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The non–gravitational effects on the dynamical evolution and on the rotational properties of the asteroids

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Abstract The importance of nongravitational effects in the evolution of asteroids has been recently acknowledged. The Yarkovsky and YORP effects have become major players in the theoretical models. More recently, the evolutionary consequences of both processes have been observed. The effects may affect the dynamical evolution of the asteroidal orbits, allowing an effective delivery of NEAs and causing a significant evolution of the dynamical families. Moreover the YORP effect plays a relevant role in the evolution of the spin vector properties of the asteroids.

1. Introduction

In the last ten years the studies concerning the non–gravitational effects have shown their importance to affect the evolution of the asteroids. Formerly, the old (and previously neglected) Yarkovsky effect has been recovered (Vokrouhlický 1998; Vokrouhlický and Farinella 1998; Vokrouhlický 1999; Spitale and Greenberg 2001). More recently, after a pioneering paper by Rubincam (Rubincam 2000), the YORP effect has gained a growing interest (Vokrouhlický et al. 2003; Čapek and Vokroulický 2004; Vokroulický et al. 2006,b; Scheeres 2007(@; Nesvorný and Vokroulický 2007, 2008; Micheli and Paolicchi 2008). Moreover, the consequences of both effects have been measured. The dynamical evolution due to the Yarkovsky effect has been observed in the asteroid (6489) Golevka (Chesley et al. 2003), while direct observations of the evolution of the spin period due to the YORP effects have been reported during 2007 (Lowry et al. 2007; Taylor et al. 2007; Kaasalainen et al. 2007). The "diurnal" Yarkovsky and YORP effects are schematically represented in Figure 1 (reproduced from Paolicchi 2005). For an explanation of the (usually by far less relevant) "seasonal" Yarkovsky effect see, for instance Bottke et al. (2002b).

2. Yarkovsky effect: dynamical evolution and NEO delivery

The Yarkovsky effect can change the orbital elements, and in particular the semimajor axis. It cannot be directly responsible for the delivery of NEOs (typically a 1 km asteroid requires

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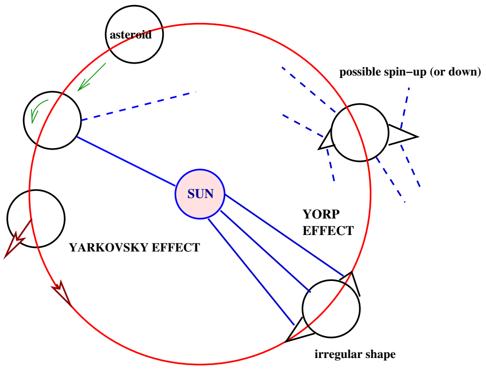

Figure 1. Yarkovsky and YORP effects.

more than 1 Gyr to change its semimajor axis by 0.5 A.U., under the super–optimistic hypothesis that it survives collisions and keeps its spin axis aligned all the time). However, even a reduced semimajor axis mobility may inject the asteroid into some of the dynamical resonances, which will do the job. The secular resonance ν_6 and the mean motion resonance 3 : 1 are the most effective to start the transfer of Main Belt asteroids towards the NEO region (Bottke et al. 2000, 2002; Morbidelli and Vokrouhlický 2003). While the collisions seem not to be able to inject a relevant number of asteroids into these resonances (see, however, Dell'Oro and Cellino 2007), the Yarkovsky effect does.

Due to the Yarkovsky effect, the semimajor axis of retrograde asteroids decreases, that of prograde ones increases. MB asteroids are continuously injected into the resonances, and later many of them become NEOs. Since the ν_6 secular resonance is close to the inner border of MB, the retrograde asteroids are more numerous among NEAs (La Spina et al. 2004; Kryszczynska et al. 2007).

3. Yarkovsky effect: asteroid families

The properties of asteroid dynamical families can be affected by the Yarkovsky effect. The extension of the families in the space of the orbital (proper) elements may be due only partially to the original properties of the family, i.e. to the ejection velocities during the originating catastrophic collisions. A relevant contribution, at least of the same value, (Dell'Oro et al. 2004) may be due to the post–impact diffusion due to the Yarkovsky effect. The distribution of the family members in the orbital elements space has been fitted taking into account the Yarkovsky effect, and also the possible preferential spin alignments due to the YORP effect (Vokroulický et al. 2006b). The obtained original ejection velocities are more consistent with the theoretical estimates obtained from hydrodynamical simulations.

However, some problems remain open. Among the others, it has been suggested that a possible correlation might connect the ejection and the spin properties of the fragments outcoming from a catastrophic process (Paolicchi 2005). If so, the following Yarkovsky evolution in the semimajor axis might enlarge or – at least at the beginning– compactify the family, depending on the impact geometry. Since the effect of the correlation should be decreased by an abundant reaccumulation of fragments after the creation stage, its possible detection (conceivably outcoming from a thorough analysis of some of the youngest families) might constrain the physics of impacts, and in particular the amount of the secundary reaccumulation into several bodies; it should be very relevant, according to some hydrodynamical simulations (Michel et al. 2002).

4. The YORP effect: evolution of the spin vector

In recent years, the relevance of the YORP effect for the spin vector properties of the asteroids has been outlined. Theoretical models have been introduced, taking into account, or neglecting, the effects of a finite thermal conductivity, and also trying to understand how the effect depends on the shape of the bodies, analyzing the effect on a sample of artificial models. In spite of the difficulties of its modeling and of discrimnating its consequences from those of other physical and dynamical effects, YORP has recently become a major player in the overall modeling of the evolution of asteroids.

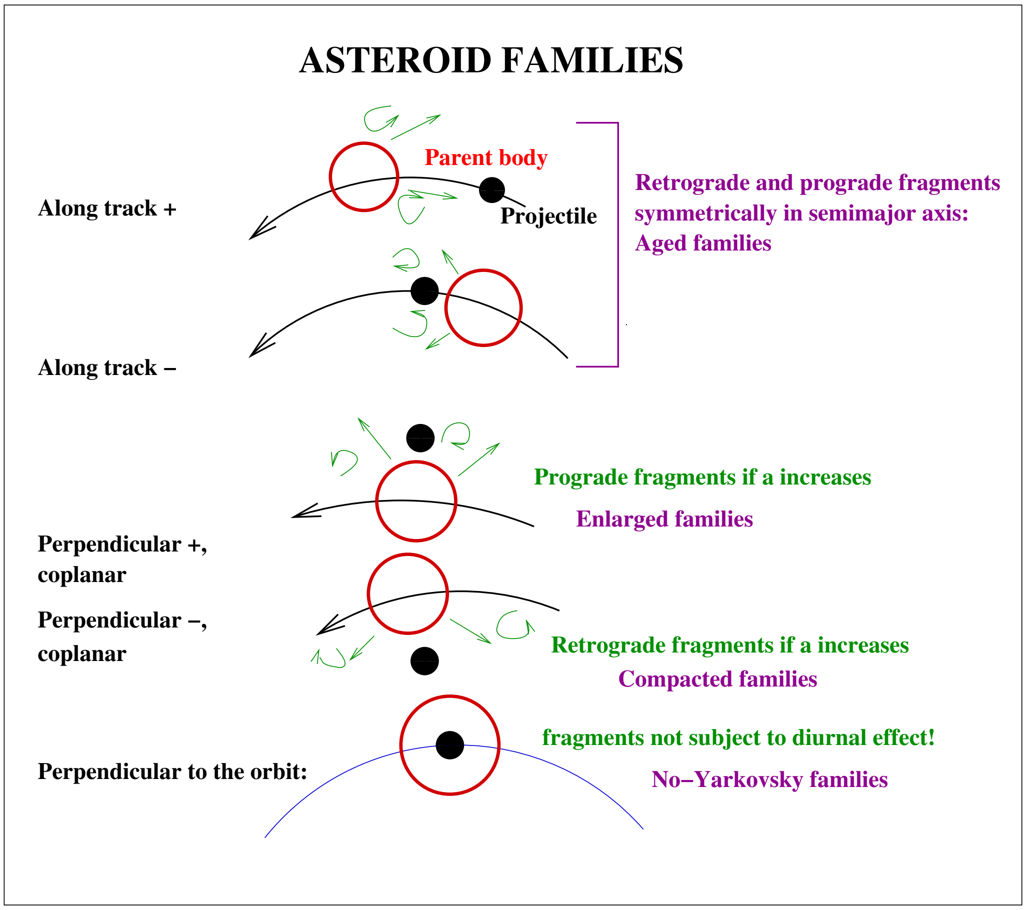

Figure 2. The spread of a dynamical family in the space of orbital elements, and in particular along the semimayor axis, depends on a combined effect of the breakup geometry and of the Yarkovsky–driven mobility. According to different impact geometries the original dispersion and that due to Yarkovsky effect may combine quadratically, consistently with the "ageing" paradigm (Dell'Oro et al. 2004, ; along track impacts). or linearly, thus amplifying or minimizing the dispersion effect (impacts perpendicular to the orbital motion). Consequently, the dispersion of a family may be very different in various cases. Similar to the figure in Paolicchi (2005), but more general.

The interaction of an asteroid with the solar radiation (reflected photons, absorbed photons and re–radiated photons) may cause a torque on the object. If we represent the asteroid as a polihedron with facets of surface dA, the torque is, for every facet, $d\boldsymbol{\tau} = \boldsymbol{r} \times \boldsymbol{f} dA$, where

$$\boldsymbol{f} = -\frac{2S}{3c}\hat{N} = -\frac{2(\hat{r_S} \cdot \hat{N})F_S}{3c}\hat{N} \qquad (1)$$

according to the Rubincam approximation and notations (Rubincam 2000; Micheli and Paolicchi 2008). The effect of the torque depends on the momentum of inertia I. It is easy to show that $\tau/I \sim {R_0}^{-2}$, where R_0 is the size of the body. Thus the YORP effect, similarly to the Yarkovsky effect, works mainly on small or moderately sized bodies.

5. YORP effect: properties and difficulties

The intensity of the YORP effect depends critically on the shape, being null for a spherical or an ellipsoidal shape. As for a first approximation, for a 100 m body one can have a variation of the spin rate of the order of $\sim 10^{-3}\mathrm{s}^{-1}$ after a time of the order of 1 Myr. Due to the steep dependence on the size, it is difficult to observe the effect, and its consequences, in bodies larger than, say, a few tens of kilometers (the YORP variation in the spin rate is moderate even during the whole age of the Solar System), while it may be dominant for small (meter sized) bodies. The effect of the torque may be divided into two relevant components, τ_s affecting the spin rate, and τ_Θ affecting the obliquity of the spin vector. For a given body, both values (averaged over the orbital motion) depend on the obliquity Θ.

A typical behaviour is represented in the Figure 3. In this regular pattern the component τ_s varies as a function of the obliquity in a bell-shaped curve, crossing the zero (and thus changing the sign) for obliquities of the order of 55 and 125 degrees, while the curve of the component τ_Θ is approximately similar to $sin(2\Theta)$. There are two specular cases, according to the sign of the curves. However this qualitative behaviour is not general. Four "taxonomic" types have been defined by Vokrouhlický and Čapek (2002) among the real objects, extended to five by Micheli and Paolicchi (2008). However, a theoretical analysis by Nesvorný and Vokroulický (2007, 2008) has generalized the classification, representing a general shape in terms of a series of harmonic functions. In general, according to the analysis of the known shapes, the basic types include something as 2/3 of the real bodies (Micheli and Paolicchi 2008). It can be shown that, in general, the most complex YORP models correspond to weaker effects. They are usually due to smaller scale features, so that the most regular bodies exhibit the oddest YORP properties. However, the small scale features cannot be neglected at all, especially

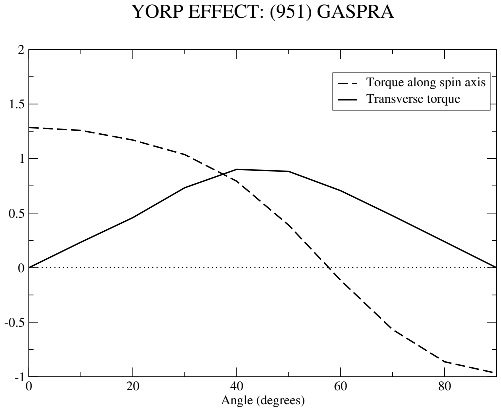

Figure 3. A "normal" YORP type: the case of (951) Gaspra (Micheli 2007). The torque components along the spin axis τ_s (dotted curve) and the transverse one τ_Θ (solid curve) are normalized, in order to eliminate the dependence on mass and size, and are in units of $10^{-20}\mathrm{s}^{-2}$.

when the overall effect is weak: even the sign of τ_s may depend on small scale features.

Also the surprising change of sign of τ_s has been subject to several analyses, and initially related to the properties of insolation of oblique rotating objects. It has been shown that, when the effect is more relevant, the zeros of the function τ_s are closer to the "standard" value (Micheli and Paolicchi 2008). It has also been shown that, at least for shapes not too irregular, the "55 degree conundrum" can be explained in terms of complex mathematical properties (Nesvorný and Vokroulický 2007). We are now beginning to understand -partially- how the YORP effect works! The complex behaviour of the YORP effect cannot mask its importance, especially for small bodies. The effect can explain the anomalous slow rotation of several medium–small sized asteroids (Vokroulický et al. 2006c). In some cases it might even cause a very fast rotation. The real general statistical consequences on the spin properties of the asteroids have to be explored in detail. YORP favours the spin vectors to be –prograde or retrograde– not far from being perpendicular to the orbital plane. It recalls a well known statistical property of the spin vector: they are rarely close to the ecliptic or to the orbital plane. However, the sample of bodies in the spin vector database contains mainly large bodies (Kryszczynska et al. 2007); in general they should be too large for having been affected by YORP –at least, for what we know. However the point needs to be clarified. A future analysis, both of new data –hopedly, concerning also the spin vector of small bodies– and of theoretical models, is certainly urged.

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