METEORITE DELIVERY AND TRANSPORT

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Abstract. Understanding how meteorites and near–Earth asteroids reach their Earth–crossing orbits starting as fragments from main–belt asteroids is a basic prerequisite to identifying the original parent bodies of these objects and building a self–consistent cosmogonical interpretation of the observed properties of meteorites. We review the recent progress made in this area and the most important remaining open problems. These concern the physics of asteroidal collisions, the size distribution of small main–belt asteroids, the efficiency of different dynamical routes, and the relationships between asteroid taxonomic types based on spectrophotometry data and meteorite classes having different thermal histories and compositions.

1. Introduction

Every day, tons of interplanetary material fall into the Earth's atmosphere. Occasionally fragments heavier than a few kilograms partially survive atmospheric crossing, to reach the Earth's surface and become meteorites. The fall of larger bodies also occurs, with a frequency roughly proportional to the -2 power of the chosen threshold diameter — corresponding to the typical size distribution of the interplanetary complex. The typical interval between two impacts is a few centuries for 50–meter sized bodies, causing a 10 Mton of TNT explosion like that which in 1908 devastated the Siberian *taiga* at Tunguska; a few times 10^5 yr for km–sized objects; and $\approx 10^8$ years for an asteroid or comet 10 km across, causing a global climatic and ecological catastrophe, such as that recorded at the K–T boundary. Averaged over geologic time, a total influx of about 1.7×10^8 kg/yr hits the Earth over the mass range from 10^{-21} to 10^{15} kg (Ceplecha 1992).

Where does this material come from? Until 200 years ago, the fall of stones from outer space was widely believed by scientists to be a matter of superstition; on the other hand, at the beginning of this century, meteorites were thought to be interstellar objects travelling on hyperbolic orbits. Today, we know that cometary nuclei and debris contribute to the interplanetary complex (though apparently not to the small solid bodies reaching the Earth's surface), and there is evidence that a tiny fraction of the meteorites come from the Moon and Mars. However, the birthplace of most meteorites has been recognized to lie in the main asteroid belt, where the growth of a full–sized planet was aborted during the early evolution of the solar system (see Lipschutz et al. 1989, for a recent review). Therefore, for scientists interested in the earliest history of the Earth and the planetary system,

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meteorites are veritable Rosetta stones that include a wide variety of materials which have survived almost unaltered since 4.5×10^9 years ago.

However, until recently serious problems remained in understanding the asteroid–meteorite connection. As a consequence of interasteroidal impact events, fragments are usually ejected at velocities of the order of 100 m/s, far too small for directly causing the drastic orbital changes needed to achieve planet–crossing orbits. On the other hand, impulsive velocity increments of several km/s would induce in the meteoritic material shock and thermal modifications which in general are not observed. Thus the interplay between collisions and subtle dynamical effects is required to transport material from the asteroid belt to the Earth. A long–standing issue in planetary science is that of identifying and estimating the efficiency of these dynamical routes. Also, the meteorite delivery models should be consistent with the observed properties of meteorites, such as orbits, fall times and cosmic–ray exposure ages, and with the inferred (dis)similarities in composition and thermal history between the meteorite and asteroid classes. As we shall see, in recent years significant progress has been achieved in addressing these problems — albeit of course a number of puzzles are still awaiting a convincing solution.

The remainder of this paper is organized as follows. In Secs. 2 and 3 we will discuss the ejection of fragments from main–belt asteroids, in particular the evidence concerning ejection velocities and the way the fragment yield depends on size of the source object. Sec. 4 will be devoted to dynamics, both of fictitious asteroid fragments and of real near–Earth objects. The overall efficiency of the meteorite transport process will be estimated in Sec. 5, and the evidence provided by asteroid spectrophotometry will be shortly reviewed in Sec. 6. Sec. 7 will summarize the open problems and the most important areas of future work.

2. Fragment ejection velocities

Interasteroidal collisions provide an effective mechanism not only to generate the observed distribution of asteroid sizes and spins (Davis et al. 1989), but also to eject fragments out of the surfaces and even the interiors of existing asteroids. When fragments exceeding several km in size are ejected in dynamically "quiet" regions of the asteroid belt, the resulting orbital clusterings may remain detectable for billions of years as *dynamical families* (Milani et al. 1992; Zappalà and Cellino, this volume). On the other hand, when fragments are injected into chaotic zones of the phase space, they may end up as planet–crossing asteroids/meteoroids.

However, a crucial quantitative problem concerns the typical ejection speeds of asteroid fragments. Since the orbital velocities of main belt–asteroids are of the order of 20 km/s, velocity increments of hundreds of m/s are required just to achieve a 1% change in the orbital elements. Moreover, it is easy to estimate that the escape velocity of an asteroid of (mean) radius R is $V_{esc} = (60\,\mathrm{m/s}) \times (R/50\,\mathrm{km})$ (we have assumed here a density $\rho \approx 2.5$ g/cm^3 — note that $V_{esc} \propto \sqrt{\rho}$, so that uncertainties in the density do not affect much V_{esc}). Therefore, ejection velocities ≈ 100 m/s are needed just to escape "to infinity" from any sizable asteroid.

In fact, most current models of the outcomes of asteroidal collisions, involving either catastrophic break–up or cratering of the target (Greenberg and Chapman

1983; Wetherill 1987; Davis et al. 1989; Farinella et al. 1993a,b; Petit and Farinella 1993) assume that the magnitude of the fragment ejection velocity V_{ej} follows a power–law distribution with a lower cutoff. This is a reasonable approximation of the shape of the distribution observed after laboratory experiments on hypervelocity impacts (see Gault et al. 1963, and Stöffler et al. 1975, for craters; Davis and Ryan 1990, and Nakamura and Fujiwara 1991, for break–up events). Then the number of fragments ejected with speeds in the interval $(V_{ej}, V_{ej} + dV_{ej})$ is

$$dN(V_{ej}) = C\ V_{ej}^{-\alpha}\ dV_{ej}\ , \tag{1}$$

for $V_{ej} > V_{min}$, while $dN(V_{ej}) = 0$ for $V_{ej} < V_{min}$ (implying that V_{min} is the lower–cutoff velocity). For the exponent α the value 3.25 is roughly consistent with experimental results quoted above (the total kinetic energy of the fragments is finite only provided $\alpha > 3$). Provided $\alpha > 2$, the mean value $< V >$ of the distribution is $\frac{(\alpha-1)}{(\alpha-2)} V_{min}$ ($= 1.8\, V_{min}$ for $\alpha = 3.25$). Note that Eq. (1) implies that the distribution of the relative velocity "at infinity" V is given by :

$$dN(V) = CV(V^2 + V_{esc}^2)^{-(\alpha+1)/2}\, dV\ , \tag{2}$$

for $V_{min} < V_{esc}$; otherwise, $dN = 0$ whenever $V < (V_{min}^2 - V_{esc}^2)^{1/2}$. The peak of (2) occurs at $V = V_{esc}/\sqrt{\alpha}$, namely at a relative velocity smaller than, but comparable to the target's escape velocity; however, this is true only provided $V_{min} < V_{esc}$, otherwise the peak is at $V = (V_{min}^2 - V_{esc}^2)^{1/2}$.

Clear evidence on the typical values of $< V >$ or V_{min} is provided by asteroid families. From the escape velocity of their largest members and the observed dispersion of proper elements, typical relative velocities of a few hundreds of m/s are easily inferred (Zappalà et al. 1984, 1990; Bendjoya et al. 1991). However, such values are definitely *not* consistent with the results of laboratory experiments. In all the hypervelocity impact fragmentation experiments performed so far, typical fragment ejection velocities have been found to be only ≈ 10 m/s. As for the cratering events, the experiments with basalt targets carried out by Gault et al. (1963) indicate $V_{min} \approx 50$ m/s, while lower values were observed for "softer" targets. Again, asteroid families (in particular, the Vesta family as recently studied by Binzel and Xu 1993, see Sec. 6) provide convincing evidence that in giant impact cratering events large fragments (up to ≈ 10 km) can be ejected at velocities of several hundreds of m/s. Such values are confirmed by Vickery's (1986) analysis of the distribution of secondary craters surrounding some large impact craters on the Moon and Mars (though she pointed out the alternative possibility that large secondary craters are formed by clusters of small ejecta rather than single fragments).

Thus, it is worth stressing that we have a serious problem here, as the development of working meteorite delivery (and family formation) models requires the assumption that large–scale asteroidal collisions are much more efficient than the small–scale laboratory impacts in accelerating the fragments. As the physical reason for this discrepancy is not understood, further experimental and theoretical research in this area is urgently needed.

A related problem is that no correlation between fragment size (or mass) and ejection velocity, such as indicated by recent experiments (Nakamura and Fujiwara

1991; Nakamura et al. 1992) has been included in the fragment ejection models so far. This is an important limitation, as results by Petit and Farinella (1993) imply that such a correlation can affect in a significant way the overall amount and the size/velocity distribution of the escaping fragments.

3. Fragment yield vs. size of source asteroid

Meteorites represent just the end–product of a "collisional cascade", namely they are probably multi–generation fragments separated by a number of impact/ejection events — occurred both in the main asteroid belt and in planet–crossing orbits — from their primordial precursor asteroids (which are usually referred to as "parent bodies"). This is a complex process, for which realistic models have not yet been developed. However, important questions are whether collisional fragments are currently generated more effectively by large or small main–belt asteroids, and by cratering or fragmentation events. To address these questions, a simple model has been developed by Farinella et al. (1993a); while it provides useful first–approximation results, it also shows where the critical areas of uncertainty are.

The model assumes that : (i) the collision rate against a target asteroid of radius R is $P_i R^2 N_{pr}$, where P_i is a constant (the average intrinsic collision probability, see Farinella and Davis 1992) and N_{pr} is the assumed number of projectiles; (ii) the projectile population has a power–law cumulative size distribution with a negative exponent $-b$, i.e., the number of projectiles larger than r is $N(> r) = Kr^{-b}$, where K is a constant (b is assumed to be < 3, so that the total mass in the distribution is finite); (iii) catastrophic fragmentation of the target occurs whenever the ratio between projectile and target size exceeds a critical threshold ζ, independent of target size; (iv) otherwise, a crater is created with an excavated mass proportional to the projectile's kinetic energy through a constant coefficient L; (v) the largest possible crater corresponds to an excavated mass given by a factor γ times the target mass [if the average impact velocity is V_i, it follows from assumptions (iii) and (iv) that $\gamma = LV_i^2\zeta^3/2$]; (vi) only fragments with $V_{ej} > V_{esc}$ escape reaccumulation, so that if we define $R_{min} = 83\,km\ (V_{min}/100\,m/s)$ as the target radius for which $V_{esc} = V_{min}$, namely the minimum radius for which part of the fragments are reaccumulated, then for $R > R_{min}$ the escape velocity is $V_{min}R/R_{min}$ and the fraction of escaping fragments is $(R/R_{min})^{1-\alpha}$. Note that here we have assumed that V_{min} does not depend on fragment size; different assumptions would lead to a much more complicated treatment of the fragment reaccumulation process (see Petit and Farinella 1993). Let us now consider separately (1) impact fragmentation and (2) cratering events.

(1) The frequency of catastrophic collisions for a target of radius R is $P_i R^2 N(> \zeta R) = P_i K \zeta^{-b} R^{2-b}$. Since in any break–up event the whole target mass is converted into fragments, the mass ejection rate is $(4\pi\rho K P_i/3)\zeta^{-b}R^{5-b}$ (ρ being the target density). For $R > R_{min}$, this has to be multiplied times $(R/R_{min})^{1-\alpha}$ to account for fragment reaccumulation.

(2) If we assume that craters of all sizes up to the largest possible one have been formed on the target, the total excavated mass is just L times the total delivered kinetic energy, which can be computed by integrating over projectile sizes from

0 to ζR. This yields a mass ejection rate $\frac{2\pi b}{3(3-b)} K P_i \rho V^2 L \zeta^{3-b} R^{5-b}$. Again, for $R > R_{min}$ the additional reaccumulation factor $(R/R_{min})^{1-\alpha}$ is needed.

Thus, within the simplifying assumptions described above, the same scaling rule applies to both cratering and fragmentation : the mass ejection rate is $\propto R^{(5-b)}$, and the gravitational reaccumulation of fragments can be taken into account by changing the scaling factor into $R^{(6-b-\alpha)}$ for $R > R_{min}$. For each target asteroid, a relative ***fragment delivery efficiency*** can thus be derived by multiplying the fraction of ejected fragments falling into resonances by a scaling factor proportional to $(R/25\,\mathrm{km})^{(5-b)}$ for $R < R_{min}$, and to $(R/25\,\mathrm{km})^{(5-b)}(R/R_{min})^{(1-\alpha)}$ for $R > R_{min}$. In this way the fragment delivery efficiency is normalized so as to be just equal to the percentage of delivered fragments for $R = 25$ km, and scaled for different sizes according to the rule derived above.

It is worth noting that this simple collisional model predicts that the mass ratio between crater ejecta and break–up fragments is independent of target size, and is simply given by $\frac{b}{2(3-b)} L V_i^2 \zeta^3 = \frac{b\gamma}{3-b}$. For $\gamma = 0.1$ (see Davis et al. 1989; Petit and Farinella 1993) and b ranging between 2 and 2.5 (see later), this ratio ranges between 0.2 and 0.5. These values are somewhat increased if we are interested in the crater/break–up ejecta mass ratio for fragments up to some given size $\overline{r}$, smaller than the size of the largest body included in the crater distribution. As a consequence, for asteroids such as 4 Vesta, which probably have never been shattered but have undergone giant cratering events close to the break–up threshold (Davis et al. 1985), the fragment delivery efficiency given by the scaling rule described above is overestimated only by a factor 2 or 3. Anyway, this argument shows that the contributions to the production of asteroid fragments (and to the meteorite yield) of bodies originated in cratering and break–up events are of the same order, with a possible dominance of break–up fragments by a factor of a few.

We stress that the scaling rules would be different if one assumed size–dependent impact response parameters, such as implied by the scaling theory for collisional fragmentation developed by Housen and Holsapple (1990). Their nominal model (see Fig. 4 in their paper) predicts a variation of the impact strength (hence of the cube of our coefficient ζ) of the order of a factor 100 over the asteroid size range. Thus the number of projectiles capable of shattering any given target may differ by a factor up to $\approx 100^{b/3}$ with respect to the predictions of the model adopted above, and so does the target's lifetime vs. fragmentation and the mass delivered by break–up events per unit time. However, the current strength scaling models are not reliable enough for basing on them a more refined analysis, at least until new experimental or numerical modelling work will have provided independent evidence. But clearly this is another critical area of model uncertainty.

A further serious problem is related to the projectile size distribution index b. For Earth–crossing objects, the lunar cratering record is consistent with $b \approx 2$ (Baldwin 1971; Neukum et al. 1975). Cellino et al. (1991) have analysed different zones of the belt and different size ranges (but always exceeding a suitable "completeness threshold" at a few tens of km, to avoid discovery biases) using the IRAS data base of asteroid albedos and diameters, and have found that b varies in the range from ≈ 1 to ≈ 3. For main–belt asteroids smaller than about 20 km, relevant data come from the Palomar–Leiden Survey (PLS; Van Houten et al. 1970) and from the crater counts on the surface of 951 Gaspra (see chapter by Chapman in this volume) : for PLS asteroids, typically several km in size, b appears to range between about 2 and 2.5, whereas the projectiles impacting Gaspra (between 20 and 60 m in diameter) display a steeper index, $b \approx 3.3$. Thus there is evidence that b is actually variable in a complex way, rather than constant at the 2.5 equilibrium value predicted by Dohnanyi (1969) for a collisionally evolving population with size–independent collisional response parameters.

The unknown size distribution of small asteroids affects in a critical way the relative fragment production efficiencies of asteroids of different sizes. This can be seen by recalling that for constant b, at small sizes the efficiency scaling factor is $R^{(5-b)}$, and since the number of bodies in an interval $(R, R + dR)$ is proportional to $R^{-b-1}\,dR$, for $b = 2$ all equal size intervals would provide the same contribution, and small asteroids would not be very important. On the other hand, for $b = 2.5$ one would get a logarithmic growth of the overall efficiency when the lower limit of the considered size range is decreased, hence the contribution of small asteroids would become dominant (e.g., fragments generated by asteroids with diameters between 100 m and 10 km would be as abundant as those coming from all larger bodies). Thus, in order to assess the contribution of small main–belt asteroids to the flux of Earth–crossing fragments, one should determine their size distribution in a more reliable way than it is possible with currently available data.

4. Resonant routes

After the pioneering studies of the 70's and the early 80's (e.g., Williams 1973; Scholl and Froeschlé 1977; Wetherill and Williams 1979), much work has been devoted by celestial mechanicians in recent years to understand and numerically explore the dynamics of the resonances present in the main asteroid belt and near its boundaries. Two different types of resonances are relevant here : *mean motion resonances*, occurring for nearly–commensurable values of the orbital periods of the minor body and Jupiter, and *secular resonances*, involving commensurability (actually, equality for the three main resonances) between the nodal or apsidal precession rates of the orbit of a minor body (perturbed by the planets) and the eigenfrequencies of the orbits of the planets themselves (perturbing each other). As far as meteorite transport is concerned, the 3/1 mean motion resonance (Wisdom 1983, 1985; Yoshikawa 1990) and the ν_6 secular resonance (Froeschlé and Scholl 1987, 1992; Scholl and Froeschlé 1991; Morbidelli et al. 1993) provide the most effective routes. The other main secular resonances do not cross or approach the most densely populated regions of the main belt (Knežević et al. 1991); and among the other mean motion resonances, the 4/1 resonance (Dahlgren et al. 1992) appears just to contribute to the large chaotic zone lying in the semimajor axis range between 2 and 2.1 AU due to secular resonances, whereas the 5/2 resonance (Hahn et al. 1991; Ipatov 1992) inserts fragments into Jupiter–approaching, comet–like orbits whose lifetime vs. ejection from the solar system or impact onto Jupiter is much less than the typical time needed to hit the inner planets.

The dynamics of fictitious asteroid fragments injected from real asteroids into the resonances has been recently studied both by direct numerical integration of

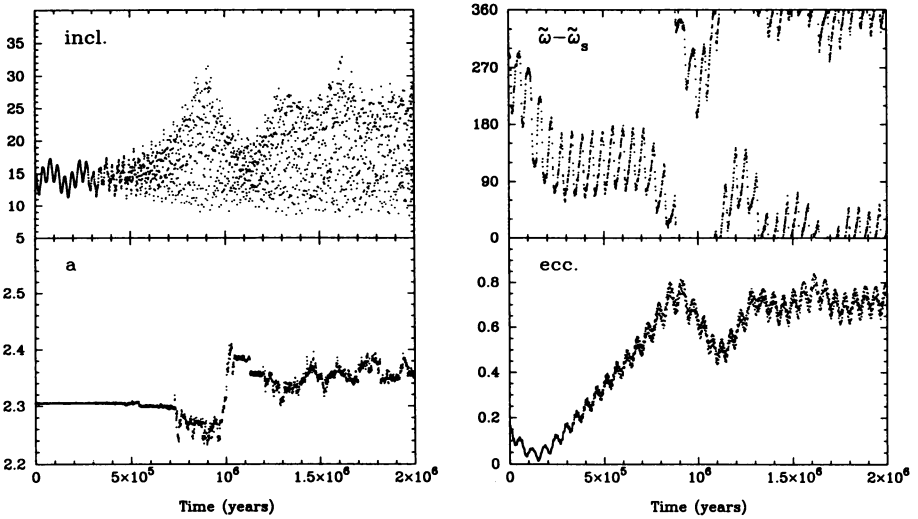

Fig. 1. Orbital evolution of a fragment from 6 Hebe, injected into the ν_6 secular resonance. The figure shows the inclination i (degrees), the semimajor axis a (AU), the ν_6 critical argument $\varpi - \varpi_{Saturn}$ (degrees), and the eccentricity e vs. time over the integration time span of 2 Myr.

their orbits (Farinella et al. 1993b), and through an *ad hoc* analytical theory for the long-term behavior of ν_6-resonant objects (Morbidelli et al. 1993). Of course the former method is more accurate in individual cases, but the latter is much faster (by a factor of several hundreds) and allows to carry out statistical studies on samples of tens of thousands of bodies with reasonable computing time requirements.

The behaviour of two fairly typical resonant fragments from the large asteroid 6 Hebe, as determined by Farinella's et al. (1993b) numerical integrations, is shown in Figs. 1 and 2. It is interesting to note that several real Earth and Mars-crossing asteroids have orbits similar to those of the integrated fictitious fragments. Also, it can be noted that one of the three photographically recorded meteorite falls, named Příbram, yielded the following orbital elements : $a = 2.40$ AU, $e = 0.67$ and $i = 10°.5$ (Ceplecha 1977). Both the semimajor axis and the inclination are very close to the corresponding elements of 6 Hebe. Of course it is not possible to trace back the origin of a meteorite or a near-Earth asteroid by dynamical arguments only, since for chaotic orbits numerical integrations over very long spans of time provide only qualitative information. However, the results shown in Fig. 1, where a Hebe fragment ends up with a Příbram-like orbit within less than 1 Myr, support the idea that this meteorite (an H5 ordinary chondrite) may be a fragment ejected from Hebe, whose eccentricity was pumped up by the ν_6 resonance.

The statistical results obtained with the analytical algorithm of Morbidelli et al. (1993) are summarized in Table I. For each of 20 asteroids close to the ν_6 resonance, the Table columns give the number, the diameter, the taxonomic type and the percentages of fictitious fragments injected into the 3/1, 5/2 and ν_6 resonances

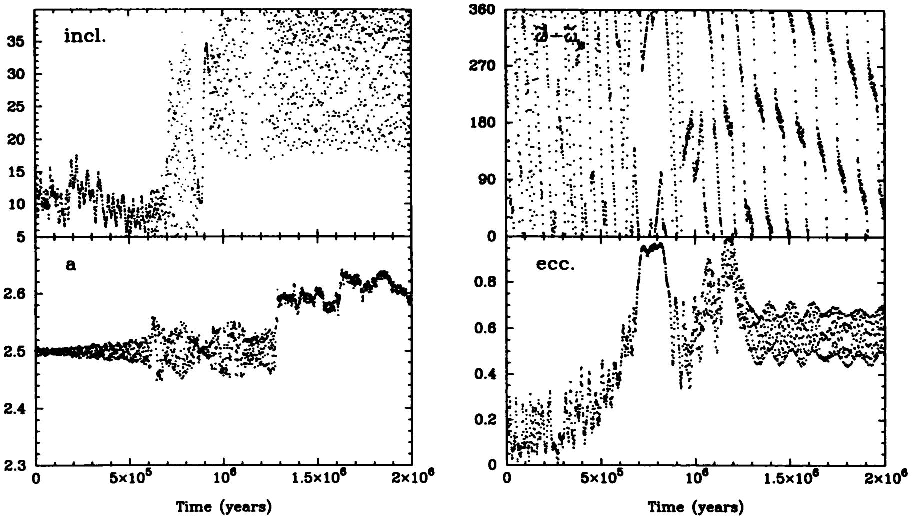

Fig. 2. The same as Fig. 1, but for a Hebe fragment injected into the 3/1 mean motion resonance.

(in the latter case, the maximum eccentricity achieved due to secular resonant perturbations was used to distinguish between Mars- and Earth-crossers). The fragments were assumed to be ejected isotropically at random times from the source body, with a velocity distribution computed from Eq. (1) and $V_{min} = 100$ m/s.

The Table shows that several of these asteroids are likely to be efficient sources of meteorites. This applies in particular to the largest ones, such as 6 Hebe, 304 Olga, 739 Mandeville and 759 Vinifera, because the percentages given in the Table should be multiplied by the scaling factor discussed in Sec. 3. Assuming $b = 2.5$, this implies for instance that Hebe's 3.3% of Earth-crossing fragments (adding up the contributions of the ν_6 and the 3/1 resonances) corresponds to a meteorite yield 11 times that of 1468 Zomba and 980 times that of 2368 Beltrovata. Both b and the diameters of small asteroids are uncertain, but these ratios show clearly that sheer size is very important in determining meteorite yields. Other objects deliver a substantial fraction of their fragments into the 3/1 (623 Chimaera, 1892 Lucienne) and 5/2 (631 Philippina, 907 Rhoda, 1222 Tina) Kirkwood gaps. As we will discuss later, these asteroids should become the targets of detailed spectrophotometric investigations, to assess their similarity to some of the known meteorite classes.

An important remark is that, over a time scale of the order of 10^8 yr, many Mars-crossing (or even Mars-grazing) fragments are likely to end up into Earth-crossing orbits, as a consequence of repeated Mars encounters changing their location in a random-walk fashion with respect to the ν_6 resonance (Wetherill and Williams 1979). While this indirect mechanism requires a longer time for transporting fragments into Earth-crossing orbits, its efficiency with respect to direct resonant transport is increased by the fact that most source asteroids deliver a much larger proportion of Mars-crossers than of Earth-crossers (see Table I). A

TABLE I
Percentages of resonant fragments from 20 real asteroids.

No.	D (km)	Type	3/1	5/2	ν_6 Mars-cr.	ν_6 Earth-cr.
6	192	S	2.4	0.0	7.6	0.9
304	68	C	0.9	0.0	33.2	2.6
623	46	EMPC	18.0	0.0	5.2	0.4
631	60	S	0.3	18.8	1.9	0.6
739	110	EMP	0.0	2.3	35.8	3.5
759	53		1.0	0.3	30.0	8.4
907	66	C	0.4	28.7	1.4	0.6
930	39		3.1	0.0	10.0	1.5
963	11	S	0.1	0.0	14.6	0.7
1222	14		0.0	29.0	19.4	2.5
1468	18		0.1	0.0	99.2	80.0
1892	17		15.1	0.0	2.0	0.4
1916	4	S	0.0	0.0	100.0	13.4
2033	9		0.0	0.0	85.4	3.6
2368	3	SQ	0.1	0.0	99.1	79.3
2548	12		0.7	0.2	31.1	0.8
2604	18		0.4	0.0	72.4	2.4
3402	3		0.0	0.0	97.1	25.8
3833	3		0.0	0.0	96.8	70.9
4095	5		0.0	0.0	47.7	3.3

quantitative assessment of this mechanism requires an algorithm accounting for the effects of close encounters between fragments and planets and of fragmentation *en route* to the Earth, in addition to resonances. This is also needed to model the further evolution of fragments once they have reached Earth–crossing orbits. Since direct numerical integrations of thousands of bodies over 10^8 yr in the inner solar system are still out of reach, refined analytical models for the resonant effects will have to be coupled with Monte–Carlo statistical treatments of close encounters and collisions, building upon the pioneering work of Wetherill (1985, 1987, 1988).

What about the dynamical evolution of real near–Earth asteroids? For a general study and a classification of their amazingly complex behaviour, we refer the reader to Milani et al. (1989). However, due to computing time constraints and the parallel structure of their computer (requiring a fixed stepsize integration method), these authors could only treat the close encounters in an approximate fashion, and the integration time span (2×10^5 yr) was not long enough to detect secular resonances. We have thus repeated some of these integrations, using a variable stepsize method and extending the time span to a few Myr. The results will be discussed in detail in a forthcoming paper (Froeschlé et al. 1994). Figs. 3 and 4 show two interesting examples, involving two near-Earth asteroids whose spectral properties have been recently interpreted as suggesting a relationship to some meteorite classes.

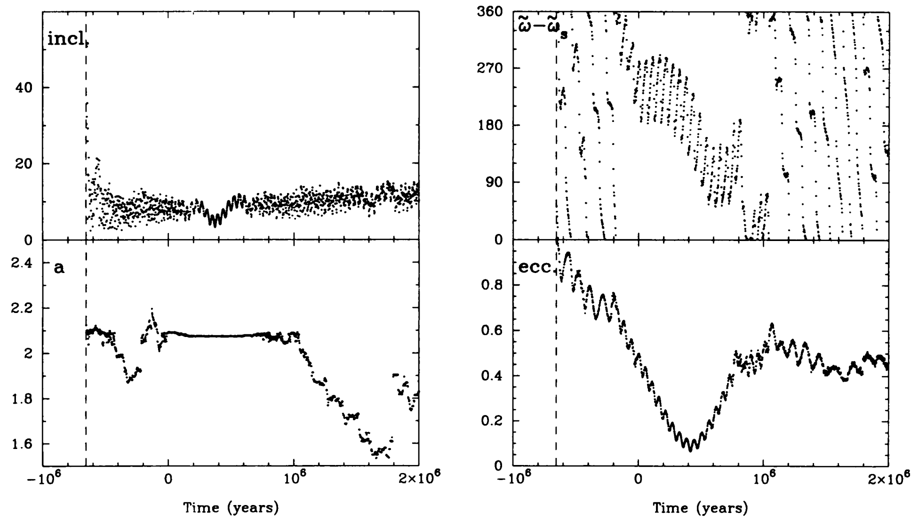

Fig. 3. Orbital evolution of asteroid 3551 (1983 RD) over 3 Myr. The integration backward in time is stopped (dashed line) when the asteroid's distance from the solar centre becomes $< R_\odot$.

Asteroids 3551, 3908 and 4055 have all V–type near–infrared spectra very similar to those of Vesta and of the basaltic achondrite meteorites (Cruikshank et al. 1991). Their osculating orbits are fairly similar, leading to the suggestion that at least 3551 and 3908 are members of an "association" or "stream" which includes also some bright meteors (Drummond and Wisniewski 1990; Drummond 1991), and was generated by the break–up of a common precursor. However, the results of the numerical integrations show that over a few Myr the dynamical evolution of these three objects is very different, suggesting that unless the three objects have been separated very recently ($< 10^5$ yr ago, a very unlikely possibility), the current similarity of the three orbits is coincidental. As shown in Fig. 3, the orbit of 3551 is currently locked into the ν_6 resonance, and as a result the eccentricity reaches Earth–crossing values both in the past and in the future. Close encounters within 10^5 km occur both with the Earth and with Venus, and at $t = -656,000$ yr the eccentricity gets so close to 1 that the asteroid hits the Sun! Of course, this does not imply that the real asteroid is younger than that, nor it proves that it really passed very close to the Sun, as the orbit is chaotic and integrations over so long time spans are not "deterministic" — but it is a good example of the drastic orbital changes caused by the coupling between encounter and resonance effects.

Fig. 4 shows the behavior of asteroid 3103, which has been suggested by Gaffey et al. (1992) to be related to the enstatite achondrite meteorites and to the E–type

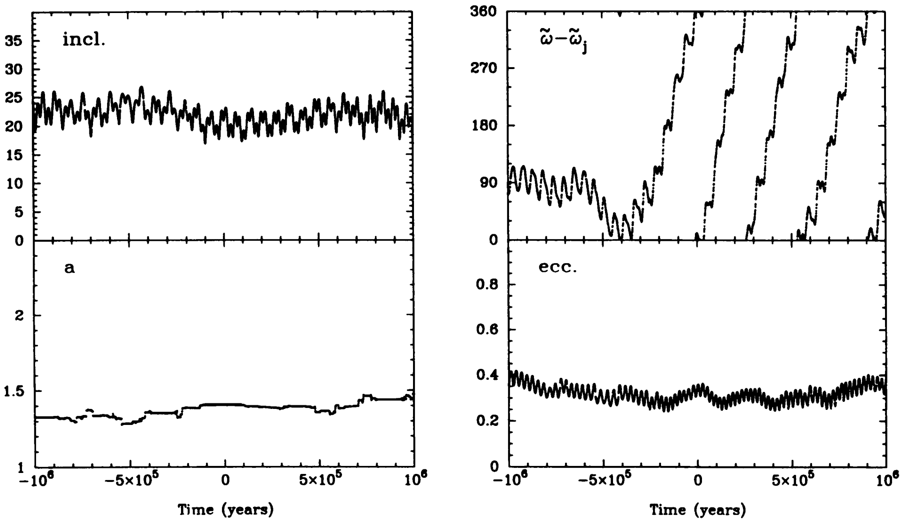

Fig. 4. Orbital evolution of asteroid 3103 (1982 BB) over 2 Myr. The evolution of the ν_5 critical argument $\varpi - \varpi_{Jupiter}$ of the ν_5 is shown here in the right upper plot.

asteroids present in the Hungaria region (at the innermost edge of the belt, with semimajor axes $\approx$ 1.9 AU). In the classification of Milani et al. (1989), this is a fairly typical Geographos-type orbit, whose encounter-driven evolution is slowed down by the large inclination. The 3/5 mean motion resonance with the Earth detected by Milani et al. appears to be short-lived; however, some 0.5 Myr in the past the orbit gets locked into the ν_5 secular resonance. There is no sign that this object may have evolved from the Hungaria region, but our integration time span is still much shorter than the impact lifetime of the asteroid.

These numerical experiments suggest that the orbital evolution of Earth-approaching asteroids and meteorites is diverse, complex and caused by several dynamical mechanisms acting over different time scales. In particular, secular resonances often play an important role. Due to the properties of chaos, there is no way of "going back in time" to the original fragment ejection event in the main belt just by integrating backwards the equations of motion. But the relative importance of the different dynamical pathways can be probably assessed with more confidence than it has been done so far.

5. Efficiency of the delivery and transport process

Is the total flux of Earth-impacting objects predicted by fragment delivery models similar to that observed? As argued by Wetherill (discussion following Greenberg and Nolan 1989), achieving an order-of-magnitude agreement with the observed flux is an important constraint for meteorite delivery models, in spite of the considerable uncertainty on the value of the flux itself. Although Farinella et al. (1993a) modeled only the fragment injection into resonances, and did not deal with their further dynamical and collisional evolution, some order-of-magnitude estimates can be based on their results. According to them, the total fragment mass injected into the resonant strips is of the order to 100 times the yield of a single asteroid 50 km across. Let us assume that the average lifetime of such a body is of $\approx 2 \times 10^9$ yr, derived from an average intrinsic collision probability of 2.85×10^{-18} km^{-2} yr^{-1} for main-belt asteroids (Farinella and Davis 1992) and a population of 250,000 potential disrupting projectiles. Although probably uncertain by plus or minus a factor two, due to our poor knowledge of asteroid impact strengths and of the relevant projectile flux, this lifetime is consistent with Wetherill's (1985) Eq. (6) and with the current estimates for small asteroids (Farinella et al. 1992). Of the 8×10^9 kg/yr of material thus injected in the resonances, only a few percent will reach the Earth, due to collisional comminution *en route* (the observed ratio of about 10 between the lifetimes of planet-crossing objects against impacts on the planets and the typical exposure ages of ordinary chondrites suggests that most asteroid fragments are broken up again while in planet-crossing orbits) and other possible outcomes of the dynamical evolution (impact against other planets, ejection from the solar system). This small "survival factor" is in rough agreement with Wetherill's (1985, Tables 4 and 5) Earth impact efficiencies of $\approx 10^{-4}$ for random ejecta from asteroids whose fragments can reach the 3/1 resonance, because in Farinella's et al. (1993a) model the average fraction of fragments delivered to the resonances by all the asteroids, weighted to account for the source size as described in Sec. 3, is of the order of a few percent. Thus, within the assumptions stated above, the model predicts an Earth flux of asteroid fragments of the order of 10^8 kg/yr, in good agreement with the estimate of $\approx 1.7 \times 10^8$ kg/yr derived by Ceplecha (1992) for all the interplanetary bodies hitting the Earth (including those of cometary origin). Note that the flux of bodies in the meteorite size range (up to about 1 meter) is about two orders of magnitude smaller (Halliday et al. 1984; Ceplecha 1988); this corresponds to the fact that only $\approx 1\%$ of the mass of asteroid fragments lie in the meteorite size range, according to the typical size distribution of fragments from hypervelocity impacts.

6. Evidence from spectrophotometry

In the last few years, a growing amount of work has been dedicated to comparing asteroid and meteorite properties, in order to determine the likely composition and thermal history of asteroids and to find out candidate sources for the different meteorite classes. In particular, the comparison of asteroid and meteorite spectra has been based on new, high-quality CCD observations (Vilas and McFadden 1992; see also the chapter by Burbine and Binzel in this volume). Principal analysis classification of the two data samples has been performed (Britt et al. 1992), and the implications of such comparisons have been carefully assessed (Fanale et al. 1992; McSween 1992; Keil et al. 1992; Clark et al. 1992). Laboratory work on meteorite spectra has explored such specific problems as the effects of mixing different mineralogic types (Hiroi et al. 1993) and using powdered meteorite samples (Salisbury et al. 1991). Specific comparisons between individual asteroid and meteorite classes, based on spectral data, has shown that a number of intriguing similarities indeed exist, involving both main–belt (Hiroi and Takeda 1990; Burbine et al. 1992) and near–Earth asteroids (Cruikshank et al. 1991; Gaffey et al. 1992). For more details on this work, we refer the reader to the reviews by Wetherill and Chapman (1988), Lipschutz et al. (1989) and Gaffey et al. (1989, 1993). In this context, two issues have important implications on the meteorite delivery and transport studies : the new findings on the Vesta family and the origin of basaltic achondrites, and the ongoing debate on the identity of the ordinary chondrite parent bodies.

Owing to its peculiar spectral features, it has long been suggested that 4 Vesta is the parent body of basaltic achondrites (e.g., Drake 1979; Greenberg and Chapman 1983). As we already mentioned, Cruikshank et al. (1991) have recently found that three km–sized near-Earth asteroids display reflectance spectra nearly identical to that of Vesta (hence they have been classified as V–types, a class whose only sizable main–belt member is Vesta itself), and this supports the idea that fragments from Vesta can be inserted into planet–crossing orbits. The main difficulty with this possibility has always been the high ejection velocity — at least some 600 m/s — needed to reach a resonant zone starting from Vesta; this led Wetherill (1987) to the conclusion that Vesta's Earth–impact efficiency must be very low. Farinella et al. (1993a) have confirmed that the average ΔV of fictitious Vesta fragments reaching the 3/1 resonance is about 700 m/s (and exceeds 1 km/s for ν_6); but they have also found that unless the size distribution index b is large and V_{min} is small, its large size makes Vesta a relatively efficient fragment deliverer. With $V_{min} = 100$ m/s, some 2.4% of the fragments escaping from Vesta fall in the 3/1 resonance and may become Earth–crossers; as a consequence, Vesta's fragment delivery efficiency accounts for 1% to 6% of the total from the main asteroid belt. Although the delivery efficiency might be overestimated by a factor ≈ 3 if Vesta has never been shattered (see Sec. 3), in order of magnitude these results are consistent with the observed abundance of basaltic achondrite falls.

From the point of view of cratering mechanics, it is not clear how unshocked fragments can be accelerated to speeds of many hundreds of m/s (see Greenberg and Chapman 1983, p. 475). However, both Zappalà et al. (1990) and Bendjoya et al. (1991) found that Vesta is the major body of a dynamical family, which includes many smaller members between 5 and 10 km in size. Recent observations by Binzel and Xu (1993) have revealed that the spectra of these minor family members (and also of some neighbouring objects, located between the Vesta family and the 3/1 Kirkwood gap) have the distinctive absorption bands of basaltic achondrites. This implies that large fragments have indeed been ejected from Vesta during a giant cratering event, at speeds well exceeding the escape velocity of ≈ 300 m/s. Note also that extrapolating down to 1 km diameter the family size distribution with $b = 2.5$ (typical for the families, according to Cellino et al. 1991) implies that thousands of km–sized fragments were produced in the family–forming event, hence several tens of them could reach the 3/1 resonance and become Earth–crossers. A similar mechanism might have worked for other families found to lie in the vicinity of resonances (Cellino and Zappalà 1993).

On the other hand, a convincing and unequivocal solution is still missing for the so–called "spectrophotometric paradox" (Wetherill and Chapman 1988), namely the fact that ordinary chondrites, which account for ≈ 75% of all the observed meteorite falls, cannot be matched with the typical reflectance spectra of any common asteroid taxonomic type (and in particular of S-types, most abundant in the inner belt and earlier considered as the most plausible parent bodies). Two alternative possibilities are currently favoured. Farinella et al. (1993a,b) have suggested that most ordinary chondrites may come from just a few sizable S-type asteroids (such as 6 Hebe) having high fragment delivery efficiencies and chondritic compositions, unlike those of most other S-types. This explanation would be consistent with the evidence from meteoritic groupings, which suggests that almost all ordinary chondrites come from a small number — possibly as few as three — of original asteroids (Lipschutz et al. 1989), and also with their diameters inferred from meteorite cooling histories (between 100 and 300 km; see Pellas and Storzer 1981; Pellas and Fiéni 1988). The origin of many ordinary chondrites in a few large-scale collisional events is also suggested by the observed clustering of the cosmic-ray exposure ages (Crabb and Schultz 1981; Marti and Graf 1992).

An obvious observational test for this explanation is that of obtaining for the candidate asteroids quoted above new, detailed spectrophotometry data, capable of clearly constraining their composition, as in the work reviewed by Gaffey et al. (1989) on 8 Flora, 15 Eunomia and some other bodies. Interestingly, Gaffey et al. (1994) have recently reported that a small subtype of the S-types asteroids (named S(IV), and accounting for just ≈ 10% of all S-types) display silicate assemblages consistent with, although not specifically diagnostic of, undifferentiated ordinary chondritic assemblages. The S(IV) subtype includes 6 Hebe, and is the only S subtype showing a significant concentration in the semimajor axis range between 2.3 and 2.6 AU, where both the 3/1 and the ν_6 resonances provide efficient transport routes to Earth-crossing orbits (see Sec. 4). However, the reason for this preferential location is quite puzzling, if the S(IV) subgroup includes the only S-type asteroids having escaped differentiation.

The alternative explanation is that ordinary chondrites come from the numerous main-belt population with diameters smaller than a few tens of km, for which few spectral data exist (Bell et al. 1989; Fanale et al. 1992), assuming that they have escaped the primordial heating events that led to (partial or total) melting of the larger asteroids. Binzel et al. (1993) have recently found that the 7-km asteroid 3628 Boženicová, located just outside the 3/1 Kirkwood gap, has the distinctive spectral signature of ordinary chondrites (even more than 1862 Apollo and a few other Earth-approachers, classified in the Q taxonomic type). However, this finding does not really support the idea that ordinary chondrites come from "primitive" small asteroids. In the first place, no other small asteroid in a sample of 80 surveyed by Binzel et al. shares the ordinary chondrite spectral features, and this contrasts with the large abundance of this class among the meteorite falls. Secondly, asteroids of size ≈ 10 km have collisional lifetimes much shorter than the age of the solar system (Farinella et al. 1992; see also the chapter by Chapman in this volume). If so, where are the sources for the small ordinary chondrite asteroids?

A compromise solution between the two explanations may be that the surfaces of large ordinary chondrite parent bodies are somewhat camouflaged, and only when one observes fresh fragments excavated from them the material with the diagnostic spectral features can come into view. However, more observational evidence is clearly needed to settle this important issue.

7. Open problems and future work

Future work on the subject of this paper should include a number of different issues and techniques. First, the real efficiency of the different dynamical routes between the asteroid belt and the Earth should be tested by extensive numerical experiments, both to explore in a more systematic way the relevant parts of the phase space and to determine the fate of fictitious fragments ejected — according to some plausible model of collisional outcomes — from specific asteroids, which look as promising candidate sources for meteorites and near-Earth asteroids. Second, the same asteroids should be the target of further, detailed astronomical observations, aimed at determining their physical properties, surface morphology and, in particular, their likely composition and its consistency with the assumed meteorite counterparts. Another problem whose crucial importance is apparent for the understanding of many issues related to the evolution of asteroids, and therefore should be addressed by new, *ad hoc* observational surveys, is the size distribution of small (say, km-sized) main-belt asteroids. Finally, experimental and modelling work is still needed in the field of collisional physics, in order to better understand the mechanisms of fragment acceleration and the way some basic impact-response parameters (strength, ejecta velocity distribution, crater excavation efficiency) may vary with size and material properties.

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