FORMATION OF AN EQUATORIAL RIDGE ON AN OBLATE RUBBLE PILE ASTEROID

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Abstract: Astronomical observations have revealed that some asteroids spinning at rapid spin periods ranging from 2 hr to 5 hr are oblate and have unique equatorial ridges. These objects are considered to spin up due to the YORP effect. The preferred scenario of the ridge formation is that a landslide causes surface materials to cover over the equatorial region. Based on our recent research for the internal structure analysis about such objects, the present study proposes another possible scenario of an equatorial ridge on a rubble pile asteroid. The analysis was conducted by a finite element model taking into account a plastic deformation mode. The interpretation is that if the material distribution is uniform, an equatorial ridge is likely to be formed based on permanent deformation of the internal core, leading to horizontal material flow pushing the equatorial surface outward. In addition, because of its permanent deformation, the internal core may be underdense compared to the other regions. This scenario is another insight of the ridge formation, which has not been considered before.

Introduction: With ground-based observations, scientists have believed that rapidly rotating oblate asteroids having an equatorial ridge, such as 1999 KW4 [1], are common in the solar system. A currently popular explanation for the ridge formation is that rapid rotation causes the external surface to fail structurally, leading to a landslide overlapping the equatorial region. Minton [2] and Harris et al. [3] numerically investigated the formation of an idealized shape due to the gravitational slop, while Scheeres [4] quantitatively analyzed the effect of a landslide on the formation of the idealized shape. These studies implied that the formation of the equatorial ridge may result from a surface flow.

However, regardless of these strong interpretations, less consideration of the internal structure might ignore internal permanent deformation of such a body. Also, they might oversimplify the problem by assuming an initially spherical body and zero-cohesion. Recent radar observations and asteroid exploration missions captured the irregularity of rubble pile asteroids. Jewitt et al. [5] also reported an exciting breakup event of active asteroid P/2013 R3. This event allowed us to find that the range of cohesive strength of this asteroid may be around 100 Pa [6]. Rozitis et al. [7] also confirmed that because of its rapid spin period 1950 DA may be close to its failure condition and should have cohesion of at least 60 Pa. These evidences imply that rubble pile asteroids may generally have cohesion.

Over the last decade, analyses about the internal structure of asteroids have been conducted using averaged techniques. This analytical technique is useful to calculate the limit spin of such objects. Holsapple has performed this by averaging the whole body of a uniformly rotating ellipsoid (e.g., [8, 9]). In general, however, since asteroids are neither spherical nor ellipsoidal, it is important to investigate local stresses to see more accurate deformation processes. Hirabayashi and Scheeres [10] proposed a technique for determining the conditions for local stress states in asteroid (216) Kleopatra, a dog-bone like shape, and found that its neck part is closer to its failure condition than other locations.

In this study, based on the results by a finite element model originally developed by Hirabayashi and Scheeres [11, 12], we provide an alternative explanation for the formation of an equatorial ridge. In this scenario, plastic deformation occurs in the internal core, which also implies that the interior of such a body could be more porous than the external surface [11]. This could explain why radar albedo observations may suggest a surface density higher than the overall bulk density.

Finite Element Model: Hirabayashi and Scheeres [12, 11] developed a finite element model, including a plastic deformation mode, using the commercial software ANSYS. The Drucker-Prager yield criterion is used, and the material flow follows an associated flow rule. The body forces are defined only by self-gravity and rotation. The friction angle is assumed to be 35°, and the loading is assumed to increment linearly. Here, we discuss the critical cohesion cases of 1950 DA [11] and 1999 KW4 [12].

Figures 1 and 2 describe the finite element solution on the external shape and that over the cross section of 1950 DA [11]. The colors and numbers in these figures show the ratio of the current stress state to the yield stress, so called stress ratio [13]. If this ratio is 1.0 (red), the location experiences plastic deformation. As seen in these plots, although the stress state of the external surface is below the yield condition, the internal core experiences a plastic state. This indicates that the internal core is more likely to fail structurally at an earlier stage, while the surface is still elastic. Figure 3 shows the deformation vectors of the whole body. The equatorial region is vertically and compressively pushed by the high latitude regions, while experiencing tension in the horizontal direction. Such a deformation mode causes the internal core to have permanent deformation, and so the material flow is horizontal and outward. From Figure 4 showing the deformation vectors of 1999 KW4, we confirm the same deformation mode as seen for the case of 1950 DA. In these computations, the cohesive strength of 1950 DA and 1999 KW4 were fixed as 70 Pa and 20 Pa, respectively. Since the ridge formation has already been observed on these objects, their cohesive strength might be around a few tens of pascals.

Interpretation: The sensitivity of the internal core to structural failure and the outward deformation of the equatorial plane are a new insight into the ridge formation of an oblate rubble pile asteroid. Also, given the volume increment of permanent deformation, Hirabayashi and Scheeres [11] predicted that the internal core should be underdense compared to the other regions, which could possibly be measured by a visiting spacecraft [14]. Currently, ground-based observations have found similarly shaped objects having equatorial ridges. In addition to 1999 KW4 and 1950 DA, 2008 EV5 [15], (136617) 1994 CC [16] and (101955) Bennu [17], having spin periods of 2.39 hr, 3.73 hr, and 4.29 hr, respectively, are also remarkable examples. Due to their relatively rapid spin periods, these objects could also be experiencing the proposed deformation mode to develop their equatorial ridges. This deformation mode may be more common than thought for rapidly rotating oblate objects in the solar system.

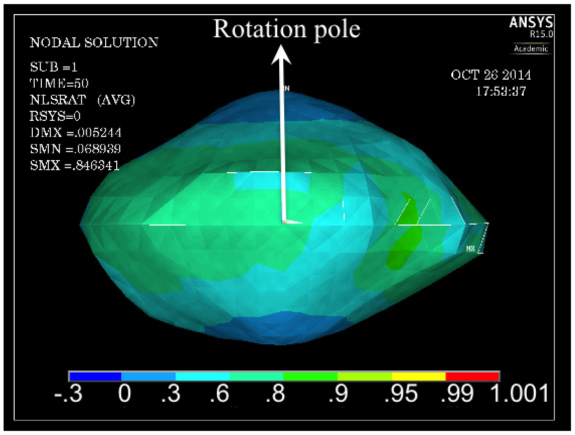

Figure 1: Unique equatorial ridge of 1950 DA [11]. The colors indicate the ratio of the current stress to the yield stress, known as stress ratio. The locations with stress ratio of 1.0, given in red, experience permanent deformation.

References: [1] S. J. Ostro, et al. (2006) *Science* 314:1276. [2] D. A. Minton (2008) *Icarus* 195:698. [3] A. W. Harris, et al. (2009) *Icarus* 199:310. [4] D. Scheeres (2015) *Icarus* 247(0):1 . [5] D. Jewitt, et al. (2014) *The ApJ Letters* 784(L8):1. [6] M. Hirabayashi, et al. (2014) *The ApJ Letters* 789(1):L12. [7] B. Rozitis, et al. (2014) *Nature* 512(7513):174. [8] K. A. Holsapple (2004) *Icarus* 172:272. [9] K. A. Holsapple (2007) *Icarus* 187:500. [10] M. Hirabayashi, et al. (2014) *The ApJ* 780(2). [11] M. Hirabayashi, et al. (2014) *The ApJ Letters* 798:L8. [12] M. Hirabayashi, et al. (2014) in *Lunar and Planetary Institute Science Conference Abstracts* vol. 45 1644. [13] P. Kohnke (2009) *Theory Reference for the Mechanical APDL and Mechanical Applications* ANSYS, Inc. 12th edn. [14] Y. Takahashi, et al. (2014) *Icarus* 233(0):179 . [15] M. W. Busch, et al. (2008) *Icarus* 195:614. [16] M. Brozovic, et al. (2011) *Icarus* 216:241. [17] M. C. Nolan, et al. (2013) *Icarus* 226(1):629 .

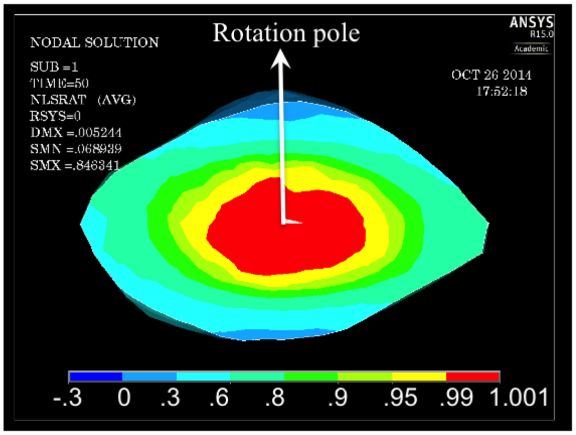

Figure 2: Stress ratio of the cross section of 1950 DA [11].

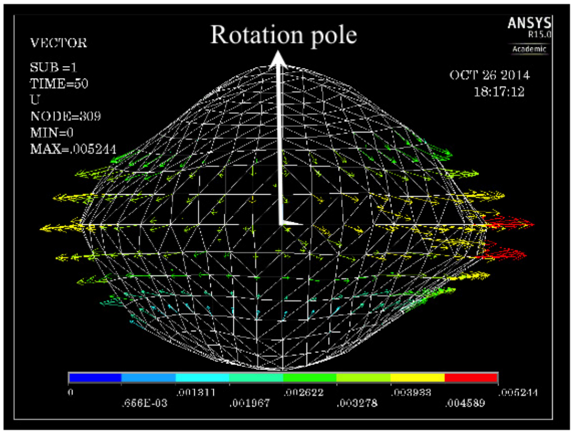

Figure 3: Deformation vectors of 1950 DA [11]. The magnitude is in meter.

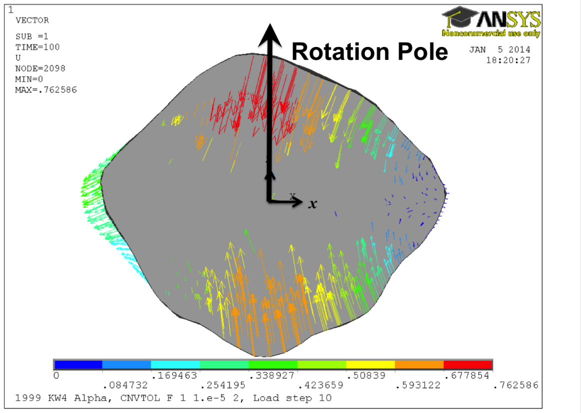

Figure 4: Deformation vectors of 1999 KW4 [12].