ROTATIONAL STATE AND SHAPES OF RYUGU AND BENNU: IMPLICATIONS FOR INTERIOR STRUCTURE AND STRENGTH. J.H. Roberts[1], O.S. Barnouin[1], G.A. Neumann[2], M.C. Nolan[3], M.E Perry[1], R.T. Daly[1], C.L. Johnson[4,5], M.M. Al Asad[4], M.G. Daly[6], J.A. Seabrook[6], R.W. Gaskell[5], E.E. Palmer[5], J.R. Weirich[5], K.J. Walsh[7], D.J. Scheeres[8], J.W. McMahon[8], S. Watanabe[9,10], N. Hirata[11], Na. Hirata[12], S. Sugita[13], D.S. Lauretta[3], [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA; [2]NASA Goddard Space Flight Center, Greenbelt, MD, USA; [3]Lunar and Planetary Laboratory, Univ. of Arizona, Tucson, AZ, USA; [4]Dept. of Earth, Ocean and Atmospheric Sciences, Univ. of British Columbia, Vancouver, Canada; [5]Planetary Science Institute, Tucson, AZ, USA; [6]The Centre for Research in Earth and Space Science, York Univ., Toronto, Ontario, Canada; [7]Southwest Research Institute, Boulder, CO, USA; [8]Colorado Center for Astrodynamics Research, Univ. of Colorado, Boulder, CO, USA; [9]Nagoya Univ., Nagoya, Japan; [10]Institute of Space and Astronautical Science, JAXA, Sagamihara, Japan; [11]Univ. of Aizu, Aizu-Wakamatsu, Japan; [12]Kobe Univ., Kobe, Japan, [13]Univ. of Tokyo, Tokyo, Japan.

Introduction: At first glance, the asteroids (162173) Ryugu and (101955) Bennu look very similar. Images acquired by the Hayabusa2 [1] and OSIRIS-REx missions [2,3], respectively, reveal that both are rocky worlds covered in rubble, including numerous boulders with diameters up to tens of meters. Both bodies have low albedos and spectra consistent with a carbonaceous chondrite-like composition with low albedos [1,2] and to first order, both are “top-shaped” rapid rotators.

A more detailed analysis of the shapes and spin states of these asteroids, however, reveals a number of differences between the two, and their unique topographic characteristics may point to differences in their internal structures. The geologic evolution of rubble-pile asteroids is driven in large part by downslope migration of surface material [4], which may be dislodged by YORP-induced spin-up [5, 6]. Thus, the rotational states and shapes of these bodies is key in understanding their histories and predicting future dynamic evolutions.

Shape: Shape models of Ryugu and Bennu have been developed from images using multiple techniques, including stereophotoclinometry (SPC) [7] and geometric stereo (SfM) [8] on images taken with the spacecrafts’ cameras, as well as from lidar data collected by laser altimeter [9, 10]. Examples of shape models for each body are shown in Figure 1. A spherical harmonic decomposition of the shapes (Figure 2) reveals a number of interesting features, which can be used to interpret the geological significance of the shape.

On Bennu, the zonal terms (components that vary only with latitude) show a sharp dichotomy between the odd and even terms, which is indicative of symmetry about the equator. These zonal terms also are particularly strong at degrees 2 and 4. The latter is largely due to the equatorial ridge characteristic of top-shaped asteroids. The next pair of spikes shown in the zonal terms at degrees 6 and 8 in Figure 2, are indicative of the terraces [11]. The strong sectoral terms (varying only with longitude) at degree 4 reflects high-standing longitudinal ridges, which are most obvious as a “squarish” outline as viewed from the poles [10].

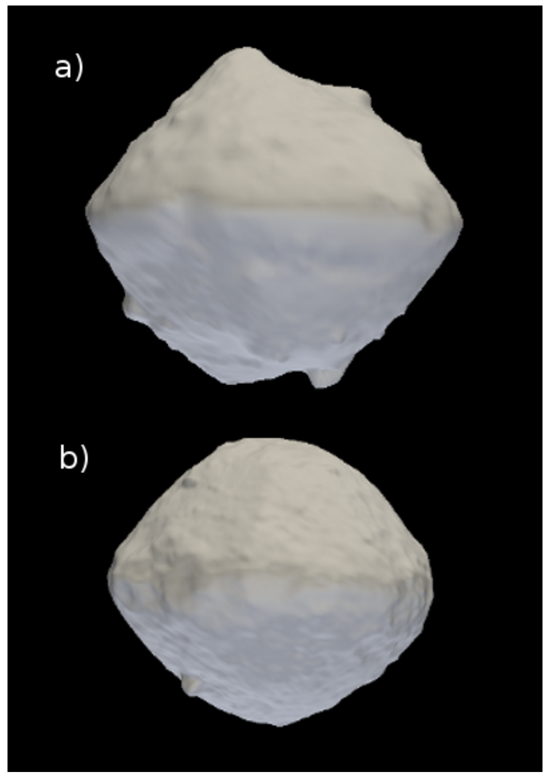

Figure 1: Equatorial views of shape models of Ryugu (a) created with SPC [8], and Bennu (b) created with a combination of SPC and lidar data. We show models with 11.7 m and 6.3 m ground sample distance on Ryugu and Bennu, respectively; roughly equivalent scaled to the body size.

Ryugu also exhibits strong degree-2 and -4 zonal terms, resulting in the general top-shape [1], and oscillation in the zonal terms indicating strong hemispheric symmetry. Otherwise, Ryugu differs significantly from Bennu. The degree-4 sectoral component is much weaker, and longitudinal ridges are not observed [12]. Viewed from above the pole, the profile of Ryugu is far more circular. The strongest non-zonal contribution are the tesseral terms at degree 3, indicating some large-scale asymmetry, which is prominent in topography relative to a reference shape model constructed from the even zonal harmonics [12]. The Tokoyo/Horai Fossae

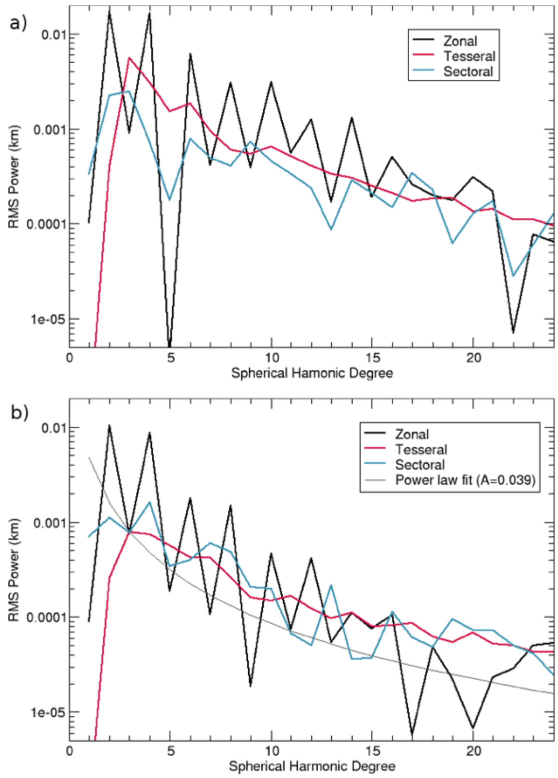

Figure 2: Spherical harmonic decomposition of Ryugu's (a) and Bennu's (b) global topography.

system in the southern hemisphere and the large plain in the northwestern mid-latitude [1] may be responsible for this shape. At smaller scales, terraces are not evident; instead, regolith run-ups and imbricated boulders are observed [13].

Rotational Stability: The differences in the long-wavelength topography of these two asteroids may be critical in controlling their rotational histories and stability of their surfaces. Sub-km bodies are susceptible to a change in rotation due to YORP [6, 14], in which asymmetric reflection and re-emission of solar radiation from the surface. The magnitude of the YORP-induced torque is sensitive to the orientation of blocks on the surface, and the longitudinal ridges observed on Bennu may act like blades on a windmill to promote spin up.

Bennu is currently rotating significantly faster than the maximum stable spin rate for a fluid body with Bennu's density and oblateness as shown in Figure 3. A rotational stability analysis demonstrates that an internal friction angle of at least 18° is necessary or a few Pa of cohesion to prevent Bennu from failure via mass wasting in the absence of cohesion. In contrast, Ryugu is very close to the Maclaurin curve (black curve in Figure 3) and only a very small amount of internal friction or cohesion would be necessary to maintain its shape.

Internal properties: The large-scale surface topography and rotation rates may also provide insight as to

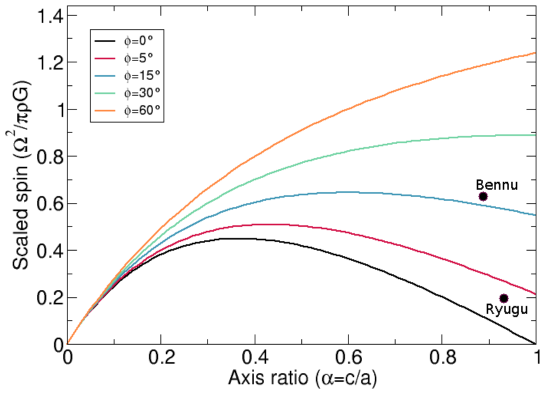

Figure 3: Maximum stable spin rates as a function of the oblateness of the body for various angles of internal friction (without cohesion). Ryugu's and Bennu's present rotation rates and shapes are indicated by the circles.

the interior structures of the asteroids. Although both objects appear to be unconsolidated rubble-piles, Bennu cannot be completely strengthless as discussed above. The longitudinal ridges may be the surface expression of an arrangement of ~4 larger (~100-m) fragments that make up the core of the asteroid, which is filled in and covered by smaller rubble. These larger clasts would resist rotational deformation and could lock up the smaller rubble. Surface landslides would still occur, and we hypothesize that the terraces are the expression of downslope migration of material as the increasing rotation rate dislodged it. That these terraces are not observed on Ryugu would thus be a natural consequence of its slower rotation. The "lumpier" structure of Ryugu would point to a different configuration of central clasts. This configuration is less susceptible to YORP spin-up. More comprehensive evolutions of the deformation and spin rates [14] of these asteroids are under investigation.

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