Apollo–Amor objects with ordinary chondrite mineralogy is that portion of the main asteroid belt adjacent to the 3:1 commensurability resonance at 2.50 AU. To agree with the observed terrestrial fall rate of these meteorites, the expected contribution of the entire size spectrum of S-asteroids in this region is required.

2. The expected meteorite flux from the innermost asteroid belt (2.17–2.25 AU) via the ν_6 resonance is found to be 9% that of the 3:1 resonance ordinary chondrite source. In contrast with the 3:1 resonance source, no significant asymmetry between morning and afternoon falls is expected for meteorites ultimately derived from this region. It is proposed that this region is the source of basaltic achondrites, exclusive of SNC meteorites, and possibly some other achondrites as well. Stony meteorites ultimately from this region usually arrive on Earth through the intermediary of larger bodies, including those observed as Apollo–Amor objects.

3. The preatmospheric terrestrial flux of carbonaceous meteorites from the 3:1 resonance region should be comparable to that of the ordinary chondrites, i.e. *ca.* 10^8 g a^{-1}. This is in addition to carbonaceous material of cometary origin, possibly recoverable only as micrometeorites.

4. The source regions of other meteorite types is uncertain. It is speculated that the Hungaria region, interior to the main belt at 1.95 AU, may be a source region of enstatite achondrites, and that iron and stony-iron meteorites may be derived from the entire asteroid belt interior to 2.6 AU.

5. There are many opportunities for further advances in our understanding the planetological context of meteoritic material. These include better theoretical understanding of the dynamics of secular and commensurability resonances, and development of techniques for calculating the orbital evolution of bodies coupled to more than one of these resonances (particularly bodies with inclinations greater than 20°). We also need to be able to interpret remote sensing data in a less ambiguous way. It may be hoped that *in situ* study by missions to asteroids will provide the 'ground truth' that may be necessary to accomplish this.

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Discussion

G. TURNER (*Department of Physics, University of Sheffield, U.K.*). How do meteorite cosmic ray exposure ages fit into the dynamical model presented? In particular to what extent do they reflect fragmentation when the object is in Earth crossing orbit, or in its original orbit in the asteroid belt? To what extent if any do they reflect the dynamical origin?

G. W. Wetherill. An advantage of the dynamical model is that it avoids uncertain assumptions regarding cratering mechanics by treating the entire system, both the asteroid belt and Earth-approaching population, as a single steady-state entity. A price that one pays for this is that distinctions of the kind asked about tend to be suppressed in the calculation, but still something can be said. Cosmic ray ages record the production of unshielded (less than about 2 m diameter) bodies from larger bodies as the ultimate, penultimate (or antepenultimate, etc.) stage of the global fragmentation hierarchy leading to the production of meteorites.

For the principal asteroidal source region, the 3:1 gap, I can estimate that about 10% of the Earth-impacting meteorite-size (100 g–1 t) fragments are produced by collisions in the asteroid belt. A somewhat greater fraction enter the broader unshielded size range while still in the asteroid belt. Meteorite-size fragments of all these larger unshielded bodies will have a multiple exposure history. The remaining cosmic ray exposures will be initiated by fragmentation of non-belt objects disrupted or cratered by collisions when their perihelia are inside the asteroid belt, including many in Earth-crossing orbits. These bodies include astronomically observable Apollo–Amor objects, but primarily intermediate size (e.g. 1–100 m diameter) bodies. Of course, all the bodies under consideration were ultimately fragments of belt asteroids.

For objects originally in the innermost belt, brought into Earth-crossing orbit by the $\dot{\nu}_6$ resonance, the fraction of cosmic ray ages initiated in the asteroid belt would be very small.

I would expect that the different orbital evolution of objects originally in these distinct asteroidal source regions would be reflected in their cosmic-ray age distribution, but only in a subtle way. I have not studied this question. Because I expect the difference would be slight, I would give higher priority to a serious quantitative test of the predictions this model makes regarding multiple exposure ages, taking into account stochastic fluctuations from the steady state. This could lead to a fine-tuning of the model (or even disclose a terrible problem with it), that would help our understanding of questions such as the origin of the 6 Ma peak in the bronzite chondrite exposure-age distribution.

F. L. Whipple (*Smithsonian Astrophysical Observatory, Cambridge, Massachusetts, U.S.A.*). Would Professor Wetherill care to comment on the SNC meteorites? Do they really come from Mars?

G. W. Wetherill. From consideration of their geochemistry, petrology, and radiogenic isotopes, these meteorites bear a strong signature of planetary, rather than asteroidal origin. Mars is the best candidate for being this planet. There is still a problem in understanding the mechanism by which an adequate quantity of material is accelerated to the martian escape velocity by an impact consistent with the martian cratering record and the young age of these meteorites.