YARKOVSKY EFFECTS: POSSIBLE CONSEQUENCES ON METEORITES AND ASTEROIDS

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The Yarkovsky effect and associated effects alter the orbits of rotating asteroid fragments in the size range roughly 1 to 100 m, because of an asymmetry between the direction of absorption of sunlight and the direction of re-radiated thermal infrared light. Here, we point out some under-appreciated possible consequences of this effect on meteorite and asteroid evolution.

The classic Yarkovsky effect was first described by a Polish engineer, I. O. Yarkovsky, around 1900, in a paper that was apparently lost, but resurrected by Öpik (1951). Radzievski (1952) and Peterson (1976) studied the effect in more detail, suggesting it might explain delivery of meteorites from the asteroid belt. The effect studied by these authors was a "diurnal" effect on slow rotators; semi-major axis increased or decreased depending on rotation sense. Rubincam (1995) and Farinella *et al.* (1997, in preparation) showed that the "diurnal" effect does not apply for fast rotators, where the longitudinal thermal asymmetry gets smeared out. A "seasonal" effect dominates fast-rotators, causing the semi-major axis to decrease. For regolith-free fragments larger than ~10 m, the critical period dividing the "diurnal" slow-rotator effect and the "seasonal" fast-rotator effect is ~100-1000 h, but for 1-10m bodies, we believe the critical period may be as low as 10 h in some cases.

Analysis of Yarkovsky effect consequences is complicated by many additional asteroid phenomena: (1) The orbital change timescales are inversely proportional to size, down to a minimal size ~10 m for the seasonal (fast-rotator) effect, but ~1 m for the diurnal (slow-rotator) effect. (2) If there are regoliths or granular insulating surfaces, the diurnal effects could extend down to ~0.1 m. (3) For irons, the conductivity is high and the "seasonal" effect always dominates above the minimum size of ~10 m. (4) Asteroid fragments may spend little time in slow rotation "diurnal"-effect states (typical asteroid periods are 5 to 20 hours). (5) In principle, if collisions reorient asteroid fragments on a timescale shorter than the time to drift to a resonance, asteroid fragments could random-walk toward resonances through a succession of drift rates. To make a crude summary, asteroid fragments in the size range 10-100 m are likely to drift inward in semimajor axis by the "seasonal" fast-rotation Yarkovsky mechanism; fragments in the range 1-10 m may spend some time in states where they drift still faster, either outward or inward, by the more classical "diurnal" slow-rotation Yarkovsky mechanism.

Obviously, the consequences depend on the timescales of the actual drift rates and their comparison with destruction and reorientation timescales due to collision. Consider fragments being produced 0.1 AU from a resonance in the asteroid belt. According to Peterson, the "diurnal," slow-rotator effect can make a 1-m dark stony body drift in semimajor axis across this distance in as little as 1.5 My, and a 10-m dark stone in 15 My. Iron bodies drift much more slowly; an iron smaller than about 2 m diameter, independent of size, drifts 0.1 AU in about 80 My. On the other hand, under the "seasonal," fast-rotator effect, a 10-m stone drifts 0.1 AU in 200 My, and a 10-m iron the same distance in about 400 My (Rubincam 1995; Farinella *et al.* 1997).

If a 1-10 m object were created close enough to a resonance and got into in a slow-rotating state, it could plausibly drift fast enough to reach the resonance and be delivered onto an Earth-crossing orbit before any reorientation event. For 1-10 m objects, "diurnal" effect cumulative timescales (from creation to collision with Earth) could remarkably fit the observed time-scales for stones and irons: roughly 1-60 My for stones and a few hundred My for irons. Meteorite cosmic ray exposure (CRE) data and size distributions affirm that the pre-atmospheric meteorite parent bodies are in the size range of 1-10 meters (Caffee *et al.* 1988). However, more modeling needs to be done to determine if the "diurnal" effect can realistically dominate in delivering either stones or irons to resonances, as suggested by Peterson.

If Yarkovsky forces are significant, several consequences could alter current understanding of meteorites and asteroids:

1. The Yarkovsky effect might explain the relative CRE ages of stones and irons. This would replace or augment the conventional paradigm that the shorter CRE ages of stones are due to their lower strength and faster impact destruction.
2. Depending on whether the production rate of meter-scale objects in the belt is steady-state or stochastic, the flux of 1-10 m objects delivered out of the belt could be biased in favor of stones -- a reversal of the conventional prediction that "the flux of meteoroids entering the Earth’s atmosphere is already biased in favor of the tougher irons" (Wasson 1985, p. 61).
3. The asteroid belt may be depleted in fragments in the 0.1 to 100 m size range, compared to the numbers expected without the Yarkovsky effect. This could feed back into affecting the collision and reorientation timescale for small bodies.
4. A depletion of 0.1 to 100 m size range fragments in the belt would affect the character of belt asteroid surfaces, especially cratering in the 1 to 100 m crater-size range. There could be less erosion at modest scale, as well as effects on the crater populations (Hartmann and Ryan 1996, Campo Bagatin *et al.* 1994).
5. Yarkovsky effects could solve a "paradox" concerning meteorite ages: dynamical studies (e.g., Farinella *et al.* 1993, 1994; Migliorini *et al.* 1997) show that dynamical lifetimes in the resonances are only a few My -- much shorter than CRE, especially for irons. Without Yarkovsky effects, asteroid fragments (especially irons) would have to stay "parked" for long times near resonances, and it is hard to understand how irons could spend hundreds of My reaching resonances, presumably changing orbits by impacts while still remaining m-scale objects.

Due to these interesting possible consequences, the various Yarkovsky effects deserve further attention and quantitative analysis.

Selected References: Öpik, E.J. (1951) *Proc. Roy. Irish Acad.* **54**, 165-199. Peterson, C. (1976) *Icarus* **29**, 91-111. Rubincam, D.P. (1995) *JGR* **100**, 1585-1594; Farinella, P. *et al.* (1997), in preparation. Hartmann, W.H., and Ryan, E.V. (1996) DPS abstract. Campo Bagatin, A.C. *et al.* (1994) *Planet Spa. Sci.* **42**, 1079-1092. Caffee, M.W. *et al.* (1988) In *Meteorites and the Early Solar System* (Tucson: Univ. Arizona Press), pp. 205-245.