Coupled shape and spin evolution of Bennu due to the YORP effect

James Roberts[1], Yun Zhang[2], Olivier Barnouin[3], Patrick Michel[2], Derek Richardson[4], Michael Nolan[5], Michael Daly[6], Jeff Seabrook[6], Eric Palmer[7], Robert Gaskell[7], John Weirich[7], Manar Al Asad[8], Catherine Johnson[8], Lydia Philpott[8], and Dante Lauretta[9]

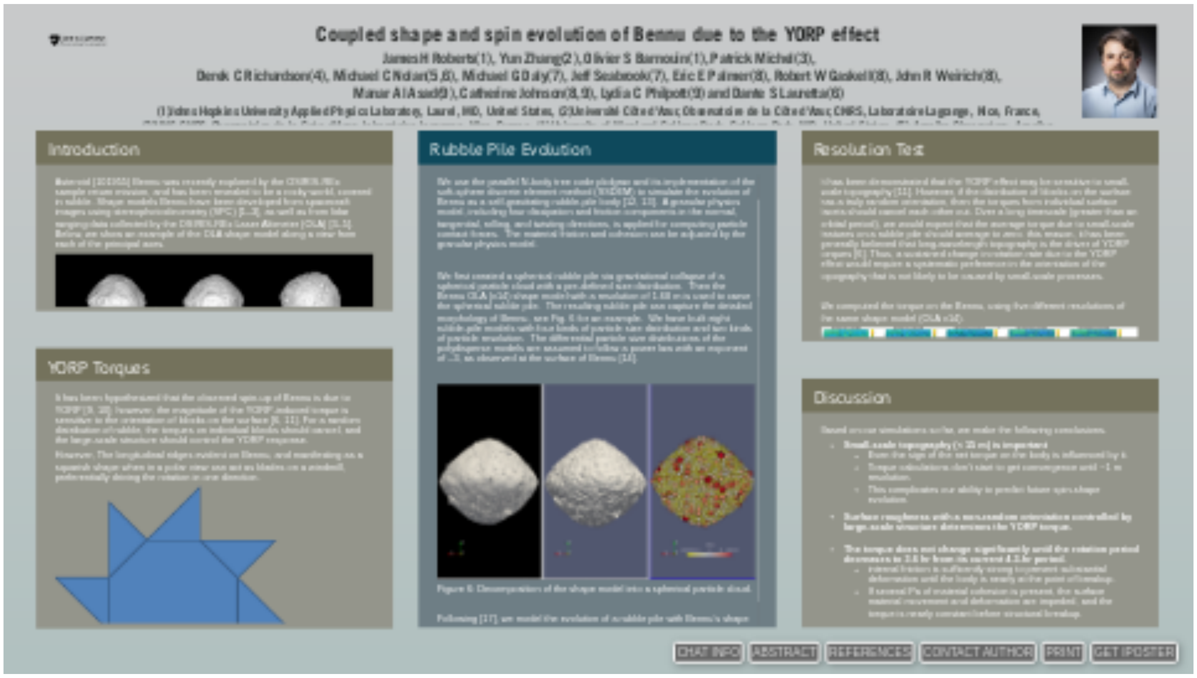
[1]Johns Hopkins University Applied Physics Laboratory
[2]UNS-CNRS-Observatoire de la Cote d'Azur
[3]Johns Hopkins Applied Physics Laboratory
[4]University of Maryland College Park
[5]Arecibo Observatory
[6]York University
[7]Planetary Science Institute
[8]University of British Columbia
[9]University of Arizona

November 23, 2022

Abstract

The rotation rate of (101955) Bennu has been observed to increase, providing evidence of the YORP effect in action. Bennu is a rubble pile with little strength. At the current spin-up rate, the rotation would result in large-scale disruption in <1 My. Such an extreme scenario is predicated on the YORP torque continuing to increase the rotation. However, YORP is sensitive to the shape and can change on a short timescale as small episodes of failure can increase oblateness, reduce spin rate, and redistribute rubble on the surface. A more comprehensive model of the shape and spin evolution of Bennu is required to understand its past and future. Here, we calculate the YORP torque on a shape model of Bennu. For a random distribution of rubble, the torques on individual blocks should cancel, and the large-scale structure should control the YORP response. However, we find the calculated torque is strongly dependent on the resolution of the shape model used, suggesting that the smaller material has an influence. As the surface roughness of the model increases, the magnitude of the torque and even its sign may change. Spin rate increases that more closely match measurements are obtained with increasing small-scale roughness. Simulated models that are coarser in resolution, but possess greater roughness than the equivalent lower-resolution shape model from observations, likewise are more consistent with the observed spin-up rate. We find that surface roughness with a non-random orientation controlled by large-scale structure determines the YORP torque. Following [1], we model the evolution of a rubble pile with Bennu's shape subject to YORP using the granular modeling tool pkdgrav and explore how the torques change as the object is deformed. The YORP torques are calculated on the present shape and applied until particles begin to move. The torques are then recomputed on the new shape, and the iteration continues. We find negligible change in the torque until the rotation period decreases to 3.6 hr from its current 4.3-hr period. At 3.53 hr, the asteroid starts to lose mass from the equator. Our results suggest that the deformation of the asteroid's shape due to YORP does not strongly alter rotation, and that if the initial shape is known to sufficient accuracy, the future shape and spin can be predicted. [1] Cotto-Figueroa D. et al. (2015) ApJ 803, 25.

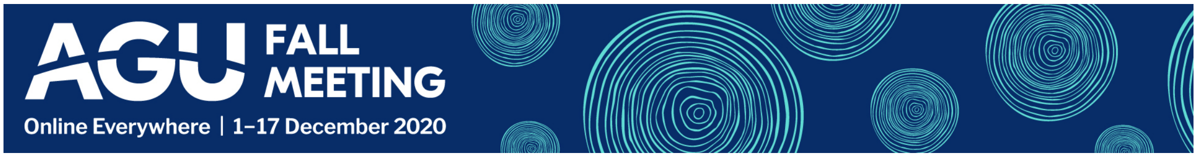
Coupled shape and spin evolution of Bennu due to the YORP effect



James H Roberts(1), Yun Zhang(2), Olivier S Barnouin(1), Patrick Michel(3), Derek C Richardson(4), Michael C Nolan(5,6), Michael G Daly(7), Jeff Seabrook(7), Eric E Palmer(8), Robert W Gaskell(8), John R Weirich(8), Manar Al Asad(9), Catherine Johnson(8,9), Lydia C Philpott(9) and Dante S Lauretta(6)

(1)Johns Hopkins University Applied Physics Laboratory, Laurel, MD, United States, (2)Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Nice, France, (3)UNS-CNRS-Observatoire de la Cote d'Azur, Laboratoire Lagrange, NIce, France, (4)University of Maryland College Park, College Park, MD, United States, (5) Arecibo Observatory, Arecibo, PR, United States, (6)University of Arizona, Lunar and Planetary Laboratory, Tucson, AZ, United States, (7)York University, Centre for Research in Earth and Space Science, Toronto, ON, Canada, (8) Planetary Science Institute, Tucson, AZ, United States, (9) University of British Columbia, Department of Earth, Ocean and Atmospheric Sciences, Vancouver, BC, Canada

PRESENTED AT:


AGU FALL MEETING
Online Everywhere | 1–17 December 2020

INTRODUCTION

Asteroid (101955) Bennu was recently explored by the OSIRIS-REx sample return mission, and has been revealed to be a rocky world, covered in rubble. Shape models Bennu have been developed from spacecraft images using stereophotoclinometry (SPC) [1–3], as well as from lidar ranging data collected by the OSIRIS-REx Laser Altimeter (OLA) [3–5]. Below, we show an example of the OLA shape model along a view from each of the principal axes.

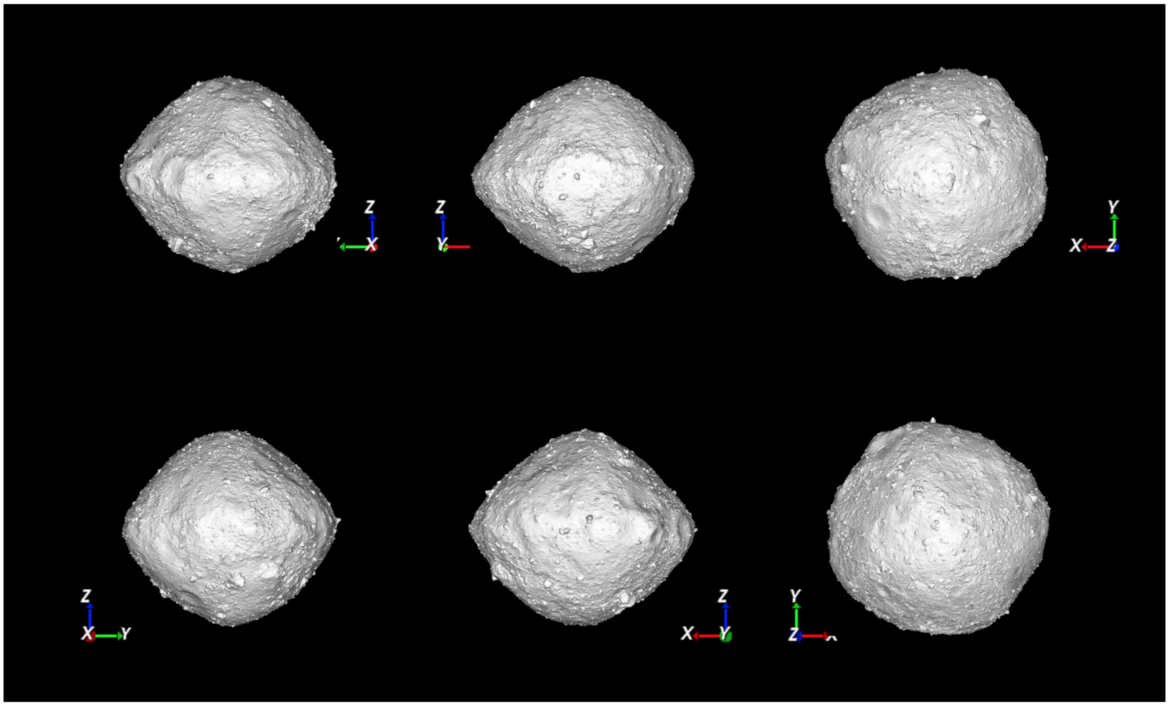


Figure 1: Shape models of Bennu v20 determined from altimetry data acquired from the OSIRIS-REx Laser Altimeter [4] with ~800,000 facets. Views are shown from each principal axis.

Bennu's overall shape is that of a top, and is not hydrostatic, indicating that it must posess some internal stiffness to maintain the current shape. Below, we show the maximum dimensionless spin rate that can be sustained in a cohesionless solid as a function of oblateness for a range of internal friction angles (Maclaurin curves). A body with a rotation rate above its corresponding Maclaurin curve will undergo despinning, flattening, and possible disruption. The horizontal and verical lines mark the current parameters for Bennu and indicate that it would need a friction angle of at least 18° to maintain its shape. Alternatively, this could be accomplished with ~6 Pa of cohesion, but observations of widesperead migration of surface rubble suggest that cohesion is quite low.

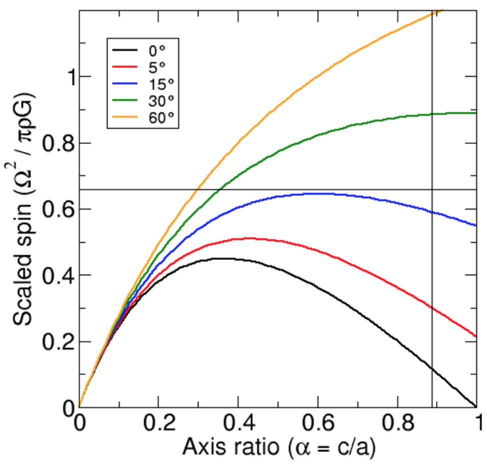


Figure 2: Rotational stability for cohesionless, solid, oblate spheroids for a wide range of rotation rates, oblateness, and internal friction. Each curve describes the limits of the allowable dimensionless rotation rate as a function of the ratio of the minor to major axes. Horizontal and vertical lines indicate Bennu's present-day properties.

Sub-kilometer bodies are susceptible to changes in rotation due to the Yarkovsky–O'Keefe–Radzievskii–Paddack (YORP) effect [6–8], in which asymmetric reflection, absorption, and re-emission of solar radiation from the surface cause torques that systematically increase or decrease the spin. The rotation rate of (101955) Bennu has been observed to increase, providing evidence of the YORP effect in action.

At the current spin-up rate, the rotation would result in large-scale disruption in <1 My. Such an extreme scenario is predicated on the YORP torque continuing to increase the rotation. However, YORP is sensitive to the shape and can change on a short timescale as small episodes of failure can increase oblateness, reduce spin rate, and redistribute rubble on the surface. A more comprehensive model of the shape and spin evolution of Bennu is required to understand its past and future.

YORP TORQUES

It has been hypothesized that the observed spin-up of Bennu is due to YORP [9, 10]; however, the magnitude of the YORP-induced torque is sensitive to the orientation of blocks on the surface [6, 11]. For a random distribution of rubble, the torques on individual blocks should cancel, and the large-scale structure should control the YORP response.

However, The longitudinal ridges evident on Bennu, and manifesting as a squarish shape when in a polar view can act as blades on a windmill, preferentially driving the rotation in one direction.

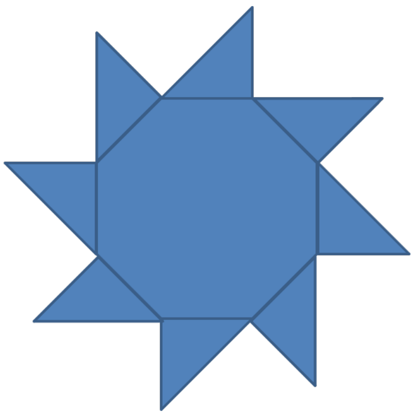
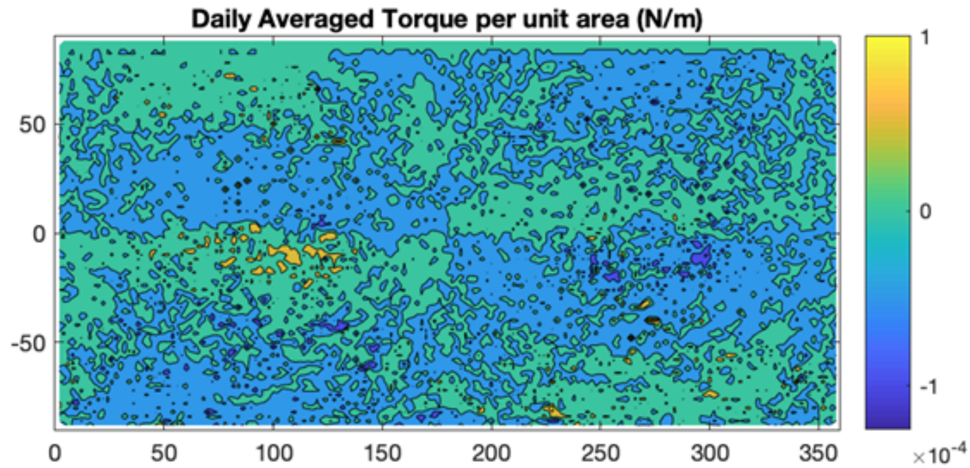
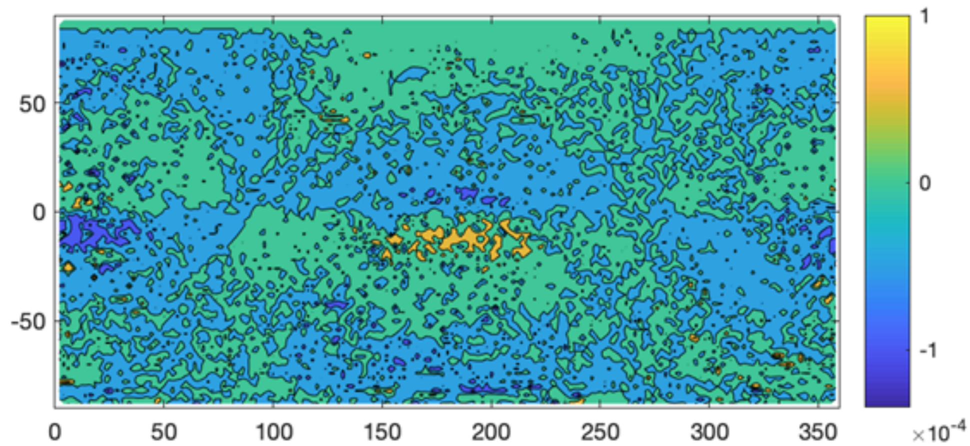


Figure 3: We hypothesize that the longitudinal ridges on Bennu may act like blades on a windmill (exaggerated here) to promote systematic spin-up.

Here, we use the shape model constructed from OSIRIS-REx Laser Altimeter (OLA) data, version 16. Following [6], we calculate the YORP torque on each facet of the shape model. We sum over all the facets to determine the net torque on the body. We then rotate the body 5° about its axis, identify the new subsolar point and recalculate. The calculation is repeated every 5° of rotation to determine the net and average torque over one full rotation. Shown below are the results at a True Anomaly of 180°.


Daily Averaged Torque per unit area (N/m)
50
0
-50
0
50
100
150
200
250
300
350
1
0
-1
×10^-4


50
0
-50
0
50
100
150
200
250
300
350
1
0
-1
×10^-4

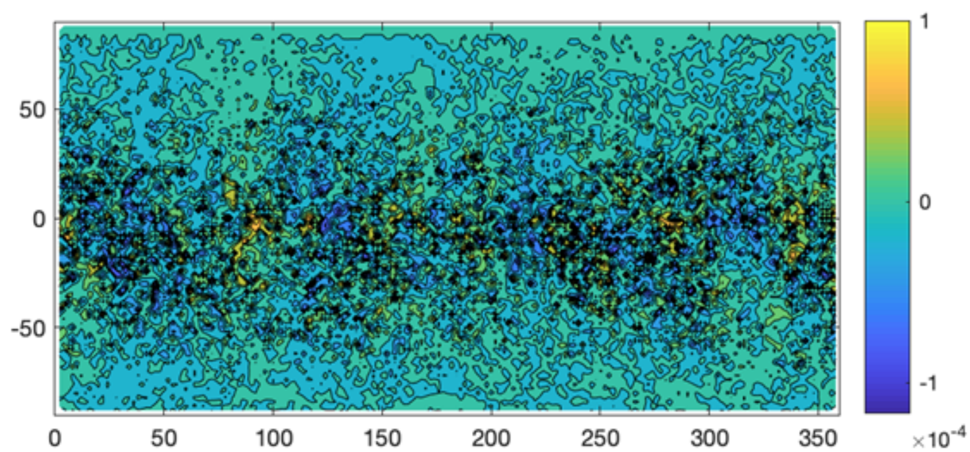

50
0
-50
0
50
100
150
200
250
300
350
1
0
-1
×10^-4

Figure 4: Daily averaged YORP tork computed at each plate of the shape model at a True Anomaly of 180°. Top, middle, and bottom panels show the torque around the x-, y-, and z-axis respectively. The z-torque affects the rotation. The other components affec tthe obliquity.

We repeat this iteration for every 5° of true anomaly to determine the net torque over one full orbital period.

RUBBLE PILE EVOLUTION

We use the parallel N-body tree code pkdgrav and its implementation of the soft-sphere discrete element method (SSDEM) to simulate the evolution of Bennu as a self-gravitating rubble-pile body [12, 13]. A granular physics model, including four dissipation and friction components in the normal, tangential, rolling, and twisting directions, is applied for computing particle contact forces. The material friction and cohesion can be adjusted by the granular physics model.

We first created a spherical rubble pile via gravitational collapse of a spherical particle cloud with a pre-defined size distribution. Then the Bennu OLA (v14) shape model with a resolution of 1.68 m is used to carve the spherical rubble pile. The resulting rubble pile can capture the detailed morphology of Bennu, see Fig. 6 for an example. We have built eight rubble-pile models with four kinds of particle size distribution and two kinds of particle resolution. The differential particle size distributions of the polydisperse models are assumed to follow a power law with an exponent of –3, as observed at the surface of Bennu [14].

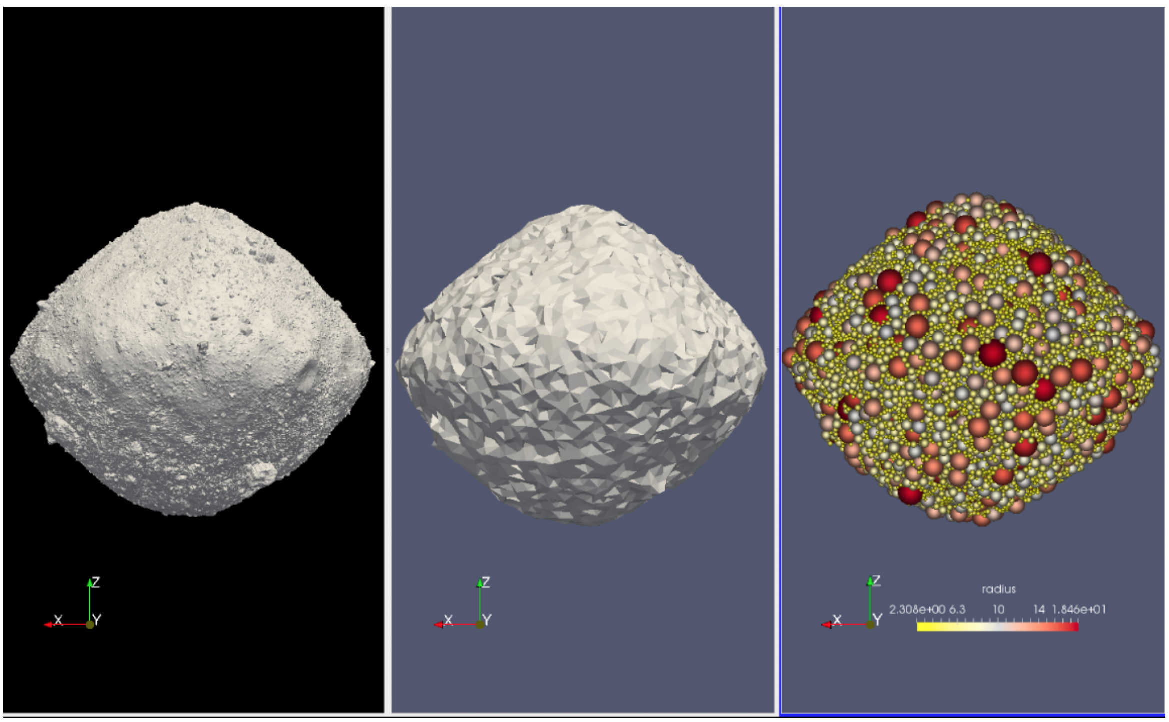


Figure 6: Decomposition of the shape model into a spherical particle cloud.

Following [17], we model the evolution of a rubble pile with Bennu's shape subject to YORP using the granular modeling tool pkdgrav and explore how the torques change as the object is deformed.

In order to compute the YORP torque for our SSDEM rubble-pile model, we need to convert the granular assembly into a polyhedral shape. We use the so-called "Alpha shape" method to carry out the shape reconstruction. An example is given in Fig. 6. We computed the YORP torque based on the produced polyhedral model, and the results are shown in Fig. 7 for all the eight cases considered in this study at Bennu's current spin period.

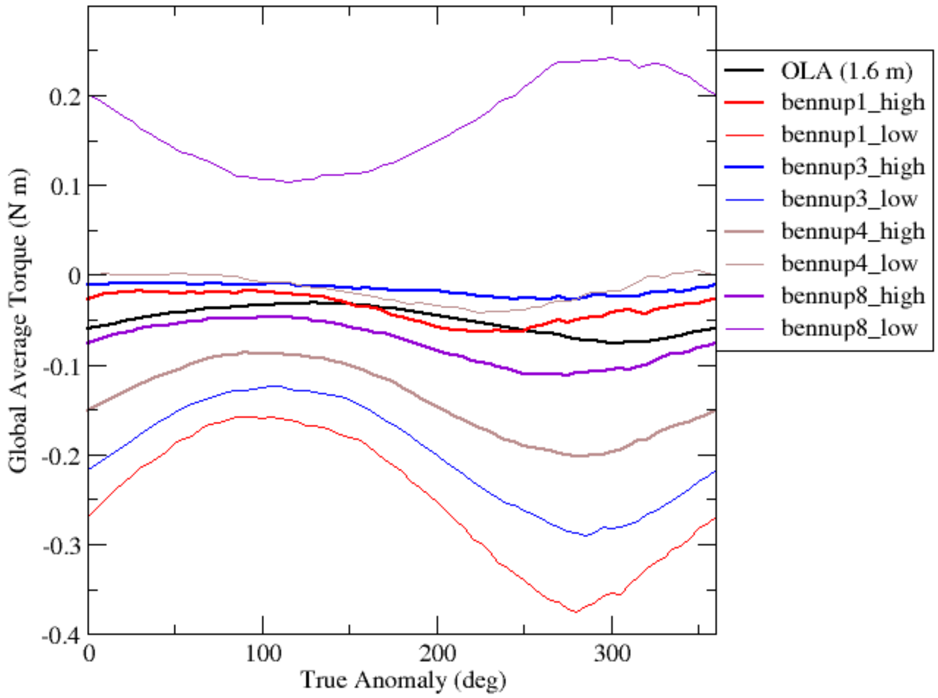
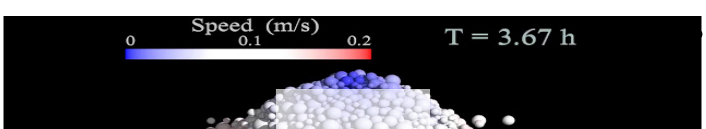


Figure 7: Comparison of the globally averaged torque over the course of an orbit on the OLA shape model (black curve), and on the SSDEM rubble pile models.

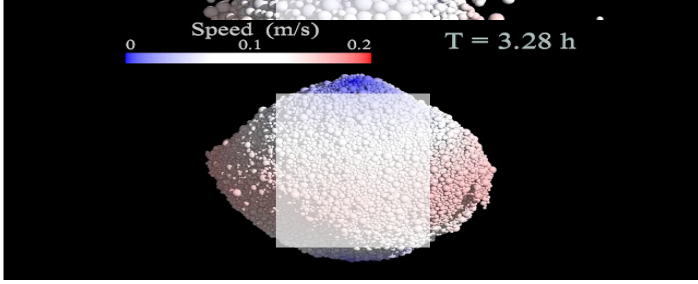
Two of these models approximate the calculated torque on the original shape model:

1. bennup3: A particle size distirbution with a ratio between the maxium and minimium particle radius of 3.
2. bennup4: A particle size distirbution with a ratio between the maxium and minimium particle radius of 4, at high resolution than bennup3.

For our initial simulations, we assumed no bulk cohesion. We use the pkdgrav finite element dynamics model to model the change in rotation rate and deformation of the rubble-pile under the calculated YORP torque. If significant deformation is found, the pkdgrav simulation is halted and the torque recomputed. Animations of these two cases are shown in Videos 1 and 2. For both of the models described above, we fnd negligible change in the torque until the rotation period decreases to 3.6 hr from its current 4.3-hr period. At 3.53 hr, the asteroid starts to lose mass from the equator.

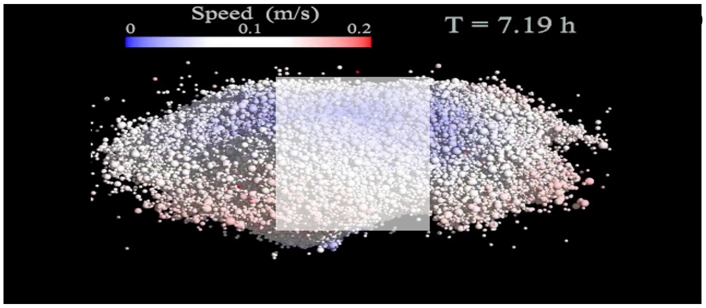


cohesion.



cohesion.

widespread surface mass movement that would be prep.). However, the longitudinal ridges may be ome degree of cohesion in the interior [16]. We repeated the simulation with model 2, except that we added 10 Pa of bulk cohesion. An animation of this model is shown in Video 3The results are largely similar to the cohesionless cases. We find that internal friction is sufficently strong in all cases to prevent substantial deformation until the body is nearly at the point of breakup.



Pa bulk cohesion

RESOLUTION TEST

It has been demonstrated that the YORP effect may be sensitive to small-scale topography [11]. However, if the distribution of blocks on the surface has a truly random orientation, then the torques from individual surface facets should cancel each other out. Over a long timescale (greater than an orbital period), we would expect that the average torque due to small-scale features on a rubble pile should average to zero. this reason, it has been generally believed that long-wavelength topography is the driver of YORP torques [6]. Thus, a sustained change in rotation rate due to the YORP effect would require a systematic preference in the orientation of the topography that is not likely to be caused by small-scale processes.

We computed the torque on the Bennu, using five different resolutions of the same shape model (OLA v14).

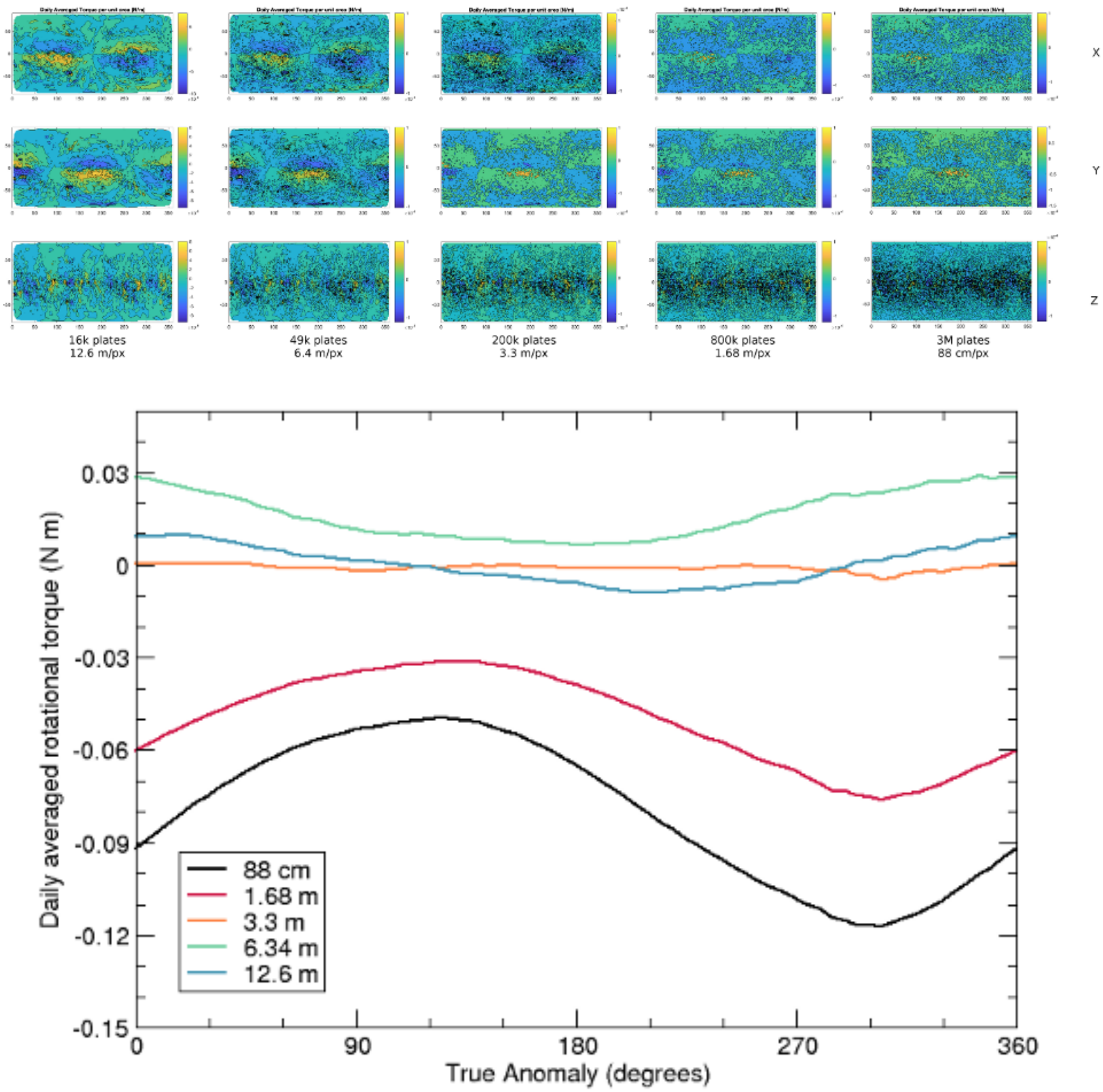


Figure 8: Daily averaged YORP torque computed at each plate of the shape model for at progressively higher resolution shape models at a True Anomaly of 180° (top). Globally-averaged torque over the course of an orbit (bottom).

We fnd the calculated torque is strongly dependent on the resolution of the shape model used, suggesting that the smaller material has an inguence. As the surface roughness of the model increases, the magnitude of the torque and even its sign may change. Spin rate increases that more closely match measurements are obtained with increasing small-scale roughness. We find that the pattern of the torque begins to stabilize at a resolution of 1.68 m, corresponding to the shape model with 800,000 plates. Further increase in resolution may change the magnitude of the torque somewhat, but not the behavior.

Simulated models that are coarser in resolution, but possess greater roughness than the equivalent lower resolution shape model from observations, likewise are more consistent with the observed spin-up rate. We have taken the 1.68-m shape model of Bennu and run this through the SSDEM routines, and recalculated the torques. We find that the resluting torque is similar to what went into it (compare solid and dashed red curves).

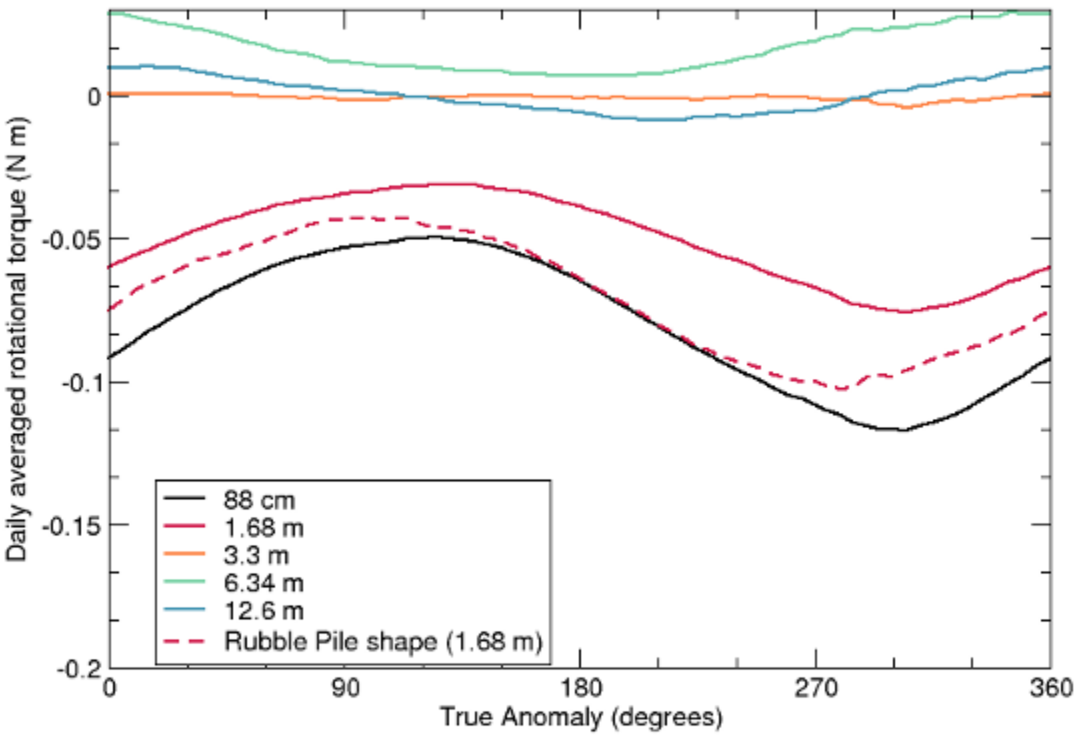


Figure 9: Globally-averaged torque over the course of an orbit (bottom) on the shape model at five different resolutions (solid curves) and on the best-fit SSDEM rubble-pile model (dashed curve).

Our goal is to understand the process and not necessarily to predict the future of Bennu, and the 1.68-m resolution model appears to be adequate for this. We use this resolution shape going forward.

DISCUSSION

Based on our simulations so far, we make the following conclusions.

- **Small-scale topography (< 15 m) is important**
  - Even the sign of the net torque on the body is influenced by it.
  - Torque calculations don't start to get convergence until ~1 m resolution.
  - This complicates our ability to predict future spin-shape evolution.
- **Surface roughness with a non-random orientation controlled by large-scale structure determines the YORP torque.**
- **The torque does not change significantly until the rotation period decreases to 3.6 hr from its current 4.3-hr period.**
  - internal friction is sufficently strong to prevent substantial deformation until the body is nearly at the point of breakup.
  - If several Pa of material cohesion is present, the surface material movement and deformation are impeded, and the torque is nearly constant before structural breakup.

Our results suggest that the global deformation of the asteroid's Bennu's shape due to YORP does not strongly alter the direction of the YORP torque rotation, and that if the initial shape is known to sukcient sufficient accuracy, the future shape-spin evolution and the associated timescale can be predicted.

ABSTRACT

The rotation rate of (101955) Bennu has been observed to increase, providing evidence of the YORP effect in action. Bennu is a rubble pile with little strength. At the current spin-up rate, the rotation would result in large-scale disruption in <1 My.

Such an extreme scenario is predicated on the YORP torque continuing to increase the rotation. However, YORP is sensitive to the shape and can change on a short timescale as small episodes of failure can increase oblateness, reduce spin rate, and redistribute rubble on the surface. A more comprehensive model of the shape and spin evolution of Bennu is required to understand its past and future.

Here, we calculate the YORP torque on a shape model of Bennu. For a random distribution of rubble, the torques on individual blocks should cancel, and the large-scale structure should control the YORP response. However, we find the calculated torque is strongly dependent on the resolution of the shape model used, suggesting that the smaller material has an influence. As the surface roughness of the model increases, the magnitude of the torque and even its sign may change. Spin rate increases that more closely match measurements are obtained with increasing small-scale roughness. Simulated models that are coarser in resolution, but possess greater roughness than the equivalent lower-resolution shape model from observations, likewise are more consistent with the observed spin-up rate. We find that surface roughness with a non-random orientation controlled by large-scale structure determines the YORP torque.

Following [1], we model the evolution of a rubble pile with Bennu's shape subject to YORP using the granular modeling tool pkdgrav and explore how the torques change as the object is deformed. The YORP torques are calculated on the present shape and applied until particles begin to move. The torques are then recomputed on the new shape, and the iteration continues. We find negligible change in the torque until the rotation period decreases to 3.6 hr from its current 4.3-hr period. At 3.53 hr, the asteroid starts to lose mass from the equator. Our results suggest that the deformation of the asteroid's shape due to YORP does not strongly alter rotation, and that if the initial shape is known to sufficient accuracy, the future shape and spin can be predicted.

[1] Cotto-Figueroa D. et al. (2015) *ApJ* 803, 25.

REFERENCES

[1] Gaskell et al., 2008, Meteorit. Planet. Sci., 43, 1049–1061.

[2] Barnouin et al., 2019, Nat. Geosci., 12, 247–252.

[3] Barnouin et al., 2020, Planet. Space Sci. 180, 104764.

[4] Daly et al., 2017, Space Sci. Rev., 212, 899–924.

[5] Daly et al., 2020, Science Advances, 10.1126/sciadv.abd3649

[6] Rubincam, 2000, Icarus, 148, 2–11.

[7] Walsh et al., 2008, Nature, 454, 188–191.

[8] Cotto-Figueroa et al., 2015, Astrophys. J. 803:25

[9] Nolan et al., 2019, Geophys. Res. Lett., 49, 1956–1962

[10] Hergenrother et al., 2019, Nature Communications, 10(1), 1291.

[11] Statler et al., 2019, Icarus, 202, 502–513.

[12] Schwartz et al., 2012, Granualr Matter, 14, 363–380.

[13] Zhang et al., 2017, Icarus, 294, 98–123,

[14] Walsh et al., 2019, Nat. Geosci., 12, 242–246.

[15] Barnouin et al., 2020, J. Geophys. Res. in prep.

[16] Hirabayashi and Scheeres, 2015, Astrophys. J. Lett., 798, L8.