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The geophysical environment of Bennu

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ABSTRACT

An analysis of the surface and interior state of Asteroid (101955) Bennu, the target asteroid of the OSIRIS-REx sample return mission, is given using models based on Earth-based observations of this body. These observations have enabled models of its shape, spin state, mass and surface properties to be developed. Based on these data the range of surface and interior states possible for this body are evaluated, assuming a uniform mass distribution. These products include the geopotential, surface slopes, near-surface dynamical environment, interior stress states and other quantities of interest. In addition, competing theories for its current shape are reviewed along with the relevant planned OSIRIS-REx measurements.

1. Introduction

The OSIRIS-REx mission to Asteroid (101955) Bennu provides an unprecedented opportunity to thoroughly map and investigate the geophysical state of a primitive asteroid. OSIRIS-REx is a sample return mission to Bennu, launching in 2016 and returning with a sample in 2023 (Lauretta, 2015). Bennu is a B-type asteroid, which is a subclass among the larger group of C-complex asteroids. Bennu is of interest scientifically due to its primitive nature and due to its spheroidal shape with a visibly prominent equatorial ridge. These properties provide the opportunity to both evaluate the geophysical processes that may occur on and within a primitive body, and to probe the genesis of the frequently seen equatorial ridges on small asteroids. Due to its low density and apparent high porosity (when compared with analog meteorites) Bennu is likely to be a rubble-pile (Chesley et al., 2014), which adds to the scientific interest of this body. Bennu is also of interest as it currently has a non-negligible probability of impact with Earth in the future (Chesley et al., 2014), and thus it is relevant to understand all aspects of this body for potential impact mitigation.

As part of the preparatory activities for the rendezvous of the OSIRIS-REx spacecraft with this asteroid, a series of scientific papers have been published that cover fundamental aspects of what is known regarding this body from Earth-based observations, summarized in Hergenrother et al. (2014). Previous papers have already discussed estimates of this asteroid's shape (Nolan et al., 2013), mass and density (Chesley et al., 2014), rotation state (Hergenrother et al., 2013), spectral signature (Binzel et al., 2015; Clark et al., 2011), photometric properties (Hergenrother et al., 2013), thermal inertia properties (Emery et al., 2014) and cosmochemical and dynamical history (Bottke et al., 2015; Lauretta et al., 2015; Walsh et al., 2013). The current paper integrates results from several of these papers in order to perform an analysis of the geophysics of this body. This study will be of use to motivate observation plans for the OSIRIS-REx mission, and once these are taken it can be used to test the limits of our ability to analyze asteroids using Earth-based observations.

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The quantities of interest for understanding the geophysics of Bennu and its past geophysical evolution are its shape, spin state, gravity field (including total mass), visible surface morphology and spectra, topography, and the distribution and properties of surface regolith. From these quantities one can determine the geophysical environment on and within the body, potentially detect density inhomogeneities, and compare the estimated environment with visible surface features. These also provide a physical context for better understanding and interpreting spectral and compositional observations taken of the surface. All of these can be synthesized into theories of the formation and subsequent evolution of Bennu.

The current paper will map out current understanding of this body, describe existing models for geophysical evolution currently in the literature, and review the specific measurements of the Bennu system that will be taken by the OSIRIS-REx mission and describe how these will be used to develop theories for the formation and evolution of this system. Although the fidelity of these models is currently limited, especially as compared to the fidelity of the eventual OSIRIS-REx models (Lauretta et al., 2015), it is remarkable that detailed predictions of the expected environment both on, about and within this body can be developed. It should be noted that the set of existing models of Bennu are distinguished in their completeness and detail, and thus are worthy of study independent of the pending OSIRIS-REx rendezvous and exploration activities. Study and analysis of small rubble-pile bodies such as Bennu have the potential to shape our understanding of how small bodies in the solar system are formed, how they evolve and what their ultimate fate is.

Previous missions and observations have contributed greatly to our understanding of small asteroid interiors and morphology, as reviewed in Scheeres et al. (2015). Most significant among these are the NEAR mission to Asteroid (433) Eros (Veverka et al., 2000) and the Hayabusa mission to Asteroid (25143) Itokawa (Fujiwara et al., 2006). Main conclusions from the observations of Eros, which is about 10 km in average radius, are that this body has a remarkably uniform density distribution (Miller et al., 2002), and that it was able to transmit impact shock waves across and through the body efficiently enough to erase a subset of its craters (Thomas and Robinson, 2005). Intriguing surface features and structures were also found, some of them global, that indicate that the body may have significant subsurface features beneath the blanket of regolith that covers the body (Cheng et al., 2001; Prockter et al., 2002; Robinson et al., 2002). Itokawa, which is much smaller with a 160 m mean radius, provided a first clear view of a rubble-pile body and showed itself to be comprised of rocks with a size distribution that approximately followed a d^{-3} size distribution, where d is the rock diameter, across its surface down to the meter level (DeSouza et al., 2015; Mazrouei et al., 2014; Michikami et al., 2008), with an indication of a less steep distribution (between -2 and -3) at the sub-meter level (Noviello et al., 2014). Further, the sample obtained from its surface also showed a similar size distribution, but ranged down to micron sized grains (Tsuchiyama et al., 2011). Surface properties of Itokawa were measured during one of the sampling attempts (Yano et al., 2006) and the existence of surface flow of regolith was shown based on analysis of regional imaging (Miyamoto et al., 2007) and a global assessment of surface roughness (Barnouin-Jha et al., 2008) and block aspect ratio investigations (Michikami et al., 2010). The total mass of Itokawa was measured based on imaging and lidar measurements (Abe et al., 2006). Unfortunately, precise Doppler tracking of the spacecraft when it was in close proximity to Itokawa has not been published, which has prevented the estimation of any gravity field coefficients, preventing analysis of its interior mass distribution (although there has been speculation about possible density inhomogeneity in this body (Lowry et al., 2014), which was critically assessed in Scheeres et al. (2015)). Thus, despite the many fundamental advances in understanding that arose from these missions, key insight into some geophysical aspects of small bodies remain opaque.

One specific question of interest for Bennu revolves around how its equatorial ridge formed, as this will provide direct insight into the shape evolution of such rubble-pile bodies. It will potentially even inform us of the process by which binary asteroids are formed, as an equatorial ridge is a common feature on primaries of small binary systems, based on radar observations (Benner et al., 2015). The ridge is used as motivation in this paper, given that it is the most prominent feature in the radar-derived shape model correlated to the geophysical evolution of Bennu. There will be many additional questions of interest that arise once rendezvous with Bennu occurs, however to understand these features will likely involve the same methods and measurements for understanding the ridge. Key measurements that will inform this investigation include the surface topography and morphology, surface heterogeneity of material and its size distribution properties, crater morphologies and number, the bulk density and any constraints on density inhomogeneities within the body, the presence or absence of an excited rotation state, and any evidence for surface landslides, material infall or uplift of the surface. In sum, the integrated observations of this body will provide the essential foundations for understanding how it arrived at its current state. The current paper sets up a number of different analyses and interpretations of the existing data, and hopefully will serve as a springboard for the detailed investigation of this body once the OSIRIS-REx spacecraft has its rendezvous with Bennu in 2018.

The paper is split into the following sections. Section 2 reviews the existing models for this body with a focus on the essential values that influence our understanding of the Bennu geophysical environment. Section 3 reviews the derived models essential for our analysis. Section 4 provides a series of geophysical calculations that define the possible state of the body's surface and interior, and which place limits on possible past states that this body may have had. Section 5 focuses more narrowly on describing the array of current theories for the genesis of the current Bennu shape. Then Section 6 covers the primary measurements that will be made and indicates how these can be applied to discern between some of these competing theories. Finally, the Conclusion section provides a brief review of the results.

2. Defining models and current values

There is a remarkable amount of current knowledge on Bennu, due to a combination of many different observation campaigns. These include astrometric, photometric, radar, thermal infrared, and spectral observations of this body that have been reported elsewhere (Binzel et al., 2015; Emery et al., 2014; Hergenrother et al., 2013; Nolan et al., 2013). These observations have been combined through a large-scale effort into a model of good fidelity that enables the current study, and helps to formulate the appropriate questions and investigations to pursue at this body. In the following, the major aspects of this body are recounted in a combined manner, although many of these specific elements came from disjoint methods of observation.

2.1. Surface constraints

Measurements of the thermal spectral flux of Bennu as a function of rotation with the Spitzer Space Telescope point to a fairly homogeneous, relatively fine-grained surface estimated to be of size 0.1–1 cm (Emery et al., 2014). Variations of disk-integrated thermal flux with rotation are consistent with being entirely due to shape-induced changes in cross-sectional area, suggesting that the physical properties of the surface do not vary dramatically