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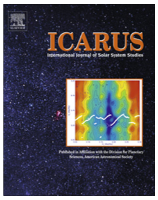

In search of the source of asteroid (101955) Bennu: Applications of the stochastic YORP model

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ABSTRACT

Asteroid (101955) Bennu, the target of NASA's OSIRIS-REx sample return mission, is a $D \approx 0.5$ km diameter low albedo near-Earth object. It has a spectral signature consistent with primitive carbonaceous chondrites, and an orbit similar to that of the Earth. A plausible evolution scenario for Bennu is that it migrated inward across the inner main belt from a low albedo family by Yarkovsky thermal forces over many hundreds of Myr. Eventually, it entered a resonance that took it into the terrestrial planet region, where a combination of planetary encounters and resonances took it to its current orbit over a few Myr to tens of Myr. When it departed the main belt, Bennu probably had an eccentricity $0.1 < e < 0.2$ and an inclination $1^\circ < i < 6^\circ$. Several low albedo families have the appropriate dynamical, color, albedo, and broad spectral characteristics to produce Bennu: Clarissa, Erigone, Eulalia, New Polana, and Sulamitis.

Here we used a suite of numerical simulations to determine the ages of the families above, how Bennu reached its current orbit, and the most probable source family for Bennu. Specifically, we tracked test Bennu-like asteroids evolving in semimajor axis by the coupled Yarkovsky/YORP effects, incorporating a new formalism for how YORP torques modify the spin vector evolution of small asteroids. Using results and insights provided by Statler (Statler, T.S. [2009]. Icarus 202, 502–513), we assumed that modest shape changes to asteroids, produced by a variety of processes (e.g., crater formation, changes to asteroid rotational angular momentum by YORP), caused the test asteroids' spin rates, but not their obliquities, to undergo a random walk. This "stochastic YORP" mechanism slows down how often asteroids reach YORP endstates (i.e., spinning up so fast that the asteroid sheds mass, spinning down so much the asteroid enters into a tumbling rotation state). This new model allowed us to reproduce the semimajor axis distribution of observed family members from Clarissa, Erigone, Eulalia, New Polana, and Sulamitis. In the process, we derived model family formation ages of $\sim$60 Myr old, 130 ± 30 Myr old, 830^{+370}_{-100} Myr old, 1400 ± 150 Myr old, and 200 ± 40 Myr, respectively.

Next, using a Monte-Carlo code to track millions of test asteroids from each of the families above to main belt escape routes capable of producing Bennu-like orbits, we found the most likely parent families for Bennu are Eulalia and New Polana. On average, more than twice as many 0.5 km objects from the New Polana family reach Bennu's orbit as those from the Eulalia family. This corresponds to the New Polana and Eulalia families having a $70^{+8}_{-4}\%$ and $30^{+4}_{-8}\%$ probability of producing Bennu, respectively. Comparable runs to deduce the source of the Hayabusa 2 target, the low albedo 0.87 km diameter near-Earth object (162173) 1999 JU3, produced similar probabilities for both families. The former Marco-Polo-R target, the 1.9 km asteroid (175706) 1996 FG3, however, has a $85^{+4}_{-83}\%$ probability of coming from the Eulalia family and a $15^{+83}_{-4}\%$ probability of coming from the New Polana family. The reason for this switch is that 1996

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FG3 may have been part of Yarkovsky/YORP-produced wave of like-sized bodies that is only now reaching the terrestrial planet region. We suggest that the top-like shape of Bennu is a byproduct of mass wasting and/or mass shedding events produced by YORP spin up during its long journey across the inner main belt.

1. Introduction

NASA's OSIRIS-REx (Origins Spectral Interpretation Resource Identification Security Regolith Explorer) mission is planning to visit and return a sample from near-Earth asteroid (101955) Bennu, (its provisional designation was 1999 RQ_{36}; hereafter we will call it Bennu) (Lauretta et al., in press). Bennu is a low albedo $D \approx 0.5$ km diameter B-class asteroid whose spectral signature is most consistent with primitive CI or CM carbonaceous chondrites (Clark et al., 2011; Nolan et al., 2013). The goal is for OSIRIS-REx to bring back pristine materials and organic compounds that can help us better understand the characteristics of planetesimals that may have been the building blocks for life. Consider that while km- and sub-km-sized near-Earth objects (NEOs) with C-complex taxonomy and low albedos comprise about a fourth to a third of all NEOs (Stuart and Binzel, 2004; Mainzer et al., 2012), carbonaceous chondrite meteorites only provide <3% of all meteorite falls (Burbine et al., 2002). This suggests that many CI and CM meteorites fail to survive passage through Earth's atmosphere. Even those that do make it to the ground are quickly contaminated by terrestrial organics and volatiles. Hence, by returning samples directly from Bennu's regolith, OSIRIS-REx will avoid contamination while gleaning insights into the kinds of primordial volatiles and organic compounds delivered to Earth early in its history. With its Earth-like orbit, Bennu is accessible to the OSIRIS-REx spacecraft on a low velocity trajectory, and thus is a superb candidate for sample return.

To maximize the OSIRIS-REx science return, it is crucial to understand as much as possible the origin and evolution of Bennu and its parent body. There is much we do not know. For example, it is likely that Bennu's parent body spent most of its life in the main asteroid belt, but we cannot yet say whether it was indigenous to the main belt region (e.g., Bottke et al., 2006b; Bottke and Asphaug, 2013; Levison et al., 2009; Walsh et al., 2011). Bennu's parent body may have also experienced a wide range of physical processes, such as thermal metamorphism, aqueous alteration, and impact heating. Many of these effects have potentially left their mark on Bennu material. By returning samples from Bennu, analyzing them, and then asking the best possible questions within a plausible evolutionary framework for Bennu, we hope to learn much about how planetesimals, small body reservoirs like the asteroid belt, and the planets reached their current state.

Goals for this analysis would be to (i) understand the precise formation mechanism for Bennu's parent body, (ii) glean insights into the history of the parent body over the last 4.5 Gyr of Solar System history, (iii) probe when Bennu, or its immediate precursor, formed as a collisional byproduct of an impact event on its parent body, and (iv) constrain the evolution of Bennu from its original orbit in the main belt all the way to its current orbit near Earth. A key starting point for all of this is to determine where Bennu came from in main asteroid belt, how long it took to get from this location to its observed orbit, and what likely happened to it en route.

1.1. A conceptual model of Bennu's origin and evolution

In broad strokes, using what we have learned about asteroid evolution over the past several decades, we can already construct a reasonable scenario describing how Bennu reached its current orbit. Bennu probably started its life as part of a much larger body. This parent body was created by planetesimal formation mechanisms that may have involved the turbulent concentration of very small bodies in the primordial solar nebula (e.g., Johansen et al., 2007, 2012; Cuzzi et al., 2010). Insights into this process indicate Bennu's parent body probably had a diameter $D > 100$ km when it was born (Morbidelli et al., 2009, though see Weidenschilling, 2011 for a contrasting view). The formation location could have been the main asteroid belt, but it may also have been another region altogether (e.g., the outer Solar System beyond Jupiter; Levison et al., 2009; Walsh et al., 2011; Bottke et al., 2006b; Bottke and Asphaug, 2013). If the latter is true, dynamical processes implanted the parent body within the main belt within the first few hundreds of Myr of Solar System history. Once formed, the parent body would have experienced early thermal evolution by the decay of radiogenic nuclides (e.g., McSween et al., 2002), while its surface would have been battered by impacts for billions of years of cratering events (e.g., Bottke et al., 2005a,b).

The portion of Bennu's story investigated in this paper starts when Bennu's parent body experienced a large cratering event or, more likely, a catastrophic disruption event. This collision would have created enormous numbers of fragments near the impact site, some which were Bennu-sized. We refer to the clustered proper semimajor axes a, eccentricites e, and inclinations i of the bodies as an asteroid family (see review by Knežević et al. (2002)).

Once created, Bennu, or perhaps a somewhat larger precursor, began to undergo dynamical evolution via the non-gravitational forces referred to as the Yarkovsky and Yarkovsky–O'Keefe-Radzievskii-Paddack (YORP) effects (Rubincam, 2000; see Bottke et al., 2002b, 2006a; Vokrouhlický and Bottke, 2012 for reviews). The Yarkovsky effect describes a small force that affects the orbital motion of $D < 40$ km bodies. It is caused by sunlight; when these bodies heat up in the Sun, they eventually re-radiate the energy away as heat, which in turn creates a tiny thrust. This recoil acceleration is much weaker than solar and planetary gravitational forces, but it can produce substantial secular semimajor axis changes over timescales ranging from many millions to billions of years. The same physical phenomenon also creates a thermal torque that, complemented by a torque produced by scattered sunlight, can modify the rotation rates and obliquities of small bodies as well. This rotational variant has been coined the YORP effect (Rubincam, 2000). During the past decade or so, the Yarkovsky and YORP effects have been used to explore and potentially resolve a number of unsolved mysteries involving asteroids and meteoroids.

The coupled Yarkovsky and YORP effects likely modified Bennu's spin axis or its precursor to a value approaching 180°, the same value it has today. This allowed Bennu or its precursor to drift inward by the Yarkovsky effect far enough to reach a dynamical resonance capable of pushing it out of the main belt and onto a terrestrial planet-crossing orbit. If Bennu or its precursor had a high enough eccentricity within the main belt, and the right initial orbit, it could have also drifted directly onto a Mars-crossing orbit by the Yarkovsky effect. From there, a combination of planetary close encounters and resonances would have moved it to where we see it now, namely on a very Earth-like orbit.