INTERACTION OF THE YARKOVSKY-DRIFTING ORBITS WITH WEAK RESONANCES: NUMERICAL EVIDENCE AND CHALLENGES

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Abstract. Long-term numerical simulations of main-belt meteoroid and small asteroid orbital evolution with the Yarkovsky effect resulted in several puzzling (and challenging) facts when the orbits got into interaction with weak resonances. Orbits of small asteroids, slowly drifting due to the Yarkovsky effect, may reside in the resonance zone for sufficiently long time. Thereupon the eccentricity and inclination may slowly evolve. Overlapping of close resonances, or multiplets of a single high-order resonance, may cause that the classical theory of capture in a single resonance (as previously applied to tidal evolution of satellites of PR-evolving dust orbits in low order exterior resonances with inner planets) is not applicable. Here we show few examples of these processes based on numerical simulations. Analytical estimation of the chaotic diffusion rate in eccentricity and inclination in these more complex dynamical situations is an important challenge for the future theory.

1. Introduction and motivations

The Yarkovsky nongravitational force is able to noticeably move semimajor axes of meteoroids and small asteroids in the size range of meters to kilometers within their estimated lifetime smaller than the age of the Solar System (e.g. Vokrouhlický 2001, Bottke et al. 2001a). The estimated maximum drift in the semimajor axis is comparable to the distance to nearest strong resonances (≈ 0.1 AU for meteoroids) or a typical width of an asteroid family (≈ 0.01 AU for km-sized asteroids). However, a fine grid of weak (mean motion or secular) resonances presents an obstacle in this process. A detailed understanding of the Yarkovsky effect role in the evolutionary processes in the asteroid belt (such as the meteorite delivery or the long-term diffusion of the asteroid families) thus requires a quantitative analysis of the interaction of the Yarkovsky-drifting orbits with these weak resonances. Here we present several examples of such interaction from numerical simulations of the dynamical evolution in asteroid families. Some of them indicate that the classical adiabatic theory of resonance capture and release may not be easily applicable, since either (i) two, but different, nearby resonances or (ii) different multiplets of a single high-order resonance may overlap. The interacting resonances (though weak) typically result in a long-term chaotic diffusion of eccentricity and inclination, having thus importance for distribution of members in the families. However, due to limited space, we do not discuss these implications in detail.

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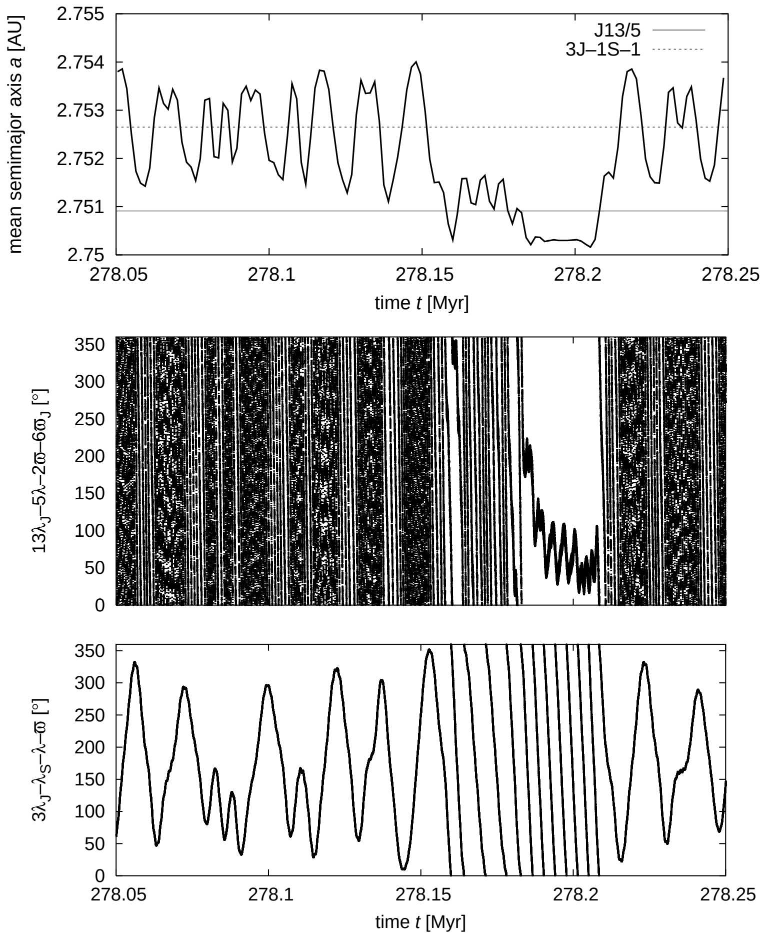

Figure 1. Top: mean semimajor axis vs. time (in Myr) for numerically integrated orbit of a small asteroid at the bottom edge of the Dora family. Approximate location of the J13/5 and (3J,−1S,−1) mean motion resonances is shown by the horizontal lines. The orbit apparently jumps from one resonance to the other, corresponding to the their overlap at the value of eccentricity ≈ 0.19 appropriate for the Dora location. Middle and bottom: behavior of the corresponding critical angles of the two mean motion resonances. Interchanges between librations and circulations correlate with the behavior of the mean semimajor axis (top).

1.1. High-order and three-body mean motion resonances

Figure 1 corresponds to an orbit of a small (size ≈ 4 km) asteroid in the Dora family region (see also Fig. 2). Yarkovsky effect has been taken into account (we use `swift_rmvsy` first-order quasi-symplectic integrator; Brož et al. 2001). It has a twofold role in our simulations: (i) it allows to bring the objects on nearby orbits

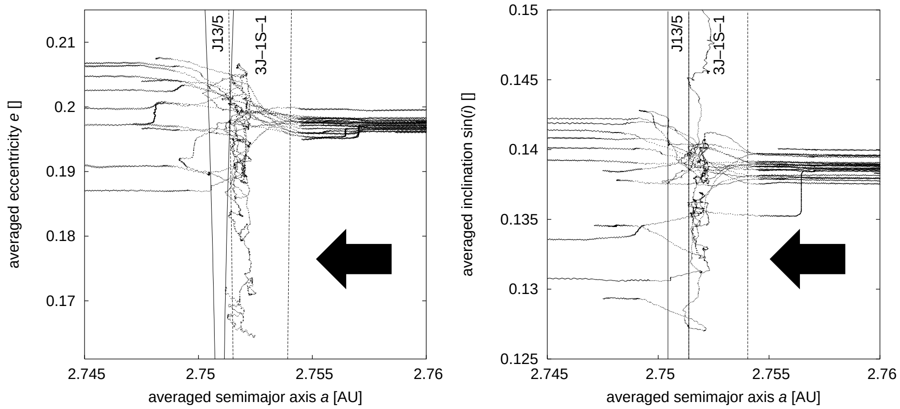

Figure 2. Long-term averaged mean elements of 12 asteroids in the Dora family (we use averaging over a 5 Myr step-window for simplicity). Vertical lines indicate separatrix of the major resonance component in the circular restricted three-body problem (the $(3J,-1S,-1)$-resonance separatrix taken from Nesvornỳ and Morbidelli 1998). The arrow points out direction of the Yarkovsky drift in semimajor axis. Note significantly larger dispersion in eccentricity and inclination after the orbits crossed the resonance region. Indeed, Dora family terminates at $a \approx 2.75$ AU.

to the resonance region, but (ii) it may also cause escape of the orbit from the resonance. Only a short interval of the 300 Myr simulation is shown here. Temporary captures in at least two weak resonances are clearly seen, notably J13/5 (with the librating resonance angle $13\lambda_J - 5\lambda - 2\varpi - 6\varpi_J$) and the three-body resonance $(3J,-1S,-1)$ (with the librating resonance angle $3\lambda_J - \lambda_S - \lambda - \varpi$). Thanks to the great inequality in the motion of Jupiter and Saturn (i.e. their proximity to the mutual 5/2 resonance), the mentioned weak resonances naturally reside very close each other (in fact overlap for $e \geq 0.19$ as seen on Fig. 2).

Asteroids of the indicated size (determining the corresponding mean drift in the semimajor axis due to the Yarkovsky effect), can temporarily reside in this resonance region for Myr up to tens of Myr (the largest capture in our simulation was 70 Myr). The eccentricity and inclination chaotically diffuse as a result of interaction of the overlapped resonances (e.g. Murray and Holman 1999). Figure 2 nicely shows this feature for 12 small asteroid orbits that reached the J13/5 and $(3J,-1S,-1)$ resonance region (the nominal family is located at higher values of the semimajor axis).

Lost and fugitive family members. The large scatter in eccentricity and inclination for asteroids crossing weak resonances has important implications for the long-term fate of the orbital elements distribution within the family. In this particular case, the asteroids, previously members of the Dora family, likely "disappear" in the background population. Note that the acquired effective change of the velocity is $\Delta v \approx \frac{1}{2} na\sqrt{(\Delta e)^2 + (\Delta I)^2} \approx 100$ m/s for $\Delta e \approx 0.01$ and $\Delta I \approx 0.3°$ (Fig. 2). This is about (or even more) the treshold by which this family separates from the background population. A similar situation occurs in the Themis family, which is terminated at small semimajor axes by the pair of resonances J11/5 and (3J,−2S,−1) (thanks to lower order of these resonances $\Delta e \approx 0.15$ is typically attained after crossing the resonance zone).

Another, well-documented example are Eos asteroids in the J9/4 resonance. Having noticed that this resonance crosses the Eos family, Morbidelli et al. (1995) predicted that some former members might have been driven by the chaotic dynamics to higher eccentricities. Since asteroids in this family have significantly distinct spectral characteristics (K-type), Zappalà et al. (2000) were able to confirm this prediction by identifying ≈ 10 K-type asteroids at high-eccentricity orbits in this resonance. Note, however, that the model of dynamical evolution in families with the Yarkovsky effect adds another important point of view: the asteroids supply in the resonance is continuous and this may explain current existence of these objects (typical residence time in the J9/4 is of the order of hundreds Myr at maximum, while the family itself may be $\approx$ Gyr old). Obviously, secondary disruptions in the family may also inject fresh objects to the resonance, but the likelihood of both "feeding" processes needs to be evaluated; especially for larger asteroids (size $\approx 10-20$ km) probability of the secondary injections rapidly drops.

Getting "hotter". Weaker resonances are not capable in producing such a large changes in eccentricity and inclination as reported above, while they are still affecting these elements as the Yarkovsky drifting orbits cross them. Although the concerned asteroids still reside in the corresponding family, the eccentricity and inclination dispersion increases as a result of this process. Analysis of the distribution data for asteroids in families thus needs a great care: the role of initial velocity dispersion together with subsequent dynamical processes driven by the Yarkovsky effect should be minutely considered. Recent work supports a growing evidence that the so far neglected dynamical evolution in families may even dominate for older families (see, e.g., Nesvorný et al. 2001, Bottke et al. 2001b), but this conclusion awaits further justification.

Though vast numerical simulations start to acummulate evidence for the above illustrated interaction of the Yarkovsky drifting orbits with weak resonances, an analytic estimate of the overall diffusion rates in eccentricity and inclination would be interesting. This presents a great challenge for the future work, since the classical theory of the adiabatic resonance-capture theory is far too simple for these cases.

1.2. High-order secular resonances

Another striking feature related to the Yarkovsky-driven long-term evolution of the asteroid familes concerns the role of high-order secular resonances (e.g. Milani and Knežević 1992, 1994). In a purely gravitational model, these resonances do not cause macroscopic chaos even on $\approx$ Gyr timescales and result only in long-term $\approx$ Myr oscillations of eccentricity and/or inclination. Though they are of concern

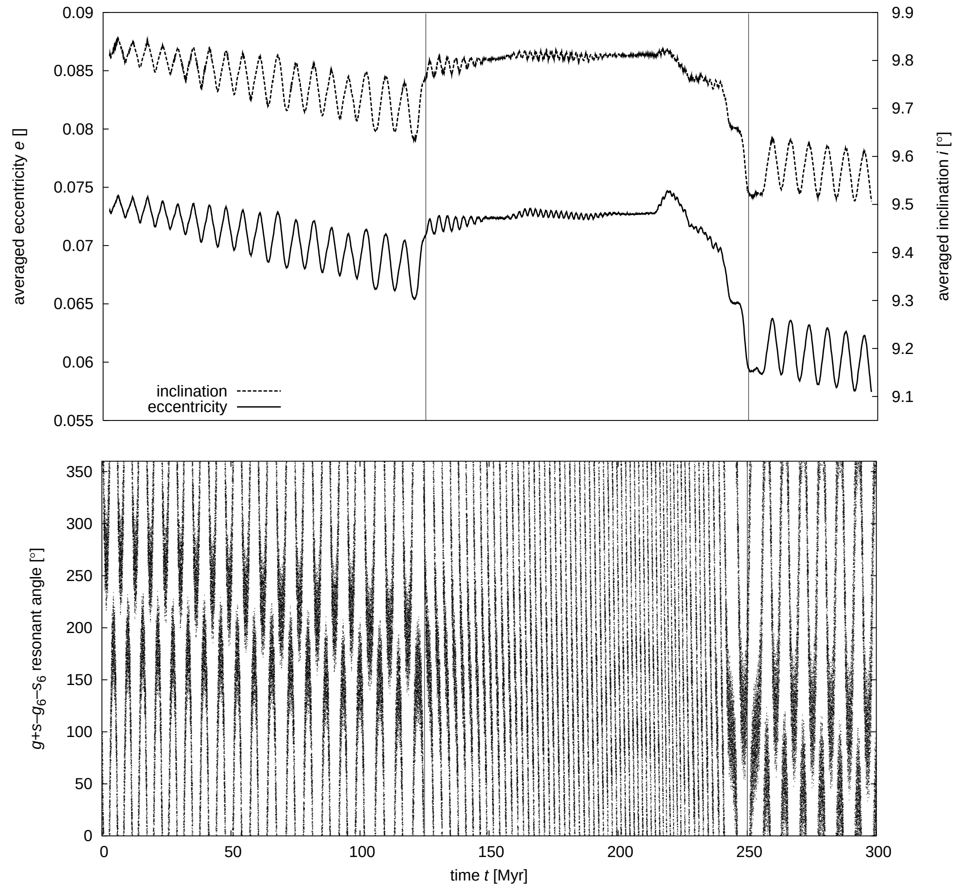

Figure 3. Top: averaged eccentricity (left ordinate, lower curve) and inclination (right ordinate, upper curve) vs. time (in Myr) for a numerically simulated orbit of a small asteroid, member of the Eos family. The coupled ≈ 5 Myr oscillations of both eccentricity and inclination at the beginning and the end of the integration are triggered by a capture in the $z_1 = g + s - g_6 - s_6$ secular resonance. Bottom: behavior of the critical angle of this secular resonance. Wide-amplitude libration corresponds to the features on top. At $t \simeq 120$ Myr the orbit was extracted from this resonance, probably due to interaction with a mean motion resonance.

for the theories of proper elements, their contribution to the secular evolution of the orbital elements over very long timescales would be thus negligible.

However, orbits of small asteroids which move in semimajor axis due to the Yarkovsky effect, can be transported to a specific places in the phase (orbital-element) space as they "adhere" to these secular resonances. Figure 3 shows an example of the orbital evolution of a small (size ≈ 3 km) asteroid in the Eos family. Except from the ≈ 100 Myr interruption due to interaction with mean motion resonance, the orbit stays captured by the $z_1 = g + s - g_6 - s_6$ secular resonance.

The accumulated change in eccentricity and inclination is ≈ 0.015 and $\approx 0.3^\circ$ over the integrated timespan of 300 Myr (the simultaneous change in the semimajor axis during this timespan was ≈ 0.025 AU). Note that 300 Myr is still very short interval of time as compared to the likely $\approx 1-2$ Gyr age of this family (obviously, larger-size asteroids would drift slower, with a rate approximately inversely proportional to their size).

If the process of the adiabatic "sliding" along the secular resonances is not interrupted by an encounter with mean motion resonances, the model may be able to explain several puzzling features of the distribution of asteroids in families. The most interesting cases, Koronis and Eos families, are being closely examined and the results will be reported soon (Bottke et al. 2001b).

Note. To obtain more details about the numerical simulations of the Yarkovsky driven, long-term evolution in the asteroid families visit our web-site http://sirrah.troja.mff.cuni.cz/˜mira/mp/ and related links.

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