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Spin axes and shape models of asteroid pairs: Fingerprints of YORP and a path to the density of rubble piles

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ABSTRACT

An asteroid pair consists of two unbound objects with almost identical heliocentric orbital elements that were formed when a single "rubble pile" asteroid failed to remain bound against an increasing rotation rate. Models suggest that the pairs' progenitors gained the fast rotation due to the YORP effect. Since it was shown that the spin axis vector can be aligned by the YORP effect, such a behavior should be seen on asteroid pairs, if they were indeed formed by the described mechanism. Alternatively, if the pairs were formed by a collision, the spin axes should have a random direction and small or young bodies might have a tumbling rotation.

Here I apply the lightcurve inversion method on self-obtained photometric data, in order to derive the rotation axis vectors and shape models of the asteroid pairs 2110, 3749, 5026, 6070, 7343 and 44612. Three asteroids resulted with polar-directed spin axes and three objects with ambiguous results. In addition, the secondary member 44612 presents the same sense of rotation as its primary member 2110, and its spin is not tumbling. Finally, I use a rotational fission model, based on the assumption of an angular momentum conservation, and match it to the measured spin, shape, and mass ratio parameters in order to constrain the density of the primary members in the pairs. Using this method, low density values that are expected from a "rubble pile" are derived. All these results lead to the conclusion that the disruption of these asteroid pairs was most likely the outcome of the YORP effect that spun-up "rubble pile" asteroids.

1. Introduction

1.1. Spin evolution mechanisms

The Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect is a thermal torque imposed on asteroids due to the reflection and re-emission of sunlight from the body's asymmetric surface (Rubincam, 2000; Bottke et al., 2006). Since the YORP effect is applied by the momentum carried by sunlight photons, it is mainly a function of the asteroid radius R and its heliocentric distance, characterized by its semi major-axis a. The resulted change in the spin rate of the asteroid $d\omega/dt$ can be defined by (Scheeres, 2007):

$$\frac{d\omega}{dt} = \frac{Y}{2\pi\rho R^2}\frac{F}{a^2\sqrt{1-e^2}} \quad (1)$$

where ρ is the density of the body and e is the eccentricity of its orbit. F is the solar irradiance (1.361 kW/m^2, at 1 AU) modified by the speed of light to derive solar radiation pressure and normalized to a unit distance ($\sim 1 \times 10^{14}$ kg km s^{-2}; Scheeres, 2007). Y is a non-dimensional YORP coefficient determined by the asymmetric shape of the asteroid and the obliquity of its rotation. The YORP timescale τ_{yorp} is defined by:

$$\tau_{yorp} = \frac{\omega}{\left|\frac{d\omega}{dt}\right|} \quad (2)$$

where ω is the spin rate. The change dP/dt in the rotation period P can be defined by (Rozitis and Green, 2013):

$$\frac{dP}{dt} = \pm\frac{P^2}{2\pi}\frac{d\omega}{dt} \quad (3)$$

Observational studies have shown that the YORP effect can double the spin rate of an asteroid in a relatively short timescale of about a million years for a km-sized near-Earth asteroids (e.g., Lowry et al., 2007; Taylor et al., 2007; Kaasalainen et al., 2007; Ďurech et al., 2008, 2012). Such a short timescale makes the YORP effect a very efficient mechanism to control the spins of small bodies (up to diameter of ∼10 km) among the near-Earth asteroids (NEAs) and main-belt asteroids (MBAs) alike, according to their

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spin distributions (e.g., Pravec et al., 2008; Polishook and Brosch, 2009; Statler et al., 2013). While the rotation of an asteroid can also be spun-up by sub-catastrophic impacts (Paolicchi et al., 2002), the YORP effect seems to be a more robust and efficient process for small-sized asteroids (Marzari et al., 2011, Jacobson et al., 2014).

The YORP effect is also known to modify the obliquity of asteroids since the re-emitted light has a non-orthogonal component imposed on the spin axis. Hanuš et al. (2011) found that the latitude distribution of small asteroids ($D < 30$ km) is clustered towards ecliptic poles and explained it by the YORP effect. Slivan (2002) found that asteroids of the Koronis family tend to cluster in two specific states (one in prograde and the second in a retrograde rotation) even though the Koronis family asteroids were formed in a catastrophic collision, and their obliquities and rotation periods should have a random distribution (Asphaug and Scheeres, 1999; Paolicchi et al., 2002). Vokrouhlický et al. (2003) showed how the measured obliquities of the Koronis family can be the result of the YORP effect and a spin–orbit resonance. Therefore, asteroids that were formed by a catastrophic collision, within a recent time that is shorter than the timescale of the YORP effect, should present a randomized obliquity distribution rather than a distribution biased for a specific rotation state. This is also true for large asteroids that were formed by catastrophic collisions: since their YORP timescale exceeds the age of the Solar System, they present a randomized obliquity distribution (Hanuš et al., 2013).

Not only do catastrophic collisions randomize the obliquity distribution of the fragments, they also give the resulted asteroids a wide range of rotation periods characterized by complex rotations as was shown by numerical calculations (Asphaug and Scheeres, 1999) and laboratory experiments (Giblin et al., 1998). Complex rotations around a non-principal axis are referred to as *tumbling asteroids* (Pravec et al., 2005) and the time τ_{damp} needed to damp the excited spin into an uniform rotation was derived by Burns and Safronov (1973) as:

$$\tau_{damp} \sim \frac{\mu Q}{\rho K_3^2 R^2 \omega^3}. \quad (4)$$

where μ is the rigidity of the material the asteroid is composed of, Q is the ratio of the energy contained in the oscillation to the energy lost per cycle (''quality factor''), ρ is the asteroid's density, R is its mean radius and ω is its spin rate. K_3^2 is a dimensionless factor relating to the asteroid's shape. Using reasonable values described by Harris (1994), one can calculate that the damping time for a tumbling km-sized asteroid is $\sim 10^6$ to $\sim 10^8$ years depending on the rotation period. Therefore, asteroids that were formed by a catastrophic collision, within a recent time that is shorter than their damping timescale, should present tumbling rotations rather than a relaxed rotation around a single axis.

1.2. Asteroid pairs

Pairs of asteroids that share almost identical heliocentric orbits were shown by dynamical calculations to originate from a single progenitor and not to be a mere coincidence (Vokrouhlický and Nesvorný, 2008, 2009; Pravec and Vokrouhlický, 2009). Members belonging to the same pair present similar spectral behavior or broadband colors, without a single case of a significant mismatch observed (up until now, similarities were observed among 20 *asteroid pairs*: Moskovitz, 2012; Duddy et al., 2012, 2013; Polishook et al., 2014; Wolters et al., 2014). This result supports the notion of a single origin for each pair to a significance of almost 5σ.

The formation of *asteroid pairs* was explained as the subsequent outcome of the YORP effect: following the spin-up of an asteroid by the YORP effect, an asteroid gains sufficient angular momentum to cross the breakup limit for a strengthless, ''rubble pile'' object (Margot et al., 2002; Scheeres, 2007; Walsh et al., 2008; Jacobson and Scheeres, 2011), and the asteroid split into a *pair* of asteroids[1] (Pravec et al., 2010). Alternatively, a catastrophic collision could form the pairs (Durda et al., 2004), even though the slow drifting velocity between the components of each pair is less likely in a scenario of a collision (Vokrouhlický and Nesvorný, 2008).

1.3. Study goals

Measuring the spin axis of asteroid pairs could disentangle between the two formation models: if the latitude distribution presents high preference for ecliptic poles then the YORP effect is the relevant mechanism for the pairs formation; if the latitude distribution is randomized than collisions shuttered the pairs' progenitors. In addition, a collision event can explain two members of a single asteroid pair that have significantly different spin axes, while the rotational fission model cannot. The model suggested by Pravec et al. (2010) assumed that the spin axes of a pair's members are parallel, and their model matches to the measurements of the pairs' spin periods and mass ratios. This match suggests that their assumption is indeed valid. Here, I am directly measuring the spin axes of asteroid pairs in order to confirm this assumption.

An important factor is the short time that passed since the pairs formation (10^4–10^6 years; Vokrouhlický and Nesvorný, 2008; Pravec et al., 2010; Polishook et al., 2014), that is referred here as the ''dynamical age''. If this time is shorter than the YORP timescale than we can assume that the YORP effect did not alter the spin vector since the fission event occur.

Same goes for the internal damping timescale. If an asteroid pair has a damping timescale that is longer than its dynamical age, and if the spin does not presents a tumbling nature, then the pair was not formed by a catastrophic collision. This is especially true for the smaller members of the pairs that have longer damping times.

In addition, knowing the sense of rotation of *asteroid pairs* is important for calculating the time passed since their formation: the sense of rotation determines the sign of the Yarkovsky drag (Bottke et al., 2006) imposed on the asteroid and it modifies its heliocentric orbit. This is an essential parameter when integrating backward an asteroid's orbital elements to derive the dynamical age of the pair.

And finally, deriving the spin axis by the lightcurve inversion method also constrains the shape model of the asteroid. Assuming a pair formed by the YORP effect, the shape and spin parameters can further constrain the density of the rotational-fissioned asteroid using an angular momentum conservation model as describe below. If the derived density values are low compared to the density of the material the asteroids consist of, than we can conclude these asteroids have a strengthless, *rubble-pile* structure, an essential characteristic for the rotational-fission mechanism to take place.

2. Observations, reduction, measurements and calibration

2.1. Observations from the Wise Observatory

I collected photometric data on six asteroids during more than 110 nights between 2007 and 2014 (fortunately, most observations

[1] In this context, the term ''*asteroid pair*'' originates from the discovery circumstances of this class of objects, but it also describes an asteroid that broke apart into multiple bodies. This was recently observed by Jewitt et al. (2014) that follow the disintegration of the main belt asteroid *P/2013 R3* into, at least, 10 fragments. The main belt asteroids *P/2010 A2* and *P/2013 P5* probably suffered from the same fate (Jewitt et al., 2010, 2013).