DEVIATION OF THE SHAPE OF BENNU FROM ROTATIONAL FIGURES OF STABILITY. J.H. Roberts[1], O.S. Barnouin[1], C.L. Johnson[2,3], M.G. Daly[4], M.E Perry[1], R.T. Daly[1], M.M. Al Asad[2], E.E. Palmer[3], J.R. Weirich[3], P. Michel[5], W.F. Bottke[6], K.J. Walsh[6], M.C. Nolan[7], D.J. Scheeres[8], J.W. McMahon[8], G.A. Neumann[9] , D.S. Lauretta[7], and the OSIRIS-REx Team. [1]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA (James.Roberts@jhuapl.edu); [2]Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, Canada; [3]Planetary Science Institute, Tucson, AZ, USA; [4]The Centre for Research in Earth and Space Science, York University, Toronto, Ontario, Canada; [4]York University; [5]Observatoire de la C'ôte d'Azur, University of Nice, Nice, France; [6]Southwest Research Institute, Boulder, CO, USA; [7]Lunar Planetary Laboratory, University of Arizona, Tucson, AZ, USA, [8]Colorado Center for Astrodynamics Research, University of Colorado, Boulder, CO, USA. [9]NASA Goddard Space Flight Center, Greenbelt, MD, USA.

Introduction: Images of asteroid (101955) Bennu acquired by the OSIRIS-REx mission during its Approach and Preliminary Survey phases [1] reveal a rocky world covered in rubble, including numerous boulders with diameters up to tens of meters. The asteroid appears to be a "rubble pile." The geologic evolution of Bennu is driven in large part by downslope migration of surface material [2] and rubble which may be dislodged from an initial state by number of processes, such as YORP-induced spin-up [e.g., 3,4], re-accumulation processes [5,6], impact-induced seismic shaking, thermal stresses, or tidal disruption by close encounters to larger bodies.

Although unconsolidated, Bennu is not completely strengthless [7,8] because the shape [9] deviates from a hydrostatic surface (e.g., Maclaurin or Jacobi ellipsoid). Indeed, knowledge of these surfaces is crucial for identifying the slope relative to the surface and predicting the direction of movement. Understanding the deviation of the actual shape from these surfaces of hydrostatic stability will constrain the strength of the interior, and the cohesion of the near-surface material.

Here we present the figures of rotational stability for an object with the observed rotational period and bulk density of Bennu [10,11], and the deviation from these surfaces of the shape models obtained through stereophotoclinometry (SPC) [12] of the imaging data collected by the OSIRIS-REx Camera Suite (OCAMS) [9], as well as maps of the inferred slopes. For context, we also present similar results for other asteroids for which we have high-resolution shape models, including Eros, Itokawa, Ida, Gaspra, and Mathilde. We then present estimates of internal strength consistent with these slopes.

Rotational Figures of Stability: The simplest model of rotating ellipsoidal figures in equilibrium is the Maclaurin spheroid; an oblate spheroid which arises when a fluid, self-gravitating body of uniform density ρ (a reasonable assumption for a small, rubble-pile asteroid [11]) rotates with constant angular velocity Ω. When generalized to cohesionless solids [14], the scaled spin is defined by

$$\frac{\Omega^2}{\pi G\rho} = \frac{2\alpha\sqrt{m+2\alpha^2}}{m(1-\alpha^2)^{3/2}}\cos^{-1}\alpha - \frac{2(m+2)\alpha^2}{m(1-\alpha^2)}$$

where G is the gravitational constant, α is the ratio of the polar (c) and equatorial (a) axes, and $m = (1+\sin\phi)/(1-\sin\phi)$, where ϕ is the angle of internal friction. A strengthless (i.e., fluid) body with no internal friction would have $m = 1$, the Maclaurin formula. Alternative figures of equilibrium exist; asteroids more prolate than Bennu (e.g., Eros) may be better represented by a Jacobi ellipsoid, which admits triaxial solutions [2,14].

We have computed curves of rotational stability for cohesionless, solid, oblate spheroids, and determined the maximum scaled spin parameter for which stable solutions exist as a function of ϕ and α. There are no stable solutions for a fluid body (ϕ = 0) with the observed density (1.2 g cm^{-3}) and rotation rate of Bennu (4.3 h) [11], which implies that some level of internal friction (or cohesion) is necessary to prevent Bennu from further flattening, and either despinning or undergoing binary fission. We find that $\phi > 18°$ is necessary for a cohesionless solid object of Bennu's shape and rotation.

Shape Models and Slopes: The shape model of Bennu has been developed from SPC performed on images, validated by limb measurements, and further constrained by data from the OSIRIS-REx Laser Altimeter (OLA) [9,13]. Shape models for the other bodies have been derived from imaging data (either stereo or SPC) and lidar.

We generate the slope maps by computing the gradient of the heights of the shape models relative to the equilibrium figures. In Figure 1, we show the height of the Bennu shape model (derived using SPC from the Preliminary Survey images) above the equilibrium spheroid consistent with Bennu's parameters. In Figure 2, we show the slope map for Bennu. These slopes further constrain the angle of internal friction, which must be high enough to support material from sliding downslope to meet the equilibrium surface.

Discussion: Although the stability constraints require that the angle of internal friction be at least 18°,

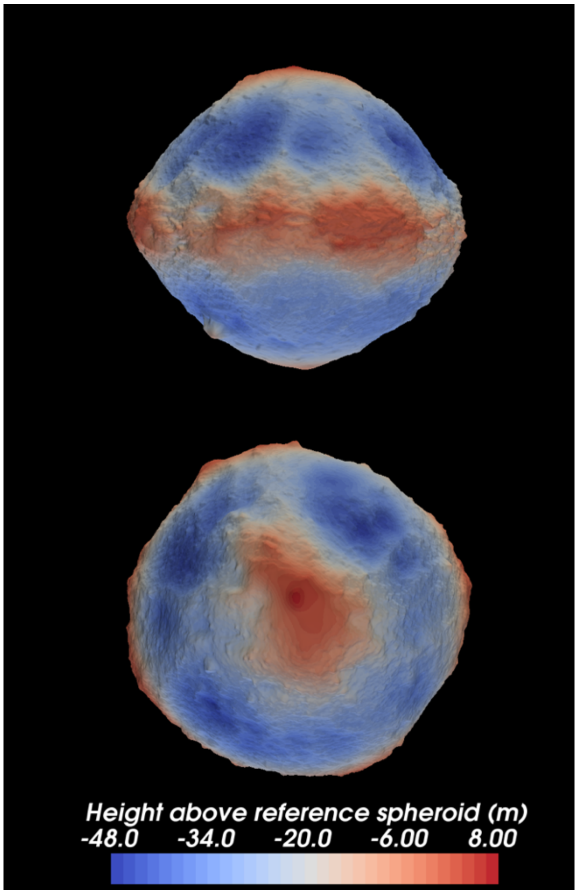

Figure 1: Height of SPC-derived shape model of Bennu above equilibrium spheroid. Top: Equatorial view at prime meridian. Bottom: North (+z) polar view.

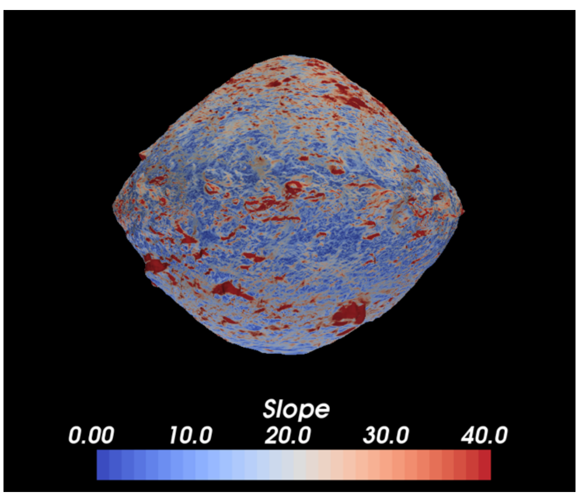

Figure 2: Slope of Bennu from SPC-derived shape model relative to geopotential surface.

higher values cannot be ruled out. Angles of ~30° are common for geologic materials. This internal friction prevents material from sliding downslope (equatorward), and adding to the equatorial ridge to greater extent than is observed.

We note that the results shown here are subject to a number of caveats. We have assumed a constant density for Bennu. This is a fair assumption if the asteroid is indeed a rubble pile all the way through, and not a single monolith or a few large fragments of competent rock overlain by regolith (as may be the case for, say, Itokawa). This assumption will be refined based on the gravity solution obtained from the radio science experiment [10] as the mission progresses. We also note that the Maclaurin and Jacobi ellipsoids are only first-order shapes. The scaled spin parameter $(\Omega^2/\pi G\rho)$ for Bennu is of order unity, and a higher-order theory of figures [15] may need to be invoked to identify the true surface of rotational stability. Indeed, the observed shape of Bennu shows a substantial contribution at spherical harmonic degree 4. The zonal component is largely due to the equatorial ridge, but there is also a non-zero sectoral component, which results in the "squarish" shape seen in the polar views. This component may point to an underlying structure; if not a solid core, then a few large fragments which anchor the smaller rubble.

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