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Rotational properties of asteroids: a tool to understand their evolution?

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Abstract Recent studies have evidenced that the statistical properties of the asteroids' rotation periods are a fundamental source of information on the physics of collisions and on the collisional evolution. Moreover, also the properties of the spin vector may be important to constrain the evolutionary processes. In this context, the Yarkovsky effect (and similar ones, based on the interaction of asteroids with the solar radiation) may play a fundamental role. The analysis of the rotational properties –both periods and spin vectors– may furnish several observational constraints to theoretical models, as well as suggest possible new fields of analysis. These studies support also systematic observational campaigns devoted to the computation of the asteroid poles.

1. Introduction

The spin period of asteroids is easily obtained from astronomical observations: we know the period of about 1000 objects (Pravec et al. 2002). In contrast, it is difficult to obtain the pole orientation angles, i.e. the ecliptic latitude and the longitude. Consequently, the spin vector is obtained rather rarely and often with some ambiguity. About 150 asteroids are listed in the database (Kryszczynska et al. 2005):

www.astro.amu.edu.pl/Science/Asteroids

For about 1/3 of them we have contradictory solutions; in many cases we have ambiguous solutions.

2. Theory and observations

The spin properties of asteroids depend certainly on their collisional evolution, only the largest ones preserving a memory of the original properties. Recently the so called YORP effect (Rubincam 2000; Vokrouhlicky et al. 2003) has been shown to be capable of affecting the spin properties of moderately sized asteroids.

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2.1. Collisional transfer of angular momentum; catastrophic collisions involving big objects

The effect of collisional processes on the rotational properties can be schematically analyzed in a few cases, to obtain some order–of–magnitude indications. We define the effect of a collision as catastrophic whenever, at the end of the process, the mass of the largest remnant is smaller than half of the mass of the parent body. For what concerns the collisions involving very large asteroids, the strongest condition to be fulfilled, in order to have a catastrophic breakup, is that most of the ejecta outcoming from the fragmentation process escape faster than the escape velocity of the parent body. It entails an energy condition, involving the impact kinetic energy (m_p is the mass of the projectile and V_{imp} the impact velocity), the fraction of this energy converted into kinetic energy of the fragments (f_{ke}), and the gravitational binding energy of the parent body (mass defined as m, radius as r). Approximately

$$1/2 m_p V_{imp}^2 f_{ke} \simeq Gm^2/r$$

where $f_{ke} \ll 1$ (as argued according to the properties of the so–called LAMAs (Davis et al. 1989), or consistently with the result of the hydrodynamical simulations (see, for instance Michel et al. (2002)); note that f_{ke} may be slightly larger for previously shattered bodies (Michel et al. 2004). Thus we obtain:

$$m_p/m \simeq 2Gm/(rV_{imp}^2 f_{ke}) = [V_e/V_{imp}]^2/f_{ke}$$

where $V_e \simeq 0.001r$ (if we use seconds as time unit) is the escape velocity of the parent body (or, maybe more precisely, of the combined body formed by the target and the projectile). For a 200 km body we have m_p/m values between 1 and 10%.

The transferred angular momentum can be estimated on the basis of elementary considerations:

$$\omega \simeq (m_p/m)V_{imp}/r.$$

It entails rotational periods, due only to the collisionally transferred angular momentum, of the order of one hour or even less; however, we have a massive fragmentation of the target, and most of the a.m. is used for orbital motions. As a side consequence of the large transfer of a.m. we have many binary systems, either through bursting fissions (high ejection velocities – consistently with the traditional scenario of family formation) or post event captures (moderate ejection velocities – recent theories) (Paolicchi et al. 1999).

2.2. Collisional transfer of angular momentum: small bodies

For the collisions involving small bodies we can assume that the energy required to obtain a catastrophic process is mainly devoted to overcome the solid–state binding energy. For this case we can, as a first approximation, adopt the energy scaling assumption. If we assume that the values of critical specific energy coming out from laboratory experiments (tipically around 10^7erg/g) hold also for asteroids, we obtain a relation such as $\omega = C/r$ (where $C \simeq 0.01$km/s); it entails a ten minute period for a kilometer sized body. However, if we assume that (as the most recent theories suggest) the specific critical energy is smaller for km–sized bodies than for laboratory targets, and that most of a.m. is transferred to debris, the resulting periods can be far larger.

Thus, at least for small fragments, the contribution of the “breakup angular momentum” acquired as a consequence of their ejection field may be dominant. This term is obviously present in all cases, independently on how large target and projectile are and on the geometry of impact. It depends only from the ejection velocity scale. Approximately, if the typical ejection velocity is V_*, the acquired rotation period of a fragment of size R should be $T \simeq 2\pi R/V_*$. For velocities of the order of 100m/s (typical of the fragments originated within the collisions leading to the formation of dynamical families) a kilometer sized fragment should have a period of about one minute.

Due to this effect the small asteroids should begin to spin up (in comparison to the larger ones) starting from a size of, say, ten kilometers. The qualitative scenario we expect from the present theoretical arguments is represented in Fig. 1.

2.3. Observational scenario

The observations (Pravec et al. 2002) show that all the asteroids larger than, say, about 100 – 200 m, never rotate faster than in two hours (recently, an exception has been found, for a body of about 900 m Pravec & Kusnirak (2001)). Consequently, also the mean rotation rate varies rather slowly with size. Bodies smaller than 100 m can rotate faster (even a lot faster, thus the mean rotation rate increases steeply going towards smaller sizes). This behaviour is compared in Fig. 1 to the above discussed theoretical ideas. The discrepancy concerning small bodies, as well as the lack of

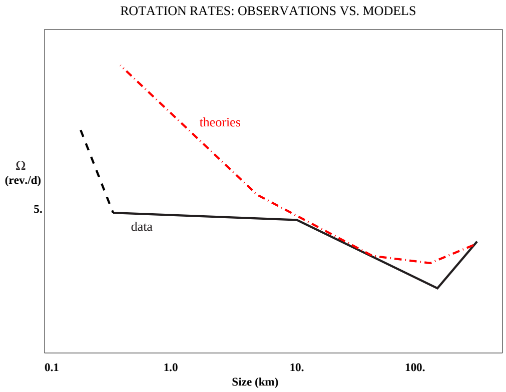

Figure 1. Qualitative comparison between the rotation rate vs. size observed relation (Pravec et al. 2002) and a possible theoretical one (according to the above discussed modellings (Davis et al. 1989). The strong discrepancy for what concerns bodies smaller than 1km has been claimed as a proof of the rubble pile structure of asteroids larger than a few hundred meters.

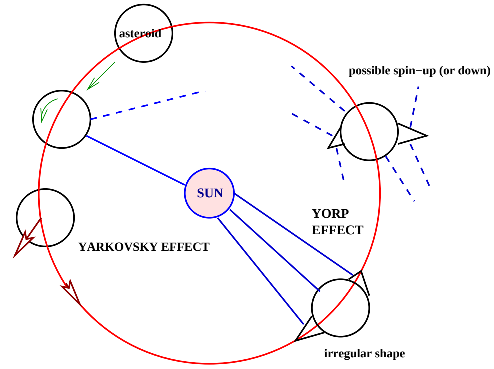

Figure 2. A schematic representation of the Yarkovsky–YORP effects. The solar radiation is partly absorbed and re–emitted with a time delay; the rotation of the asteroid causes a misalignment between the absorption and re–emission direction, thus causing a possible momentum transfer along the orbital motion (Yarkovsky effect), secularly affecting the semimajor axis of the orbit. Moreover, if the asteroid has not a regular shape, the absorption/re–emission of solar radiation may cause a transfer of spin angular momentum (YORP effect).

fast spinners above 100 m supports the suggestion (already coming out from the hydrocodes) that only very small asteroids can survive their collisional evolution as monoliths. The *pile of rubble* idea seems to prevail. The dominance of rubble piles even at small sizes is consistent with the scenario coming out from the hydrocodes: the asteroids are easily shattered by collisions (far more easily than previously assumed) but the fragments are ejected at low velocities, thus allowing a massive reaccumulation, due to self gravity, into several bodies (Michel et al. 2002, 2004). Unfortunately, within this scenario the collisional models cannot reproduce the observed spread of dynamical families in the space of orbital elements nor obtain the orbital mobility required to refill the NEO region.

3. Yarkovsky effect comes in

These problems may be solved invoking the Yarkovsky effect (Vokrouhlicky 1998; Vokrouhlicky and Farinella 1998; Vokrouhlicky 1999; Spitale and Greenberg 2001).

The Yarkovsky effect causes a slow diffusion of objects in the space of orbital elements, can simulate larger ejection velocities within the asteroid families, and allows the injection of a steady flux of small and intermediate sized asteroids into the major dynamical resonances. Among them, the 3:1 and the ν_6 are the most effective to inject bodies into the NEOs region (Bottke et al. 2000, 2002; Morbidelli and Vokrouhlicky 2003).

If the Yarkovsky effect dominates the semimajor axis mobility, consequences concerning the pole distributions may come out. In fact, due to the Yarkovsky effect, the semimajor axis decreases whenever the rotation is retrograde, increases when it is prograde. Thus, for example, one should observe retrograde asteroids in the inner part of a family, prograde in the outer one. When a fragment is formed, depending on the impact geometry, one has a correlation between the ejection velocity and the sense of rotation. The original properties af the family and the Yarkovsky ageing interact in various ways; only if Yarkovsky completely dominates the previous statement remains valid (Fig. 3). For the moment we have only one family for which a significant sample of poles has been computed, i.e. Koronis (Slivan 2002). If we compare the distribution of semimajor axes for prograde and retrograde spinning asteroids, we see that the mean value for prograde bodies is 2.884A.U., compared to 2.774A.U. for retrograde objects. The result might be of some interest; however, note that the observed poles concern only 10 bodies: thus the statistics is very poor. Moreover, and more important, all the observed bodies have sizes (few tens of kilometers) for which the time required for a significant Yarkovsky–driven semimajor axis mobility is rather large. Consequently, we cannot rely too much on the significance of this result, and further observational work –mainly devoted to smaller sizes– is urged.

3.1. Yarkovsky and NEOs

As discussed before, the retrograde bodies may enter the resonances backward and the prograde bodies inward. It may cause observable effects among NEOs. We compared (La Spina et al. 2004) the pole distribution of MB bodies (87) and of NEOs (21)(Fig. 4).

While the "ecliptic–plane depopulation" is similar for MB and NEO samples, the NEOs exhibit a strong excess of retrograde, instead of prograde, bodies. Note that almost 50% of NEOs are in the first bin (of seven). A statistical analysis confirms that the NEO and MB distributions may be considered as similar only with a probability of about one percent.

If we accept the Yarkovsky hypothesis we can easily show that only retrograde bodies can enter the ν_6 (which is close to the inner border of the Main Belt), while the 3:1 and the other possible resonances can be reached in both ways. According to the estimated rates it entails a retrograde vs. prograde excess of about 2:1, which is exactly (even too exactly, given the poor statistics) what we see.

4. New topics: $2D$ distribution, spin statistics

The $2D$ distribution (latitudes vs longitudes Kryszczynska et al. (2005)) shows again the depopulation close to the ecliptic plane. It

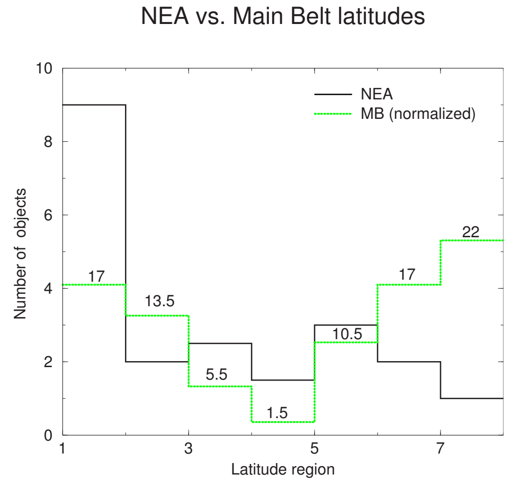

Figure 4. The figure (adapted from La Spina et al. (2004)) compares the latitude distributions for MB asteroids and NEOs. The latitude bins have been defined in order to have, in the case of a isotropic spin–vector distribution, equal numbers of bodies in every bin (Pravec et al. (2002), see Fig.6 therein; La Spina et al. (2004)). The MB distribution has been normalized to the same number of objects as that corresponding to NEOs, in order to ease the comparison. Labels above the bins refer to the real number of objects. Half–integer values are present whenever the latitudes have a twofold designation (in these cases the body has been counted $1/2$ for each corresponding bin). The comparison shows the significant excess of retrograde bodies among NEOs, which can be explained in terms of a selection effect due to the Yarkovsky effect (La Spina et al. 2004). The results are essentially the same with the updated database (Kryszczynska et al. 2005).

shows also some clusterings. The most evident clusters correspond to the so called Slivan Asteroids, members of the Koronis family (Slivan 2002). Their properties have been explained (Vokrouhlicky et al. 2003) in terms of YORP effect. In turn, YORP concentrates bodies close to the ecliptic poles; it might explain also the ecliptic plane depopulation. However, YORP has been claimed to work for bodies up to 40 km, which are almost absent in our MB sample. Further analysis should be required.

Note also (La Spina et al. 2002) that whenever the pole distribution is not isotropic, the usual statistical assumptions leading to the

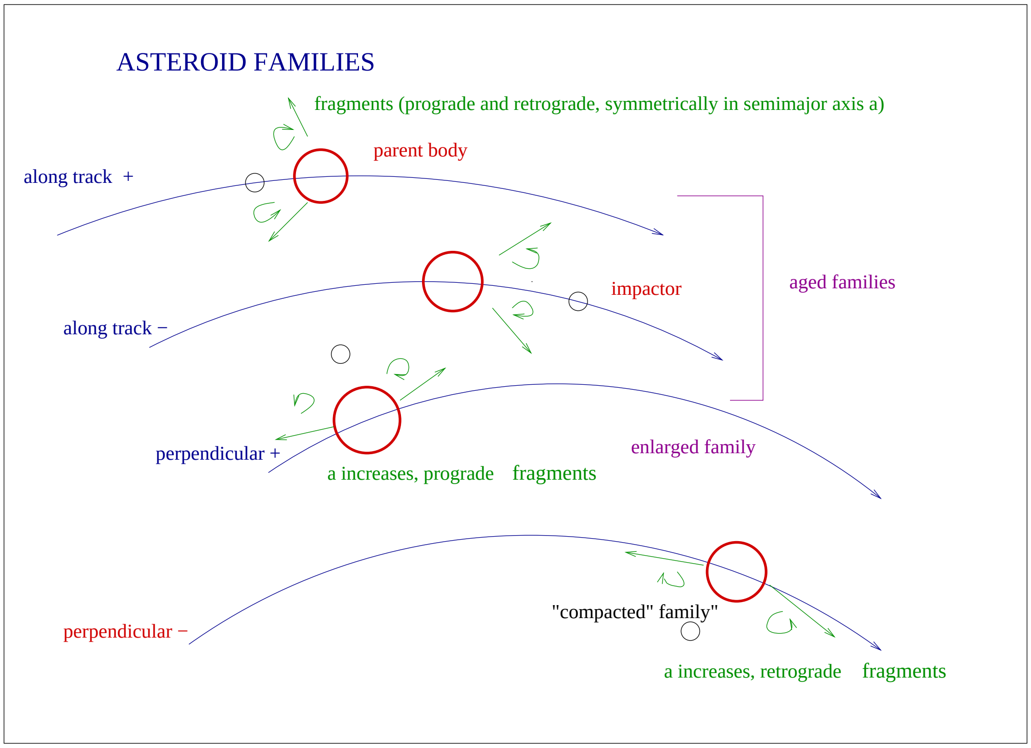

Figure 3. The spread of a dynamical family in the space of orbital elements, and in particular along the semimayor axis, depends on a combined effect of the breakup geometry and of Yarkovsky–driven mobility. According to different impact geometries the original dispersion and that due to Yarkovsky effect 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. However, if Yarkovsky mobility dominates, one should always expect to observe in mean prograde asteroids at larger semimajor axes than retrograde ones.

maxwellian distribution of the rotation rates (Ω) are no more working. The resulting distribution should be different (usually broader). The effect has to be taken into account when analyzing the spin distribution.

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