Meteoritics & Planetary Science 34, A161–A167 (1999)

Reviewing the Yarkovsky effect: New light on the delivery of stone and iron meteorites from the asteroid belt

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(Received 1998 February 5; accepted in revised form 1999 January 14)

Abstract–We give a nonmathematical review of recent work regarding the Yarkovsky effect on asteroidal fragments. This effect may play a critical, but underappreciated, role in delivering meteorites to Earth. Two variants of the effect cause drifts in orbital elements, notably semimajor axes. The "classic" or "diurnal" Yarkovsky effect is associated with diurnal rotation at low obliquity. More recently, a "seasonal" effect has also been described, associated with high obliquity. Studies of these Yarkovsky effects are combined with studies of resonance effects to clarify meteorite delivery. If there were no Yarkovsky drift, asteroid fragments could reach a resonance only if produced very near that resonance. However, objects in resonances typically reach Earth-crossing orbits within a few million years, which is inconsistent with stone meteorites' cosmic-ray exposure (CRE) ages (5–50 Ma) and iron meteorites' CRE ages (100–1000 Ma).

In the new view, on the other hand, large objects in the asteroid belt are "fixed" in semimajor axis, but bodies up to 100 m in diameter are in a constant state of mixing and flow, especially if the thermal conductivity of their surface layers is low. Thus, small asteroid fragments may reach the resonances after long periods of drift in the main belt. Yarkovsky drift effects, combined with resonance effects, appear to explain many meteorite properties, including: (1) the long CRE ages of iron meteorites (due to extensive drift lifetimes in the belt); (2) iron meteorites' sampling of numerous parent bodies; (3) the shorter CRE ages of most stone meteorites (due to faster drift, coupled with weaker strength and more rapid collisional erosion); and (4) the abundance of falls from discrete impact events near resonances, such as the 8 Ma CRE age of H chondrites. Other consequences include: the delivery of meteorite parent bodies to resonances is enhanced; proportions of stone and iron meteorites delivered to Earth may be different from the proportions at the same sizes left in the belt, which in turn may differ from the ratio produced in asteroidal collisions; Rabinowitz's 10–100 m objects may be preferentially delivered to near-Earth space; and the delivery of C-class fragments from the outer belt may be inhibited, compared to classes in other parts of the belt. Thus, Yarkovsky effects may have important consequences in meteoritics and asteroid science.

THE "CLASSIC" OR "DIURNAL" YARKOVSKY EFFECT

The "classic" Yarkovsky effect is a change in orbital elements, notably semimajor axis, of a rotating asteroidal body in the size range of centimeters up to tens of meters, due to asymmetries between the longitudes of sunlight absorption and the longitudes of maximum thermal re-radiation. Because the "afternoon" temperature tends to be higher than in the "morning" quadrant, the thermal radiation produces a nonradial force on the body. This "classic" effect, due to rotation, has been called the "diurnal" Yarkovsky effect to distinguish it from other effects discovered later (see below). The diurnal effect is maximized at zero (or 180°) obliquity of the spin axis and vanishes at 90° obliquity. An interesting quality of the classic Yarkovsky effect is that it depends on the sense of rotation—prograde or retrograde. Prograde rotation causes a drift away from the Sun; retrograde causes a drift toward the Sun. Reorienting collisions could thus cause a random walk evolution in the orbit of a fragment.

The "classic" Yarkovsky effect was discovered around 1900 by the Russian engineer, I. O. Yarkovsky (Neiman *et al.*, 1965). Yarkovsky's work was soon forgotten and the original publication has apparently been lost. However, the effect was resurrected by the prescient planetary scientist, Ernst Öpik (1951), who reminisced in a characteristic way that he had seen Yarkovsky's work "in a pamphlet published in Russian at St. Petersbourg [*sic*] about 1900; the writer read the pamphlet about 1909 and can refer to it only from memory." Öpik then proceeded to re-derive the effect and went on to point out its importance in mobilizing meter-scale asteroid debris in the solar system. A similar re-derivation was performed by Radzievskii (1952).

The work of Yarkovsky, Radzievskii, and Öpik was virtually ignored for some decades until Peterson (1976) reexamined it with new calculations (see also review by Burns *et al.*, 1979). Peterson pointed out that the effect is much stronger on stone (especially dark stones) than on iron meteorites, because iron meteorites have much larger thermal conductivity, tending to erase the asymmetry mentioned above. (This statement is complicated, however, by dependencies on spin rate and regolith-induced thermal inertia as well as conductivity.) For rotation periods, Peterson adopted a fixed characteristic asteroid value of 5 h (though for small bodies this is questionable—see below). Peterson concluded that such a rotating 1 m diameter black stony sphere required 30 Ma to move from 3 AU to 1 AU, whereas a similar iron body took roughly 1600 Ma in his calculation. For larger stony bodies, Peterson noted that the timescale is proportional to size; a 10 m black stone would thus take 300 Ma to move from 3 AU to 1 AU. This number assumes no collisional reorientation or consequent random walk effects. Below a size of ~0.5 m for stone and 2.4 m for iron meteorites, Peterson's result is size-independent.

Peterson noted that the timescales he calculated for stone and iron meteorites were similar to the actually observed cosmic-ray exposure (CRE) ages for these bodies (Wasson, 1974, 1985; Marti and Graf, 1992); thus he suggested that direct drift from the belt to Earth by the Yarkovsky effect might be the dominant mechanism for the delivery of meteorites to Earth.

Later workers realized that Jovian resonances are a major, fast-acting agent in moving fragments from certain parts of the belt (or more accurately from certain parts of the orbital element phase-space) directly into planet-crossing orbits. Thus, we now see that the importance of the Yarkovsky effect may be to deliver small fragments from their points of collisional origin in the belt to nearby resonances. What matters in determining CRE timescales is not the time to drift from the belt to 1 AU, but the time to drift from a source region (a collision site) in the belt to the nearest resonance that may deliver the object to Earth. Instead of moving 2 AU to reach an Earth-crossing orbit, the object might typically need to move only 0.2 AU in orbital semimajor axis to reach a resonance, and even less if the parent body already lies in the vicinity of one of the main resonances.

In either case, according to Peterson, the rate of movement for bodies in the centimeter to meter diameter range was as much as 50 to 100 times faster for stone than for iron meteorites. Although Peterson's thermal models, based on a cylindrical geometry, provided a good approximation to the more realistic spherical case (later dealt with by Afonso *et al.*, 1995, and Vokrouhlický, 1998, who noted that the Afonso *et al.* derivation contained some errors), we now realize that the quantitative results obtained by Peterson depended sensitively on his specific assumptions concerning the slow spin rate of the fragments and the absence of collisional effects. The actual time for Yarkovsky drift to deliver a body to a resonance will involve collisional spin-up and pole reorientations resulting into random walk effects, as discussed below.

RECENT STUDIES OF RELATED EFFECTS: THE "SEASONAL" YARKOVSKY EFFECT

In recent years, both the Yarkovsky effect and the timescale of orbital change around resonances have been examined in more detail, and the story has become somewhat more complex. Rubincam (1995a), following his previous work on the *LAGEOS* artificial satellite (Rubincam, 1987, 1988; see also Farinella *et al.*, 1996), considered a new variant of the Yarkovsky effect: a component of the force associated with thermal re-radiation acting along the polar axis for asteroids with nonzero obliquity. It arises because the hemisphere experiencing "autumn" is hotter (and radiates more thermal energy) than the hemisphere experiencing "spring." Rubincam (1995b) and Farinella *et al.* (1998) called this the "seasonal" Yarkovsky effect, to distinguish it from the "diurnal" effect associated with "low-obliquity" rotation. A nice illustrative scheme of the way the perturbing forces associated with the two effects act on heliocentric orbits can be found in Rubincam (1998).

The seasonal Yarkovsky effect is maximized at 90° obliquity and vanishes at zero obliquity. Unlike the diurnal effect, it does not depend on spin rate and it does not ever produce increasing semimajor axis; the seasonal effect produces only inward drift. For a regolith-free basaltic asteroid of 20 m in diameter, Rubincam found the time to reduce the semimajor axis from 3 to 1 AU is ~800 Ma, and a still longer time for an iron meteorite of this size. However, chondrites have much shorter observed CRE ages, often <20 Ma, and he therefore concluded that the seasonal Yarkovsky effect is not important for chondrites. Rubincam (1995a) also devoted one paragraph to the fact that asteroids do not have to go from 3 to 1 AU by this effect, but only from mid-belt to a resonance. He cited a characteristic time of the order 100 Ma for a 10 m scale body to drift a few tenths of an astronomical unit to a resonance. Although Rubincam thus opened the door to the possibility of Yarkovsky drift delivering small bodies to resonances, he mainly emphasized longer timescales associated with drift over relatively large distances by fairly large bodies (10 to 100 m in diameter; see also Rubincam, 1998).

Farinella *et al.* (1998) recognized shorter timescales associated with smaller (1 m) bodies starting closer to resonances. They computed drift rates for a variety of parameters, including both stone and metal bodies, various sizes, diurnal (low obliquity) and seasonal (high obliquity) cases, fast and slow rotation, and regolith *vs.* non-regolith surfaces. That work gives us better understanding of the rate of drift of various types of objects in the belt. An important point to note in summary is that the dominant effect on any given object could alternate between diurnal and seasonal if collisions alter the rotation state. When the seasonal effect dominates (obliquity near 90°), the drift would be slowly inward toward the Sun; but if collisions place the body in various diurnally-dominated states (obliquity near 0° or 180°), it could random walk inward and outward, with the rate of this random walk higher for longer spin periods. Some of the steps in the overall random walk from the combined effects could be traversed much more rapidly than others.

YARKOVSKY EFFECTS AND THE DRIFT TOWARD RESONANCES

While work on the Yarkovsky effect was expanding, various authors considered the behavior of objects in or near resonances. Early work (Wisdom, 1985; Wetherill, 1985, 1987; Greenberg and Nolan, 1989) suggested that long timescales (~100 Ma) for Earth delivery could arise when objects were moved by resonances onto Mars-crossing orbits, then perturbed by Mars encounters, yet also noted that resonances could directly send objects onto Earth-crossing orbits in as little as 1 Ma.

As it began to be found that the timescale to move objects from their original location in a resonance in the main belt to Earth was much shorter, of the order 1 Ma, long CRE ages began to be seen as a problem. The problem was made more acute when it became clear that most bodies injected into the 3:1 and ν_6 main-belt resonances collide with the Sun (Farinella *et al.*, 1994), with almost all the remainder ejected by Jupiter. This has the consequence that only ~1% of the resonant asteroid fragments eventually collide with the Earth, and almost all do so within a few million years from their injection into resonance. The short transfer times from resonances have been recently confirmed by Migliorini *et al.* (1997a) and Gladman *et al.* (1997), who numerically computed the evolution of hundreds of test bodies in order to improve the statistical knowledge of the resonant transfer mechanism.

Using these results, Morbidelli and Gladman (1998) investigated several possible scenarios of origin and transport for meteorites. They found that the orbital distribution of observed chondritic fireballs (Wetherill and ReVelle, 1981; Halliday *et al.*, 1996) can be reconstructed assuming a constant injection rate into the ν_6 and 3:1 resonances (with a yield five times higher for the 3:1 resonance). The typical fall times of meteorites (67% in the afternoon) are consistent with such a model. However, this scenario predicts that unless there is a preexposure phase in the main belt, most meteorites would have exposure ages of only a few million years, which is inconsistent with observed longer ages. In general, these ages are 100 to 1000 Ma for most iron meteorites, 5 to 50 Ma for most stone meteorites, about 7–8 Ma for a subgroup of H chondrites clustered in CRE age (accounting for ~15% of all falls).

Morbidelli and Gladman thus concluded that meteorites cannot be directly injected into the resonances by the event that releases them from their shielded positions in parent bodies but must have some mechanism for delaying resonance arrival for periods up to tens of million years for stone meteorites and up to 1000 Ma for iron meteorites, after their release.

Thus, conventional models without Yarkovsky drift don't explain (a) how iron meteorites could experience hundreds of million years of CRE, and (b) why iron meteorites have distinctly longer CRE ages than stone meteorites. Wasson (1985) explained item (b) by citing weaker strengths and quicker impact-erosion times for stone meteorites, but this does not explain (a). The Yarkovsky effect, combined with differential impact erosion, explains these anomalies because it allows fragments of 0.1 to 100 m scale to be created relatively far from resonances and then to drift in the belt until they reach resonances. Because iron meteorites are stronger and have slow drift rates, they may escape break-up and drift for tens of millions of years to 1000 Ma before reaching a resonance, depending on initial location. Because stone meteorites are weaker, the meter-scale mobile bodies may be destroyed sooner than this, giving us a shorter range of observed CRE ages and preferentially sampling parent asteroids that are near resonances. Recent break-ups near resonances could create clusters of objects. The 8 Ma old group of H chondrites is consistent with a recent break-up near a resonance, whereas iron meteorites may sample many parent bodies in various parts of the belt.

A NONLINEAR PROBLEM OF COLLISIONAL EVOLUTION

The work described above opens the door to new and more sophisticated modeling of the evolution of asteroid fragments. However, this modeling will be complex because of the feedback between Yarkovsky clearing of small fragments from the belt and the erosion and collision rates among small fragments.

As Rubincam (1995a) noted briefly, Yarkovsky drift in semimajor axis may not be continuous, because collisions may change the rotation rates and spin axes on timescales less than the removal time for such bodies. This is a nonlinear problem. The rate of reorientation by collisions depends directly on the number density and size distribution of smaller objects. To estimate the number density of small objects, Farinella *et al.* (1998) extrapolated Dohnanyi's (1969) equilibrium size distribution to small sizes and found that collisions would completely reorient meter-scale bodies on timescales of several million years, and at the same time would spin them up to much shorter periods (tens of seconds) than the 5 h assumed by Peterson (1976). However, as noted by Hartmann and Ryan (1996), Yarkovsky effects may remove small (sub-meter) bodies efficiently and change these results; if the belt is significantly depleted in small bodies, then both the reorientation rates and the erosion rates could drop drastically among the meter-scale fragments. This would lengthen the mean free path between collisions, increasing the chance of direct drift to resonances from a given starting point, rather than a slower random walk.

In general, the question of random walk to a resonance *vs.* direct drift depends on the flux of smaller impactors, which controls the rate of change of rotation states. In any case, the stone meteorites tend to move about faster than iron meteorites in the size ranges we have considered, but the stone meteorites' survival depends again on the flux of small eroding impactors.

Obviously it is difficult to reduce such a complex situation to a single diagram, but Fig. 1 gives a brief overview. In some ways, this is a "best estimate overview," because we must choose the characteristics that we believe are most realistic for the 0.1–100 m size range of bodies in the figure. For example, unlike Peterson and other authors, we do not assume that small bodies have the mean rotation period of 5 h measured for large asteroids but rather assume

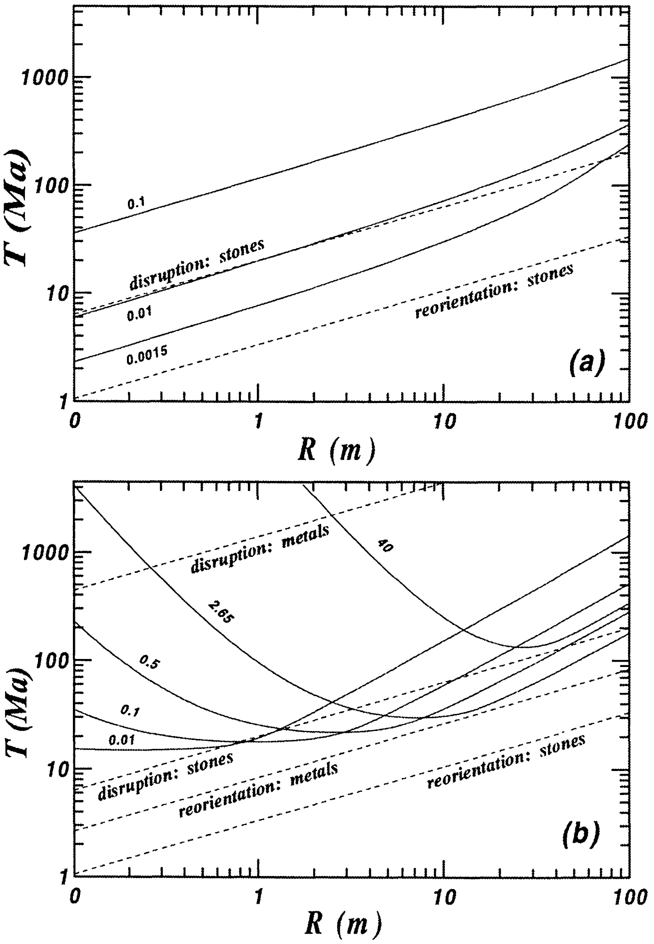

FIG. 1. The figures show the time (in million years) required by the Yarkovsky drift to move by 0.05 AU in semimajor axis an asteroid fragment of radius R (in meters, horizontal axis), starting in the inner asteroid belt at ~2.25 AU. The two plots refer to the diurnal (a) and seasonal (b) effects, respectively. We have also plotted (dashed lines) the curves corresponding to the estimated spin axis reorientation and disruption times *vs.* size. All the parameters have been chosen according to Farinella *et al.* (1998), and we have used a simple statistical model for the effect of random reorienting events (see text). Because the thermal conductivity K of the surface material is the most important parameter governing the efficiency of the two variants of the Yarkovsky effect, different curves are shown for different values of K, ranging from a very low value derived for the lunar regolith (0.0015 to 0.01 W/m/K) to values typical of porous meteorites (0.1 to 0.5 W/m/K) and bare-rock basalts (2.65 W/m/K), up to values typical of metals (40 W/m/K).

(from our lab work and from common experience) that small fragments generated by collision rotate much faster. (Following Farinella *et al.*, 1998, we adopt $P = 5$ h × (D/1 km), which is 18 *s* for a 1 m body. This has been nicely confirmed by the recent discovery of the ~10 min spin period of the 40 m near-Earth asteroid 1998 KY_{26} (see Ostro *et al.*, 1998). Also, the ~50 cm Lost City fireball had a spin period of 3.3 s according to Ceplecha (1996). On the other hand, since a millimeter-thick dusty or granular layer with a regolith-like (low) thermal conductivity could strongly affect the intensity of the Yarkovsky effect, we consider the possibility that such a low-conductivity layer is present on the surfaces. Also, in the bare-rock case, we take into account that a range of thermal conductivity values has been measured in the laboratory for real ordinary chondrites (Yomogida and Matsui, 1983). With these assumptions, Fig. 1 plots the time for objects of different sizes to move by direct drift over a characteristic distance of 0.05 AU, representing a typical distance from a point of collisional origin in the asteroid belt, such as asteroid 6 Hebe (Farinella *et al.*, 1993; Migliorini *et al.*, 1997b), to the nearest resonance. The diurnal and seasonal mechanisms are both represented in Fig. 1a,b, respectively, where we have also shown the collisional disruption and spin reorientation times as a function of size, according to Farinella *et al.* (1998).

In deriving these results, we have taken into account random walk effects as follows. The semimajor axis of a large number of test particles has been evolved under Yarkovsky effects, reorienting at random their spin axes at time steps equal to the characteristic reorientation times shown in the figures. Then, the average time to move by $\Delta a = 0.05$ AU with respect to the initial location (at $a = 2.25$ AU) has been computed. (Of course, for the diurnal effect, Δa can be either positive or negative.) Note that these results can be easily scaled to values of Δa smaller or larger than 0.05 AU, as the corresponding time span grows proportionally to Δa for the seasonal effect and to Δa^2 or the diurnal effect (at least when the distance to a resonance is large compared with the mean free path between reorientations). For a real body, of course, both effects would be present at the same time and the total drift rate would be the sum of those for the two effects. Note that here we have neglected the feedback effect between Yarkovsky drift rates and collisional time scales, which in reality may play an important role (as discussed above).

The seasonal curves show a minimum timescale (maximum drift rate) because at small sizes the seasonal thermal wave is erased by conduction through the object. The diurnal timescale decreases with size because of our assumption that spin rate is inversely proportional to size, causing the diurnal thermal wave to remain significant at small sizes. Peterson's (1976) conclusion that the diurnal drift rate became constant at small sizes was due to his assumption of a size-independent spin period.

The figures show that in the lower range of the thermal conductivity K (applicable to very loose regoliths), the diurnal effect is more efficient; whereas the seasonal one is dominant for $K > 0.1$ W/m/K. In the transition range ($K \sim 0.01$ W/m/K), the diurnal effect is more important for small bodies (diameter <1 m) and *vice versa*. However, the relative importance of the two effects depends on the assumed Δa. Due to the different dependence on Δa, the seasonal effect is more efficient to perform relatively large semimajor axis displacements. The important conclusion here is that in many cases the Yarkovsky drift times are shorter than or comparable to the disruption times, implying that the corresponding bodies can easily move by Δa ~0.05 AU (or more) in semimajor axis before being shattered.

Moreover, this figure demonstrates that the Yarkovsky effects can move meteorite-scale fragments across characteristic belt distances to a resonance on timescales comparable to the observed CRE ages. In other words, decameter- to meter-scale fragments can easily drift in the main belt for tens of million years for stone meteorites and hundreds of million years for iron meteorites. In practical reality, longer and shorter timescales can be achieved, depending on random walk effects and the distance between the source body and a resonance. Moreover, disrupting collisions eliminate the target bodies but at the same time produce new generations of fragments, forming swarms of small bodies which move at different rates through the belt. In general, drift rates are faster for stone but iron meteorites have collisional lifetimes much longer than stone meteorites, so they can move farther before being disrupted.

Some examples from Fig. 1 are instructive. A 1 m radius bare-rock stony body with conductivity typical for ordinary chondrites (Yomogida and Matsui, 1983) would take 20–50 Ma to move by 0.05 AU at the seasonal rate, comparable to its disruption lifetime. In this case, the diurnal effect is comparatively inefficient, because of the frequent spin-reorienting collisions. We conclude that these bodies can be injected into resonances only when starting from their vicinity. Of course, here "starting" refers to ejection either from sizable asteroids—such as 6 Hebe (Farinella *et al.*, 1993), 13 Egeria, and 19 Fortuna (Burbine, 1998)—or from decameter-sized immediate parent bodies, which may have themselves drifted across the belt while shielding their interiors from cosmic-ray irradiation. On the other hand, for meter-sized bodies with very low conductivities, the diurnal effect becomes very efficient, and they may drift from any starting location all the way to a resonance in a few tens of million years. Moreover, as we have already noted, higher stone survival and ejection rates would occur if the belt were depleted in erosion-causing meter-scale objects; the width of the zone around a resonance in which a stone could reach the resonance would increase in that case.

In any case, the stone meteorites created closest to resonances could drift all the way to a resonance and be ejected before destruction. Collisional events on asteroids very close to resonances (*e.g.*, Hebe) can inject bodies directly into the resonance or close enough to it to reach Earth on short timescales <10 Ma. This could explain the 7–8 Ma peak of CRE ages that is observed in the CRE age distribution of H chondrites (Graf and Marti, 1995). The peak has an intriguing structure. The H5 chondrites in the peak are observed to fall preferentially in the morning (61%—a unique case among meteorites!); whereas the H3, H4, and H5 objects fall preferentially in the afternoon (72%, higher than the average for all chondrites). According to Morbidelli and Gladman (1998), the first number is consistent with a scenario where H5 chondrites were injected directly into the ν_6 resonance 7–8 Ma ago, whereas the second number is consistent with H3/4/6 objects drifting into the resonance from a more distant source that required 3–4 Ma of drift before reaching the resonance. Possibly meteoroids of the latter group were ejected with speeds that did not lead to direct injection and required an intermediate phase of 3–4 Ma of Yarkovsky drift before hitting the resonance.

As another example, a 20 m radius solid iron meteorite would take an estimated 500 Ma to drift 0.2 AU to a resonance by the seasonal Yarkovsky effect. Because the collisional lifetime is estimated to be >1 Ga in this case (Farinella *et al.*, 1998), it could easily reach a resonance before breaking up. This may be the history of some of the iron meteorites associated with modest-sized craters on Earth. Smaller-scale iron meteorites might have direct drift timescales comparable to observed CRE ages if they started closer to a resonance (possibly transported there by decameter-sized precursors) or if their surface conductivity were lower due to porosity effects. It is also possible that many iron meteorites, like the kilometer-sized near-Earth asteroids, are inserted into Mars-crossing orbits through one of many "weak" resonances active in the belt at moderate eccentricities (Migliorini *et al.*, 1998). Thus, a complex and coupled dynamical/collisional history involving both Yarkovsky drift and resonant effects can be inferred for iron fragments.

We can anticipate that extensive numerical studies of the orbital evolution of fictitious meteoroids under Yarkovsky effects and planetary perturbations will be carried out in the next few years. Figure 2 shows an example of a numerically integrated orbit of a stony fragment, drifting into the ν_6 secular resonance via the seasonal Yarkovsky effect, with a perihelion distance reaching Earth's orbit after <6 Ma; a similar evolution into the 3:1 mean motion resonance has been shown by Farinella *et al.* (1997). Bottke *et al.* (1998) have also performed numerical integrations of test bodies driven into resonances by Yarkovsky effects. For the time being, these integrations do not incorporate random walk effects or collisional cascades of fragments in a realistic fashion, but this is clearly the next challenge for this type of work.

SAMPLING OF THE POPULATIONS OF DIFFERENT TAXONOMIC TYPES

Are the proportions of stone and iron meteorites (or the detailed statistics of various taxonomic classes), as sampled at the top of our atmosphere, representative of the proportions of those classes in the belt? Our work suggests that the "canonical view" may be too simple. According to the "canonical" view, the difference between stone and iron meteorites' CRE ages is due to the rapid erosive winnowing of stone meteorites, so that no old-age stone meteorites survive to reach Earth and (in the words of Wasson, 1985, p. 61) "...the flux of meteoroids entering the Earth's atmosphere is already biased in favor of the tougher irons." Our work complicates this picture, because the Yarkovsky effects move stone meteorites out of the belt faster than iron meteorites, and erosion effects alone can't explain the very old CRE ages of iron meteorites without invoking Yarkovsky drift, as explained above.

Consider an endmember thought experiment case in which all meter-sized stone meteorites produced in collisions were delivered instantly to Earth by very efficient Yarkovsky drift to a resonance, whereas meter-sized iron meteorites were left for 1000 Ma in the belt until ejection; then there would be virtually no meter-sized stone meteorites in the belt, whereas a steady state population of meter-sized iron meteorites would be achieved in the belt. Earth would receive both stone and iron meteorites. Delivery statistics on Earth would represent the stone/iron ratio of the meteorite parent bodies (the larger asteroids), but not the existing ratio of meter-sized stone/iron objects that would be found in the belt.

Consider a second endmember thought experiment case where stone meteorites are "instantly" eroded and destroyed by collisions. (This case might apply more to weak carbonaceous chondrites than to ordinary stone meteorites.) In this case, too, there would be virtually none of these stone meteorites in the belt but there would be a population of iron meteorites. The difference from the first case would be that Earth would receive virtually none of the stone meteorites.

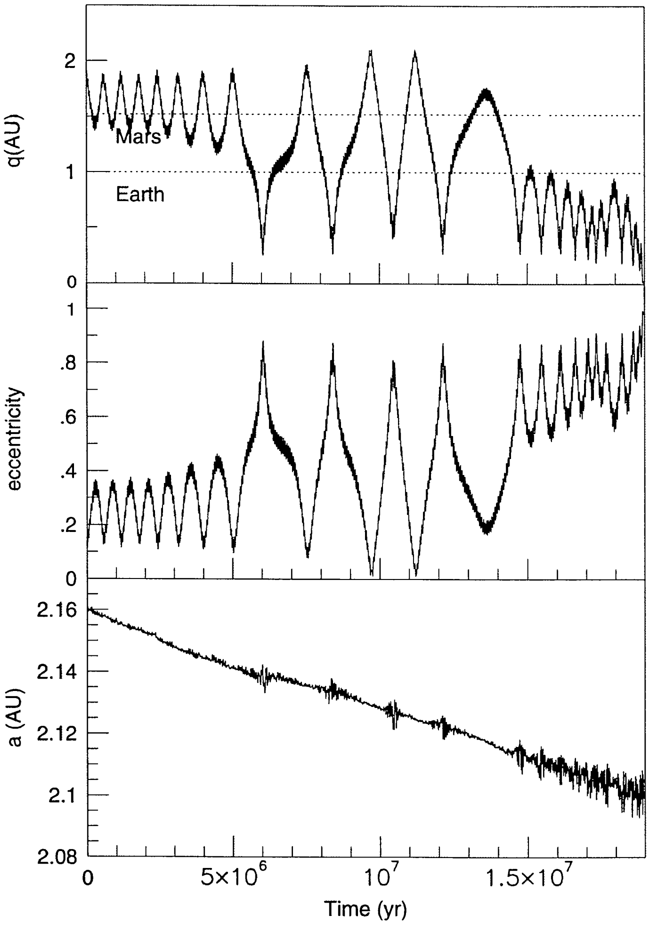

FIG. 2. The numerically integrated orbital elements (perihelion distance q, eccentricity e, and semimajor axis a) for a stony fragment 5 m in radius undergoing the seasonal Yarkovsky drift, starting from the Flora region just outside the ν_6 secular resonance at $a = 2.16$ AU, $e = 0.1$, inclination = 5°. In this simulation, the spin axis is reoriented in a random way every 3.3 Ma. When the fragment crosses the resonance, the eccentricity undergoes high-amplitude oscillations and eventually exceeds the value required for Earth-crossing. After ~19 Ma, due to resonance effects, the orbit becomes Sun-grazing and the integration is stopped. The terrestrial planets are not included in this integration; due to close encounters with them, a fraction of the resonant bodies are "extracted" from the resonance before hitting the Sun.

These endmember thought experiments illustrate that conditions actually found among small objects in the belt depend dramatically on the relative importance of erosion processes *vs.* Yarkovsky effects in controlling the small belt populations. There is a strong feedback effect: if Yarkovsky drift depletes small objects from the belt, then erosion rates drop, lifetimes increase, and more bodies are ejected from resonances before being destroyed. This feedback effect will deserve intensive study as a function of different taxonomic classes. As mentioned, all these effects are exaggerated among carbonaceous objects: they have very weak strengths, rapid erosion rates, and the greatest efficiency of Yarkovsky effects because of their high absorptivity of sunlight (and, probably, lower conductivity due to high porosity). In the actual belt, does erosion destroy 1–10 meter-scale bodies before they can be delivered to Earth, or does the rapid Yarkovsky drift win out? This question probably has different answers for different taxonomic types. Furthermore, if iron meteorites dominate the meter-scale fragments within the belt, then their high strength could affect the character of collisional-erosional processes (Hartmann and Ryan, 1996).

The requirement for further progress is reliable quantitative modeling of the erosional rates of destruction of objects of different strengths and different sizes and comparison with the rate at which they can reach resonances from given starting positions. Such modeling is more complex than the scope of our paper but needs to be undertaken to make progress on understanding meteorites and asteroids.

POSSIBLE OBSERVABLE CONSEQUENCES

Our basic result is that much stony debris in the 0.1 to 10 m size range would be rapidly cleared from the belt and delivered to planets as meteorites (or ground into dust), whereas much iron debris in this size range would have much less efficient delivery out of the belt and would acquire longer CRE ages, as observed. Additional complex effects alter the incidence of various types of material reaching Earth's surface. For example, small carbonaceous bodies are so weak that they are destroyed in Earth's atmosphere, and Earth's surface thus does not get a representative sample of carbonaceous meteorites, compared to the compositional average of interplanetary material. This is proved by the fact that the primary signature of meteoritic material in the lunar regolith is carbonaceous (Ganapathy *et al.*, 1970; Taylor, 1975), whereas carbonaceous material represents only about a few percent of the falls on Earth (Dodd, 1981; Sears and Dodd, 1988). Thus the total interplanetary flux is rich in carbonaceous material from some source.

However, ejection of carbonaceous chondrites from the belt presents a special problem. It is often assumed that these objects come from among the black C-class objects that dominate the outer half of the asteroid belt beyond 2.6 AU. Some specific similarities have been suggested between certain of these asteroids and certain carbonaceous chondrites (Bell *et al.*, 1989; Vilas and Gaffey, 1989; Burbine, 1998), and Wetherill and Chapman (1988) remark that orbital data on carbonaceous chondrites are "consistent with the expected origin of most of these meteorites from the vicinity of the 3:1 Kirkwood gap." On the other hand, this view leads to two perplexing questions. (1) The O isotopes of carbonaceous chondrites show a distinctly different pattern of abundances from other available solar system material. Ordinary chondrites, achondrites, iron meteorites, and stony-iron meteorites, plus Earth, Moon, and Mars rocks, are all grouped tightly in O-isotopic space; whereas carbonaceous chondrites have much more scattered values, as if sampling a much wider range of the outer solar system. If carbonaceous chondrites are merely samples of the black C- and P-class asteroids of the outer belt, whose orbital element distribution grades continuously into the inner belt, then why is there a discontinuity in O isotopes? (2) It is dynamically difficult to deliver C- and P-class fragments—the putative carbonaceous chondrites—from beyond 2.6 AU. As resonances in that region pump up eccentricities, the objects are lost to Jupiter before they become Earth-crossing, as Wetherill and Chapman (1988) note. Even Yarkovsky drift among small objects originating in that region would send some objects outward to the 5:2 and 2:1 resonances at 2.82 and 3.28 AU, which would produce mostly scattering by Jupiter or Jovian collisions. Also, the carbonaceous C-class bodies in the outer belt may be so weak that collisions in the belt may erode their fragments faster than they can be delivered to resonances. Thus, as a meteorite source, the C-dominated outer belt is fundamentally different from the inner belt.

Although some carbonaceous chondrites may come from outer belt objects, it may be time to reexamine delivery mechanisms for carbonaceous materials from other parts of the solar system that might explain the O-isotope systematics; these include short-period cometary material, plus effects of Yarkovsky drift on sources regions such as Trojans (dominated by very low albedo P- and D-class asteroids), Centaurs (a mix of dark taxonomic types), and Kuiper Belt objects (also a mix). Carbonaceous chondrites' parent bodies from such source regions might appear in the inner solar system as comets; they might also experience lower erosional fluxes than bodies originating in the asteroid belt. Using orbital and fall statistics, for example, Wetherill and ReVelle (1982) could not rule out a cometary source for at least some carbonaceous chondrites.

To further complicate analyses of this type, variations of ratios of one class of falls to another may also occur over geologically short (a few million years) timescales, due to possible recent fragmentation events of specific taxonomic types of objects near belt resonances or among Earth-crossers (*e.g.*, the 8 Ma H-chondrite group). This possibility is related to the longstanding debate on the alleged differences in the populations of Antarctic and non-Antarctic meteorites (*e.g.*, see Koeberl and Cassidy, 1991). Also recently, Schmitz *et al.* (1997) reported a surge of chondritic meteorites in strata of ~500 Ma age, which they attribute to an influx of material from the L chondrite breakup event. Plausibly, ratios of petrographic types among historic meteorite falls may not represent the true long-term average of deliveries to Earth (see Hartmann, 1993, p. 182, for further discussion of this idea). Moreover, it has often been tacitly assumed from the 5% ratio of iron falls to noncarbonaceous falls that iron meteorites are correspondingly rare in the belt, compared to the total of ordinary chondrites and other high-strength stone meteorites; our work suggests this is unlikely to be correct among meter-scale debris in the belt.

As an additional consequence of Yarkovsky effects, Hartmann and Ryan (1996) suggested that the possible dearth of asteroid fragments, or perhaps just stone fragments, below a few tens of meters in the belt may affect the character of asteroid surfaces. This could cause reduced cratering, erosion, and regolith production on asteroids at crater diameter scales of meters to a few hundred meters, along with a supersaturation buildup of craters at slightly larger scales (Campo Bagatin *et al.*, 1994; Hartmann 1997). As pointed out by Hartmann and Ryan (1996), there are hints that this may be the case on the main-belt asteroids Gaspra and Ida. At the same time, an enhanced ejection rate of 10–100 meter-scale objects from the belt by Yarkovsky drift delivery to resonances may have an effect on the excess of "Rabinowitz objects" among Earth-crossers in this size range (Rabinowitz, 1994). Vokrouhlický and Farinella (1998), modeling the Yarkovsky delivery of asteroid fragments to the ν_6 resonance at the inner edge of the main belt, concluded that this mechanism is effective, provided the bodies have low, regolith-like surface conductivities. (Rubincam, 1995a, also discussed Rabinowitz objects affected by Yarkovsky drift but discussed delivery all the way to Earth, not to resonances.) All of this is a fruitful area for future work but would require better information on the actual number densities of bodies in this size range in the belt.

In summary, a full understanding of meteorite delivery statistics on Earth, as well as an understanding of meter-scale debris in the belt, will require an understanding of the Yarkovsky effects and erosion processing among subtelescopic asteroid debris.

Acknowledgements–This paper is dedicated to the memory of Fabio Migliorini (1972–1997), our esteemed colleague working on issues of asteroid and meteorite dynamics whose promising career was tragically cut short. We thank W. F. Bottke, J. A. Burns, B. J. Gladman, and D. P. Rubincam for many helpful comments. At PSI, this work was supported by a grant from the NASA Lunar and Asteroid Data Analysis Program. This is PSI Contribution No. 345.

Editorial handling: R. P. Binzel

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