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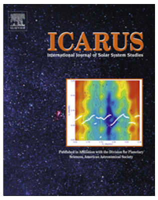

Observations of “fresh” and weathered surfaces on asteroid pairs and their implications on the rotational-fission mechanism

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ABSTRACT

The rotational-fission of a “rubble-pile” structured asteroid can result in an “asteroid pair” – two unbound asteroids sharing nearly identical heliocentric orbits. Models suggest that this mechanism exposes material from below the progenitor surface that previously had never have been exposed to the weathering conditions of space. Therefore, the surfaces of asteroid pairs offer the opportunity to observe non-weathered “fresh” spectra.

Here we report near-infrared spectroscopic observations of 31 asteroids in pairs. In order to search for spectral indications of fresh surfaces we analyze their spectral slopes, parameters of their 1 μm absorption band and taxonomic classification. Additionally, through backward dynamical integration we estimate the time elapsed since the disintegration of the pairs’ progenitors.

Analyzing the 19 ordinary chondrite-like (S-complex) objects in our sample, we find two Q-type Asteroids (19289 and 54827) that are the first of their kind to be observed in the main-belt of asteroids over the full visible and near-infrared range. This solidly demonstrates that the Q-type taxonomy is not limited to the NEA population.

The pairs in our sample present a range of fresh and weathered surfaces with no clear evidence for a correlation with the ages of the pairs. However, our sample includes “old” pairs ($2 \times 10^6 \geqslant \text{age} \geqslant 1 \times 10^6$ years) that present relatively low, meteoritic-like spectral slopes (<0.2% per μm). This illustrates a timescale of at least ∼2 myr before an object develops high spectral slope that is typical for S-type asteroids.

We discuss three mechanisms that explain the existence of weathered pairs with young dynamical ages and find that the “secondary fission” model (Jacobson, S.-A., Scheeres, D.-J. [2011]. Icarus 214, 161–178) is the most robust with our observations. In this mechanism an additional and subsequent fission of the secondary component contributes the lion share of fresh material that re-settles on the primary’s surface and recoats it with fresh material. If the secondary breaks loose from the vicinity of the primary before its “secondary fission”, this main source of fresh dust is avoided. We prefer this secondary fission model since (i) the secondary members in our sample present “fresh” parameters that tend to be “fresher” than their weathered primaries; (ii) most of the fresh pairs in our sample have low size ratios between the secondary and the primary; (iii) 33% of the primaries in our sample are fresh, similar to the prediction set by the secondary fission model (Jacobson, S.-A., Scheeres, D.-J. [2011]. Icarus 214, 161–178); (iv) known satellites orbit two of the pairs in our sample with low size ratio (D_2/D_1) and fresh surface; (v) there is no correlation between the weathering state and the primary shape as predicted by other models.

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1. Introduction and motivation

1.1. Dynamics and formation of asteroid pairs

Pairs of asteroids move about the Sun on very similar orbits (Vokrouhlický and Nesvorný, 2008), but, unlike binary asteroids,[1] are gravitationally unbound. The orbits of paired asteroids are so similar that they cannot be a mere coincidence (Vokrouhlický and Nesvorný, 2008, 2009; Pravec and Vokrouhlický, 2009). Moreover, using backwards orbital integrations have shown that members of each pair were in the same location in space sometime within the past few million years. This suggests a common origin for the components of each pair. Indeed, spectroscopic observations and broadband photometry studies have shown that members of observed pairs have similar spectra or colors (Moskovitz, 2012; Duddy et al., 2012, 2013). It was also found that asteroid pairs are not correlated to a specific type of composition or taxonomic class (Moskovitz, 2012).

Pair formation by collision has been rejected due to the low relative velocity between components at the time of their formation (e.g., Vokrouhlický and Nesvorný, 2008, 2009; Pravec and Vokrouhlický, 2009). Rather, this low velocity supports a model of a gentle separation of an unstable binary asteroid configuration. This is further supported by the distribution of the mass ratio between the members of each pair that is complementary to the distribution of gravitationally bound binary asteroids (Vokrouhlický and Nesvorný, 2008). Modeling suggests that pairs form by the fission of a fast-rotating aggregate-like asteroid (with the so-called "rubble-pile" structure) into two objects (e.g., Scheeres, 2007, 2009; Jacobson and Scheeres, 2011). Finally, photometric measurements (Pravec et al., 2010) showed that rotation periods of the larger members of asteroid pairs are correlated with the mass ratio in a way that matches the rotational-fission mechanism: (i) if the secondary (the smaller member) is massive enough, it carries a significant amount of angular momentum and the rotation rate of the primary (the larger member) will decelerate; (ii) if the secondary is not massive, the primary will continue to rotate fast. Furthermore, these measurements also confirmed that there is a limit to the secondary mass fraction at ~20% of the primary, as previously predicted by theoretical models. Larger secondaries do not have sufficient energy to leave the primary; thus they remain in its vicinity, forming binary asteroids (Pravec et al., 2010; Scheeres, 2007).

1.2. The rotational-fission mechanism

The main process to accelerate asteroids' spins is the Yarkovsky–O'Keefe–Radzievsky–Paddack effect, also known as the YORP effect (Rubincam, 2000; Bottke et al., 2006). The YORP effect is a radiation torque imposed on a rotating body due to the asymmetric reflection and re-emission of sunlight. The relatively short evolution timescale of 1–10 Myr for small-sized asteroids (with diameter smaller than ~10 km), confirmed by direct detections (e.g., Lowry et al., 2007; Taylor et al., 2007; Kaasalainen et al., 2007; Ďurech et al., 2008, 2012), makes the YORP effect a very efficient mechanism to control the spins of asteroids among the near-Earth asteroids (NEAs) and main-belt asteroids (MBAs; e.g., Pravec et al., 2008; Polishook and Brosch, 2009). While the rotation of an asteroid can also be spun-up by sub-catastrophic impacts, the YORP effect seems to be a more robust and efficient process for small-sized asteroids[2] (Marzari et al., 2011).

When the accelerated spin of the asteroid reaches the critical spin for a 'rubble-pile' object (at about 2.2 h per rotation; Richardson et al., 1998; Pravec and Harris, 2000), the asteroid fissions (Margot et al., 2002). However, different scenarios of the rotational fission process have been proposed. For instance, Walsh et al. (2008, 2012) present a model in which the fast rotation transports material towards the equator and gradually forms a near-equatorial ridge (as evidenced, e.g., by the diamond-shape of Asteroid (66391) 1999 KW4; Ostro et al., 2006; Harris et al., 2009; and other objects). If continued, this process can eject part of the equatorial mass, where it can re-accumulate into a satellite. Using this model, Walsh et al. were able to theoretically produce satellites and diamond-shape objects as seen in nature by observations. However, it is unclear if the ejected material has enough time in orbit around the asteroid to be accumulated into a satellite. In addition, Holsapple (2010) using granular theory finds that mass loss should not occur at the equator but rather the shape of the body would deform until interior failure occurs. Furthermore, the elongated shapes of some asteroid pairs (Pravec et al., 2010) do not match the diamond shapes resulted by Walsh et al. model.

Alternatively, Scheeres (2007, 2009) describes a model of a coarser internal structure of the parent body that consists of a set of larger components. His model suggests that the rotational-fission mechanism can result in the loss of a significant part of the fast-rotating body so that the ejected component (the secondary member) will start its own course around the Sun. Jacobson and Scheeres (2011) further developed this model and suggested that the secondary itself might disintegrate since it is under the pressure of the primary's tidal forces during the tens of days after its detachment and before it is lost in space. A fission of the secondary might form a third body that can crash into the primary, fall back on the secondary, or be lost to space. As the third body leaves the system it carries with it the excess of angular momentum, by that stabilizing the orbit of the secondary object around the primary, allowing them to become gravitationally bound as a binary asteroid.

The model of Walsh et al. and the model of Scheeres and Jacobson differs in duration over which the fission process takes place: the first is a gradual and slow process that can take one or more spin-up pulses induced by the YORP effect, stretching out over a long time interval (hundreds of ky to Mys). The fission by the second model is immediate, and a few days up to tens of days are needed before the ejected component is lost. This scenario is also more violent than the gradual model, since more energy is needed to remove a significant part of the asteroid, and this is probably followed with the removal of dust and debris that sink back on the main body and recoating it. Further disintegration of the secondary, and possible impacts between the ejected components to the primary object, probably results with even more dust and debris. The recent observation of the main belt object P/2013 P5 that presented a dusty structure of multi-tails and a coma (Jewitt et al., 2013) can be explained by a rotational-fission event of a fast rotating asteroid and the following fission of its secondary member, thus it supports the fast model.

While more diamond-shaped, fast-rotating asteroids have been found in recent years, supporting the Walsh et al. model, the Scheeres' model helps to better explain the relatively large secondaries of asteroid pairs and the above mentioned strong correlation between the rotation period of the primary and the mass ratio of the two components. If the two models are valid, it is unknown what conditions will favor one mechanism over the other, and which is the more frequent scenario among asteroids. One way of probing the fission models is provided by spectral observations. This is because the extent of excavation and transportation of material following rotational-fission might be revealed on asteroids of the ordinary chondrite (OC) type (part of the so-called

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[1] Binary asteroids are two objects revolve about a common center of mass, which itself moves about the Sun (e.g., Merline et al., 2002a; Richardson and Walsh, 2006; Pravec et al., 2006; Taylor and Margot, 2011).

[2] We should note that theoretically the YORP effect can also spin-down asteroid spins, depending on their physical parameters; however, this scenario is irrelevant for the rotational-fission mechanism.

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