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Matching asteroid population characteristics with a model constructed from the YORP-induced rotational fission hypothesis

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ABSTRACT

From the results of a comprehensive asteroid population evolution model, we conclude that the YORP-induced rotational fission hypothesis is consistent with the observed population statistics of small asteroids in the main belt including binaries and contact binaries. These conclusions rest on the asteroid rotation model of Marzari et al. ([2011]Icarus, 214, 622–631), which incorporates both the YORP effect and collisional evolution. This work adds to that model the rotational fission hypothesis, described in detail within, and the binary evolution model of Jacobson et al. ([2011a] Icarus, 214, 161–178) and Jacobson et al. ([2011b] The Astrophysical Journal Letters, 736, L19). Our complete asteroid population evolution model is highly constrained by these and other previous works, and therefore it has only two significant free parameters: the ratio of low to high mass ratio binaries formed after rotational fission events and the mean strength of the binary YORP (BYORP) effect.

We successfully reproduce characteristic statistics of the small asteroid population: the binary fraction, the fast binary fraction, steady-state mass ratio fraction and the contact binary fraction. We find that in order for the model to best match observations, rotational fission produces high mass ratio ($>$ 0.2) binary components with four to eight times the frequency as low mass ratio ($<$0.2) components, where the mass ratio is the mass of the secondary component divided by the mass of the primary component. This is consistent with post-rotational fission binary system mass ratio being drawn from either a flat or a positive and shallow distribution, since the high mass ratio bin is four times the size of the low mass ratio bin; this is in contrast to the observed steady-state binary mass ratio, which has a negative and steep distribution. This can be understood in the context of the BYORP-tidal equilibrium hypothesis, which predicts that low mass ratio binaries survive for a significantly longer period of time than high mass ratio systems. We also find that the mean of the log-normal BYORP coefficient distribution $\mu_B \gtrsim 10^{-2}$, which is consistent with estimates from shape modeling (McMahon and Scheeres, 2012a).

1. Introduction

The YORP-induced rotational fission hypothesis predicts that the Yarkovsky–O'Keefe–Radzievksii–Paddack (YORP) effect can rotationally accelerate rubble pile asteroids until internal stresses within the body due to centrifugal accelerations surpass the gravitational attractions holding the rubble pile elements in their current configurations. Subsequently, according to the hypothesis, these asteroids rotationally fission into mutually orbiting components that can dynamically evolve into the observed binary populations (Bottke et al., 2006; Jacobson and Scheeres, 2011a; Scheeres, 2007a; Walsh et al., 2008). This hypothesis has been constructed on two pillars: the theoretical conclusion that light imparts a meaningful torque on small asteroids, which has been named the YORP effect (Rubincam, 2000), and the observations that the majority of binary asteroid systems have rapidly rotating primaries and small semi-major axes relative to the radius of the primary. This configuration has a high angular momentum content, which is consistent only with formation from rotational fission (Margot et al., 2002).

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The hypothesis has also undergone observational and theoretical experiments. Rotational fission predicts a relationship between the angular momentum content of the fissioned asteroid system and the mass ratio between its components (Scheeres, 2007a). In the asteroid pair population, Pravec et al. (2010) discovered that the spin rates of the larger members and the mass ratio of each observed asteroid pair had the predicted relationship. This confirmed that asteroid pairs are the result of rotational fission. Jacobson and Scheeres (2011a) tested the connection between rotational fission and the observed binary population by numerically modeling the post-rotational fission process. With only the inclusion of gravitational dynamics and mutual body tides, they were able to create the most commonly observed asteroid systems (e.g. asteroid pairs, binaries, contact binaries, etc.). After including the binary YORP (BYORP) effect, all the observed binary systems are hypothesized to be natural final states after these processes (as reviewed in Jacobson et al., 2014b).

Often asteroid evolution occurs too quickly (on Solar System timescales) and too infrequently (on human timescales) to be observed *in situ*. Although, as larger telescopes are aimed at smaller asteroid systems, the possibility of capturing rotational fission events as they occur grows increasingly high (Marzari et al., 2011) (and the first such systems may have already been observed, e.g. Jewitt et al., 2014; 2010). In the meantime, these timescales present a challenge for direct confirmation of rotational fission and subsequent binary evolution, but the proposed asteroid evolution makes specific predictions for the relative abundances of each final state so a detailed asteroid population evolution model that reproduces the observed sub-populations is a strong consistency test of the YORP-induced rotational fission hypothesis. We present such an asteroid population evolution model that allows us to see if the proposed evolutionary mechanisms are sufficient to create the observed sub-populations and, perhaps more importantly, create them in the right proportions to one another.

The asteroid population evolution model is a development of the model presented in Marzari et al. (2011), which studied the rotational evolution of the Main Belt asteroid (MBA) population including both the YORP effect and collisions. This model was already an improvement and continuation of earlier projects by Rossi et al. (2009) and Scheeres et al. (2004), which studied the near-Earth asteroid population. Similar to Marzari et al. (2011), we use a Monte Carlo approach to simulate the evolution of 2×10^6 asteroid systems for 4.5×10^9 years. The spin state of each asteroid evolves constantly due to the YORP effect and collisions as in Marzari et al. (2011) (summarized in Section 2). Similar to Jacobson et al. (2014a), when the rotation rate of an asteroid exceeds a specified spin limit, the asteroid rotationally fissions and can form a binary system. The survival and lifetimes of these binary systems are determined from a separate set of calculations based on the results of Jacobson and Scheeres (2011a, 2011b).

Both the single and binary evolution schemes are built from well-developed theories in the literature. Therefore, there are very few free parameters built into the model that have not been significantly constrained elsewhere. For instance, the intrinsic probability of collision for Main Belt asteroids $\langle P_i \rangle = 2.7 \times 10^{-18}\ \mathrm{yr}^{-1}\ \mathrm{km}^{-2}$, the fundamental parameter determining the frequency of collisions in the model, has been established by the efforts of a series of authors to at least the order of uncertainty inherent in other parts of the asteroid population evolution model (Bottke et al., 1994; Farinella and Davis, 1992). Similarly, the binary evolution model utilizes the evolutionary flowchart and derived probabilities given in Jacobson and Scheeres (2011a); 2011b).

The binary evolution model does contain two free input parameters that are not well constrained by either observation or current theory. The first parameter is the initial mass ratio fraction F_i, which is the ratio of high mass ratio to low mass ratio binary systems created from rotational fission events. This parameter is determined from the interior structure of the rotationally fissioning asteroid and the mechanics of the fission event itself, neither of which are currently observed or modeled accurately enough to generate this number. The initial mass ratio fraction is distinct from the observed mass ratio fraction F_q, which reflects the evolutionary differences between high and low mass ratio systems.

The second parameter is the mean of the logarithmic normal distribution of the BYORP coefficient μ_B. It is used to determine the strength of the BYORP effect, which determines the bound lifetimes for most binary systems. The basic shape and width of the distribution is determined from the equilibrium occupied by the synchronous binary asteroid population. There has only been a single published estimation of a BYORP coefficient and the shape model used may not have had the necessary accuracy (McMahon and Scheeres, 2010a) and this effect has yet to be measured. These parameters are the knobs that will control the output from the asteroid population evolution model.

After evolving the population for the age of the Solar System, which is longer than needed for the sub-populations to reach a relative steady-state equilibrium for most choices of μ_B, we can compare the model to the observed main asteroid belt. There are four particular observables that we can compare with our model: The binary fraction F_B, which is the total number of binaries over the total number of asteroid systems, the fast-rotating binary fraction, F_F, which is a more specific comparison of the number of binaries with rapidly rotating primaries to the number of rapidly rotating asteroids, the steady-state (i.e. observed) mass ratio fraction F_q, which is defined similarly to the initial mass ratio fraction F_i above, and the contact binary fraction F_C, which is the number of contact binaries over the total number of asteroid systems. From these comparisons, we construct a simple log-likelihood model to assess which model parameters, F_i and μ_B, are the most likely to match the model population to the observations. Lastly, we discuss the best fit models and their implications for future observations and tests.

2. Single asteroid evolution

Each asteroid within the asteroid population evolution model is individually evolved. Similar to Marzari et al. (2011), the asteroid population evolution model utilizes the intrinsic probability for impact $<P_i>$ and a projectile size frequency distribution to determine the collision history of each model asteroid. Between collisions, single asteroids undergo rotational evolution driven by the YORP effect, which modifies both the spin rate and obliquity of the asteroid. Rotational acceleration can lead to rotational fission if it occurs before the next collision event. The specific conditions for triggering rotational fission and the process itself are parameterized using well-developed models (Jacobson and Scheeres, 2011a; Scheeres, 2007a).

Each asteroid system is characterized by a number of fixed and evolving parameters. These parameters change if the system undergoes rotational fission and evolves into a binary asteroid system. All systems are assigned a fixed semi-major axis $a_\odot$ and eccentricity $e_\odot$ from a Main Belt asteroid orbital element distribution. Both the YORP effect and collisions evolve the spin rate ω and the obliquity ϵ of each asteroid. The initial spin rate is drawn from a Maxwellian distribution with a $\sigma = 1.99$ corresponding to a mean period of 7.56 hr, which is consistent with Fulchignoni et al. (1995) and Donnison and Wiper (1999). Rossi et al. (2009) demonstrated for models similar to the asteroid population evolution model that the steady-state spin rate distribution is independent of the initial spin rate distribution. We draw the initial obliquity of