Numerical Simulations of Spinup of Asteroids and the Formation of Top-Shaped Asteroids

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The asteroids Ryugu and Bennu visisted by the spacecraft Hayabusa2 and OSIRIS-REx, respectively, have so-called "spinning top" shapes. The characteristics of the top shapes are as follows: pronounced equatorial ridges, cone-like surfaces from low latitudes to mid latitudes, and mostly axisymmetric shapes. Many top-shaped asteroids such as the asteroid 1999 KW4 have rapid rotations with rotation periods of about 3 hours. The axisymmetric shapes and the rapid rotations of the top-shaped asteroids suggest that top shapes are formed through the deformation due to spinup and rapid rotations of asteroids. However, how rapid-rotating asteroids deform and how top shapes form are not well understood.

Ryugu, Bennu, and many other asteroids are rubble-pile bodies, and thus friction of granular materials plays an important role for the deformation of rapid-rotating asteroids. Thus investigation of friction angles required for the formation of top shapes may lead to constrain properties of top-shaped asteroids. Although the major spinup mechanism is considered to be the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect, spinup can also be caused by reaccumulation of fragments after collisional catastrophic disruption. Spinup rate caused by the YOPR effect is much smaller than that caused by gravitational reaccumulation. Thus investigation of spinup rates required for the formation of top shapes may even constrain formation mechanisms.

In this study, we investigate the deformation of rubble pile bodies due to spinup using a Smoothed Particle Hydrodynamics (SPH) code. The code includes friction model for granular material and can treat dynamics of granular bodies. We simulate spinup of a uniform spherical body with the radius of 500 m and the density of 1.19 g/cm^3. The spinup rate is set to beta x 8.954 x 10^{-10}[rad/s^2], where beta is a parameter and beta = 1 gives acceleration from the period of 3.5 h to 3.0 h in about 10 rotations. We mainly change the friction angle phi$_d$ and the spinup rate beta.

All the simulations with beta = 1 result in axisymmetric deformation. The spinup with phi$_d$ < 40 degrees results in quasi-static and internal deformation, that with 50 degrees < phi$_d$ < 60 degrees results in dynamical and internal deformation, and that with phi$_d$ > 70 degrees results in dynamical and surface landslides. Especially, the simulation with phi$_d$ = 80 degrees produces an axisymmetric top shape.

The simulation with phi$_d$ = 80 degrees but with slower spinup rate beta = 0.05 results in non-axisymmetric landslide and the formation of a non-axisymmetric shape. Thus Our simulations show that fast spinup with beta ~ 1 of spherical body with phi$_d$ > 70 degrees produces axisymmetric top shapes.

The friction angle phi$_d$ > 70 degrees is much larger than that of cohesionless granular materials. This suggests that the other strength of granular materials such as cohesion is also important for the formation of top shapes. The YORP spinup gives beta << 1, while gravitational accumulation of fragments gives beta > 1. Thus our results suggest that top shapes are possibly formed through fast spinup due to reaccumulation of fragments or coalescence of remnants after collisional catastrophic disruption. Another possibility is multiple non-axisymmetric landslides. The timescale for the YORP spinup is mainly shorter than collisional lifetime for 1-km sized asteroids, and they probably experience multiple cycles of YORP acceleration and non-axisymmetric landslides. Multiple non-axisymmetric landslides at different places may lead to the formation of axisymmetric top shapes.

Keywords: top shapes, spinup of asteroids, numerical simulation, SPH method