MASS SHEDDING ACTIVITIES OF ASTEROID (3200) PHAETHON ENHANCED BY ITS ROTATION.

R. Nakano[1] and M. Hirabayashi[1], [1]Department of Aerospace Engineering, Auburn University, 211 Davis Hall, Auburn, AL 36849-5338 (rzn0040@auburn.edu).

Summary: Our semi-analytical model shows that Phaethon's rotation state is close to or above its structural failure condition at present. Such structural sensitivity to failure due to rotation may explain the enhancement of mass shedding events that possibly induced the Geminid meteoroid stream and those observed recently.

Introduction: Asteroid (3200) Phaethon, a possible source of the Geminid meteoroid stream [1-3], has been active during perihelion passages [4, 5].

Taylor et al. [6] reported that Phaethon might be an oblate shape with ~6 km in diameter with an equatorial ridge, or known as a top-shaped asteroid. (101955) Bennu [7] and (162173) Ryugu [8-10] are examples of top-shaped asteroids. Phaethon is currently spinning at a rotation period of 3.6 hr [6]. The radar albedo is reported to be the lowest among the cataloged near-Earth asteroids [11], implying that its spectral type is consistent with B-type [6], and thus the bulk density may be as low as ~1.0 g/cm^3 [8, 12].

The activities of Phaethon are considered to have been triggered by thermal waves at this asteroid's perihelion passages [e.g., 4, 5]. Here, we hypothesize that such activities of Phaethon may have been further enhanced by fast rotation, which helped structural failure on the surface or in the interior to induce mass shedding that developed the Geminid meteoroid stream and recently observed dust tails. Our discussion explains that mass shedding that possibly induced the Geminid meteoroid stream could be much larger than that observed recently. This contrast is consistent with the interpretations by earlier observations [13].

Semi-analytical model for structural failure: We model Phaethon as a triaxial ellipsoid with the same oblateness as Bennu, based on the earlier work [14]. This is because a detailed shape model of Phaethon is not currently available, yet, and because a triaxial ellipsoid is a good approximation of structural analysis for a top-shaped asteroid [15]. We assume that Phaethon's structure is uniform as the internal condition is unknown. The bulk density is defined to be a free parameter, but we considered to range between 0.5 g/cm^3 and 1.5 g/cm^3, which is consistent with that of a B-type asteroid [16]. We analyze when the stress field in a given element reaches its yield condition. Similar to [15, 17], we first apply a technique by Dobrovolskis [18] and Holsapple [19] to provide the stress field in a triaxial ellipsoid uniformly spinning at rotation period of P. Then, the Drucker-Prager yield criterion [20] is applied to determine the structural failure condition of a given element. We compute the minimum cohesive strength that can prevent structural failure of a given element in an asteroid rotating at P. We call this strength 'critical cohesive strength' and denote it as Y^*. Also, we use 'actual cohesive strength' as an assumed strength that an asteroid may have. We denote this as Y. Structural failure should occur if Y is smaller than Y^*.

Results: We plot the distribution of Y^* at the x-z plane for different bulk densities in Figure 1. Panels a, b, and c describe the bulk densities of 0.5, 1.0, and 1.5 g/cm^3, respectively. We find that in this range of the bulk density, the interior should have some cohesive strength to keep the original shape.

For the case of $\rho = 0.5$ g/cm^3, the critical rotation period P_c is found to be 4.8 hr. Therefore, the current rotation period is above the critical rotation period, indicating that materials should be shed and highly sensitive to structural failure. Figure 1a shows $Y^* > 0$ everywhere except the pole region. The interior exhibits higher Y^* than the surface with a maximum value of 260 Pa, indicating that the interior is more sensitive to structural failure than the surface. For the case of $\rho = 1.0$ g/cm^3, P_c is found to be 3.4 hr. Therefore, the current rotation period is slightly longer than the critical rotation period. However, the interior still exhibits Y^* in the major regions (Panel b). The maximum Y^* value at the center is 180 Pa. For the case of $\rho = 1.5$ g/cm^3, P_c is found to be 2.8 hr. Unlike the other two cases, the interior has $Y^* = 0$ in the most areas except for the surface condition, which gives $Y^* = \sim 50$ Pa (Panel c).

The results show that all these three cases infer the sensitivity of Phaethon to structural failure, requiring the existence of cohesive strength. Thus, if there is a trigger of reshaping due to thermal waves [4, 5], it is likely that the deformation process would be enhanced by rotation, as seen from the derived sensitivity.

Discussions: *Generation of dust tails at present* – At the current rotation period of 3.6 hr, the body is sensitive to structural failure regardless of the bulk density and thus needs cohesive strength to maintain its shape. The derived cohesive strength of Phaethon is less than ~50 Pa - ~260 Pa. We interpret this sensitivity as a potential enhancement of mass shedding. If there is a trigger of reshaping such as thermal waves, the structure of Phaeton would be perturbed, leading to rotationally driven reshaping at larger scales.

Possible source of the Geminid meteoroid stream – Assuming that rotationally induced structural failure helped enhance reshaping initiated by thermal waves, we expect that Phaethon's deformation mode is to become more oblate, i.e., oblateness ϵ becomes lower [15]. Therefore, Phaethon may have been less oblate and rotated faster before deformation at an earlier stage.

From this deformation process, we consider that the stress condition in the interior is more severe in the past than at present due to faster rotation. For example, if Phaethon is a sphere, the rotation period should become $P = 3.4$ h, which is close to or above the critical rotation period P_c of a spherical body. Figure 2 shows that Y^* is larger, leading to higher structural sensitivity. This implies that failure at a shorter spin period is more significant than that at a longer spin period, and thus more materials can be shed [15].

We propose a possible evolution scenario of Phaethon (Figure 3). Again, possible initiation processes such as thermal waves during Phaethon's apparition passages triggered reshaping, and rotational deformation enhanced this reshaping process significantly. Phaethon was originally less oblate and spinning at a shorter rotation period than the current period. This stage is before the Geminid meteoroid stream was generated. Because the centrifugal forces may have been severer, the reshaping process caused mass shedding at large scale, which may become a source of the Geminid meteoroid stream. Then, the current oblate shape is a remnant of earlier reshaping activities. Because the oblateness evolved, the rotation of Phaethon slowed down. The structure is less sensitive to failure but still around the structural limit. Thus, when there is similar perturbation driven by, for example, thermal waves at present, rotationally driven failure can be triggered. At this point, however, the centrifugal effect is less significant, the magnitude of mass shedding at present is less intense than that in the past.

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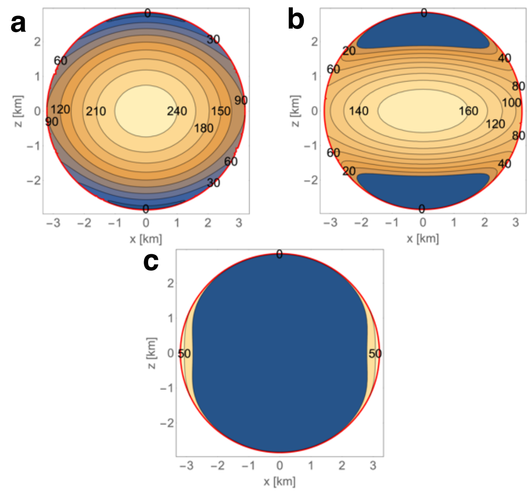

Figure 1. Distribution of Y^* across the cross-section along x and z axes. The rotation period is 3.6 hr. Panels a, b, and c describe the bulk densities of 0.5, 1.0, and 1.5 g/cm^3, respectively.

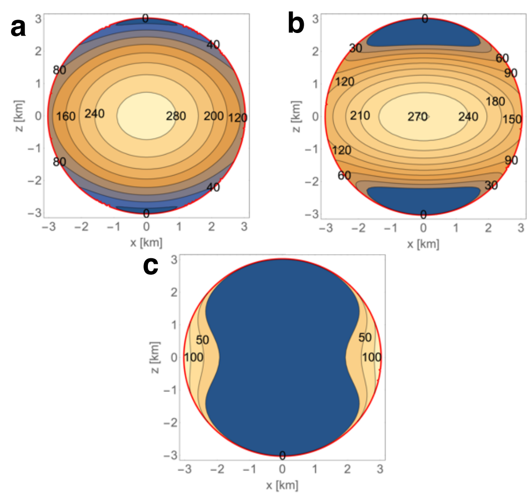

Figure 2. Distribution of Y^* across the cross-section along x and z axes. The rotation period is 3.4 hr. Panels a, b, and c describe the bulk densities of 0.5, 1.0, and 1.5 g/cm^3, respectively.

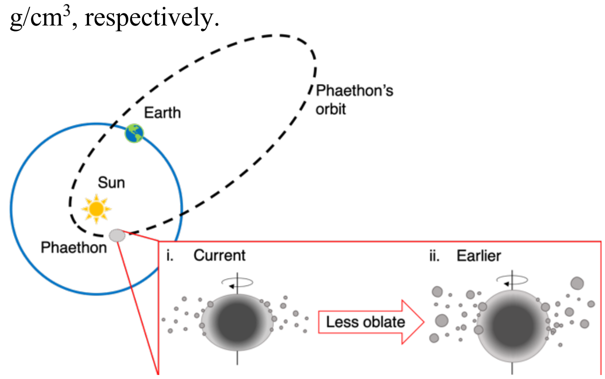

Figure 3. Possible evolution scenario of Phaethon. At an earlier stage, Phaethon was less oblate and rotating faster, leading to mass shedding at larger scale.