INTERACTION OF RESONANCES AND YARKOVSKY NON-GRAVITATIONAL EFFECTS IN THE ASTEROID BELT

DAVID VOKROUHLICKÝ

Institute of Astronomy, Charles University, V Holešovičkách 2, CZ – 18000 Prague 8, Czech Republic, E-mail:vokrouhl@mbox.cesnet.cz

and

PAOLO FARINELLA

Dipartimento di Matematica, Università di Pisa, Via Buonarroti 2, I – 56127 Pisa, Italy, E-mail: paolof@dm.unipi.it

keywords: non-gravitational forces, meteorites, NEAs

The interaction between resonances and dissipative effects has long been investigated in relationship with the dynamics of dust particles or the evolution of planetesimals in the primordial solar nebula. More recently, it has been shown that another important application of this kind of dynamics is the delivery of asteroid fragments (precursors of meteorites and NEAs) to Earth–crossing orbits. The relevant dissipative mechanism, the so–called Yarkovsky effect (Öpik 1951; Peterson 1976; Burns *et al.* 1979) has been known for a long time, but its "seasonal" and "diurnal" variants, as well as its interaction with the collisional process taking place in the asteroid belt, have been studied quantitatively only in the last few years (Rubincam 1995, 1998; Hartmann *et al.* 1997, 1998; Farinella *et al.* 1998; Vokrouhlický and Farinella 1998a,b; Vokrouhlický 1998a,b; Farinella and Vokrouhlický 1998a,b).

In the Farinella *et al.* (1998) paper we have provided a unified discussion of the Yarkovsky effect in both its variants. After computing the rate of the corresponding semimajor axis drift as a function of size and spin rate, and comparing the relevant timescales with those for collisional disruption and spin axis reorientation, we have rediscussed some issues in meteorite science which are put in a new light by the relevance of the Yarkovsky effect. In particular, this mechanism provides a good explanation for the fact that meteorite cosmic ray exposure ages (in particular for irons) are much longer than the dynamical lifetimes of objects delivered to the Earth–crossing region through resonances. Thanks to the Yarkovsky effect, small asteroid fragments in the belt undergo a slow drift in semimajor axis (with a random–walk component related to their rotational state) and therefore have enough mobility to reach the resonances after comparatively long times spent in nonresonant main–belt orbits. Metal–rich fragments have slower Yarkovsky drift rates than stones, but their much longer collisional lifetimes can explain why iron meteorites appear to sample a larger number of asteroid parent bodies compared to ordinary chondrites.

Then, we have analyzed in more detail the dynamical evolution of asteroid fragments released in the Flora region, near the inner edge of the main asteroid belt,

J. Henrard and S. Ferraz-Mello (eds.), Impact of Modern Dynamics in Astronomy, 365–368.

and drifting into the ν_6 secular resonance due to Yarkovsky effects (Vokrouhlický and Farinella 1998a). We have found that fragments 5 to 20 m in size evolve under the "seasonal" Yarkovsky effect, which causes a secular semimajor axis decay; they reach ν_6 after a time shorter than their collisional lifetime when they start within about 0.05 to 0.2 AU out of the resonance. Metal–rich fragments drift slower but have have much longer lifetimes than stony ones, so they drift farther from their formation site. Fragments around 100 m in size are mainly influenced by the "diurnal" Yarkovsky effect if their surface is covered by a (thin) insulating regolith layer, and as a result their semimajor axis undergoes a random walk controlled by impacts which reorient the spin axis. Within their lifetime of $\approx$ 100 Myr these fragments can move throughout the inner part of the belt, episodically crossing ν_6, until their orbit starts to be strongly perturbed by close encounters with the terrestrial planets. Meter–sized stony fragments, which probably deliver most meteorite falls, may also drift into the resonance under the "diurnal" effect, provided their surfaces have low thermal conductivities and/or their rotation is unusually slow.

Whereas in Vokrouhlický and Farinella (1998a) we have focused on the dynamical aspects of the Yarkovsky effects (by investigating individual fragment orbits), in Farinella and Vokrouhlický (1998b) we have modeled in a statistical way the evolution of large "swarms" of fragments released by catastrophic break-up events in the main belt. Their dynamics has been represented in proper element space by a simple, two–component model, including (i) the secular semimajor axis drift due to Yarkovsky effects, and (ii) the effects of random impact events resulting in the cascade–like generation of new populations of fragments. We have found that the combination of these mechanisms can feed efficiently the main resonances with small asteroid fragments from nearly all the locations in the main belt, and that only very close to the resonance edges direct injections are important. For instance, according to our model some 50–80 % (in mass) of the material released from a Flora–like asteroid is transported into the ν_6 resonance, either as first–generation fragments or through their collisional offspring (this should be compared to only a few percent chance of direct injection in this case). Another important result from this model is that the distribution of accumulated cosmic–ray exposure (CRE) ages in the population of fragments reaching the Earth is in fair agreement with the observations. Relatively old events are likely to generate the background CRE age profiles, peaked at 20–50 Myr for stones and 200–500 Myr for irons, while comparatively recent events may create discrete peaks in the CRE age distributions (such as the 7–8 Myr prominent peak for the H–chondrites). In the latter case, the bulk of the original fragment population may still reside in the main belt, and will supply a significant flux of meteorites in the near future. We plan to perform a detailed quantitative comparison with the observed CRE age data in order to constrain the surface thermal conductivity of fragments from different source asteroids, as this is currently the main unknown parameter of the model. Hopefully, the forthcoming interplanetary missions (such as NEAR) will allow to directly measure/estimate the surface thermal conductivity of NEAs, providing us with an independent source of information.

In Farinella and Vokrouhlický (1998a) we have noted that Yarkovsky effects are capable of providing some semimajor axis mobility even to km–sized small asteroids in the main belt. Typically, bodies in the 1 to 20 km diameter range may move in semimajor axis by $\approx$ 0.01 AU within their collisional lifetimes of 0.1 to 1 Byr. Interestingly, this result is almost independent of the thermal properties of the surface material. This mobility may be a key mechanism for feeding the high–order and/or mixed resonances in the inner asteroid belt, which have been recently identified as the most likely dynamical routes for multi–km sized Mars–crossers and NEAs (Migliorini *et al.* 1998). Other likely consequences are the eventual fall into the main resonances of fragments generated "on the brink" (Knežević *et al.* 1997) and the gradual spreading in semimajor axis of the small members of the most compact asteroid families.

Finally, Yarkovsky effects may provide a natural mechanism for explaining the observed overabundance of 10–100 m bodies among NEAs (see e.g. Rabinowitz 1993, 1994). The Yarkovsky mobility of a population of bare–rock (or iron–rich) fragments, dominated by the seasonal Yarkovsky effect, is maximum for bodies of size comparable to the penetration depth of the seasonal thermal wave (about 10 m for stones and 20 m for irons). Thus, we may expect that these bodies are preferentially removed from the main belt, and eventually show up in a relative overabundance within the population of Earth-crossing objects (Vokrouhlický and Farinella 1998a, Hartmann *et al.* 1998). Moreover, their removal from the main–belt population would imply a longer collisional lifetime for the bodies $\approx$ 100 m in size (which can be fragmented by impacts with the 10–m bodies), allowing them to drift over a wider portion of the belt and eventually to feed the resonances. Therefore the overabundance in the near–Earth population may well extend to sizes larger than those corresponding to the maximum efficiency of the seasonal Yarkovsky effect, possibly to about 100 m. We plan to develop detailed quantitative models for these complex feedback effects between Yarkovsky mobility and collisional evolution in the near future.

References

Burns, J.A., Lamy, P.L. and Soter, S.: 1979, *Icarus*, **40**, 1.
Farinella, P. and Vokrouhlický, D.: 1998a, *Science*, submitted.
Farinella, P. and Vokrouhlický, D.: 1998b, in preparation.
Farinella, P., Vokrouhlický, D. and Hartmann, W.K.: 1998, *Icarus*, **132**, 378.
Hartmann, W.K. *et al.*: 1997, in Proc. Lunar and Planet. Sci. Conf. XXVIII (Houston: Lunar Planet. Inst.), p. 517.
Hartmann, W.K. *et al.*: 1998, *Meteoritics Planet. Sci.*, in press.
Knežević, Z. *et al.*: 1997, *Planet. Space Sci.*, **45**, 1581.
Migliorini, F. *et al.*: 1998, *Science*, **281**, 2022
Öpik, E.J.: 1951, *Proc. Roy. Irish Acad.*, **54**, 165.
Peterson, C.: 1976, *Icarus*, **29**, 91.
Rabinowitz, D.L.: 1993, *Astrophys. J.*, **407**, 412.
Rabinowitz, D.L.: 1994, *Icarus*, **111**, 364.

https://doi.org/10.1017/S0252921100072742 Published online by Cambridge University Press

Rubincam, D.P.: 1995, *J. Geophys. Res.*, **100**, 1585.
Rubincam, D.P.: 1998, *J. Geophys. Res.*, **103**, 1725.
Vokrouhlický, D.: 1998a, *Astron. Astrophys.*, **335**, 1093.
Vokrouhlický, D.: 1998b, *Astron. Astrophys.*, **338**, 353.
Vokrouhlický, D. and Farinella, P.: 1998a, *Astron. Astrophys.*, **335**, 351.
Vokrouhlický, D. and Farinella, P.: 1998b, *Astron. J.*, **116**, 2032.