# YORP EFFECT ON ASTEROID 162173 RYUGU AND ITS SPIN EVOLUTION.

M. Kanamaru[1], S. Sasaki[2], T. Morota[3], Y. Cho[3], E. Tatsumi[4], M. Hirabayashi[5], N. Hirata[6], H. Senshu[7], Y. Shimaki[1], N. Sakatani[8], S. Tanaka[1], T. Okada[1], T. Usui[1], S. Sugita[3], and S. Watanabe[10], [1]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (ISAS/JAXA), Contact: kanamaru.masanori@jaxa.jp, [2]Osaka University, [3]The University of Tokyo, [4]Instituto de Astrofísica de Canarias, [5]Auburn University, [6]The University of Aizu, [7]Chiba Institute of Technology, [8]Rikkyo University, [10]Nagoya University.

**Introduction:** Thermally induced torque on an asteroid, i.e., the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect secularly changes its rotation period and spin pole direction on a time scale of about a million years [1]. The surface of the airless rocky body heated by sunlight emits thermal radiation mainly in the wavelength of mid- to far-infrared rays. In general, the thermal recoil torque on the irregularly shaped body is not cancelled over cycles of rotation and revolution. The net torque could alter the spin state of the asteroid and have a significant impact on its dynamical history.

Asteroid 162173 Ryugu is a carbonaceous asteroid that was visited by Japan's Hayabusa2 spacecraft between 2018 and 2019 [2]. The boulder-rich surface indicates that Ryugu is a rubble pile that was formed by accumulation of fragments of a parent body. For an aggregate of rocks to deform into a spinning-top shape such as Ryugu, it must have experienced a fast rotation at a spin period of ~3.5 h [2, 3].

In this study, we conducted numerical simulations of the YORP effect on Ryugu to shed light on the process of rotational deceleration from fast rotation in the past to the current slower spin at a period of 7.6 h. Understanding the dynamical history of Ryugu will help us interpret the coming results of analyses of sample materials that were brought back from Ryugu and were successfully recovered in Woomera, Australia in December 2020.

**Methods:** Given the current orbit, rotation parameters, and three-dimensional shape of Ryugu [2], we modeled the thermal radiation from the surface of the body over a cycle of revolution. In this study, we simplified the numerical model and reduced the calculation time with approximation of (1) zero-conductivity for the surface materials, and (2) isotropic radiation from each surface facet of a shape model. We also implemented intersection detection of solar rays and the meshes of the shape model to check shadows casted by the unevenness of the terrain (i.e., the self-shadowing effect). The simplified model worked adequately to reproduce the thermal torque in comparison with the thermophysical model [4] in case of low thermal inertia without small-scale roughness. The effects of small-scale roughness and reabsorption of thermal radiation (i.e., the self-heating effect) will be examined in the future.

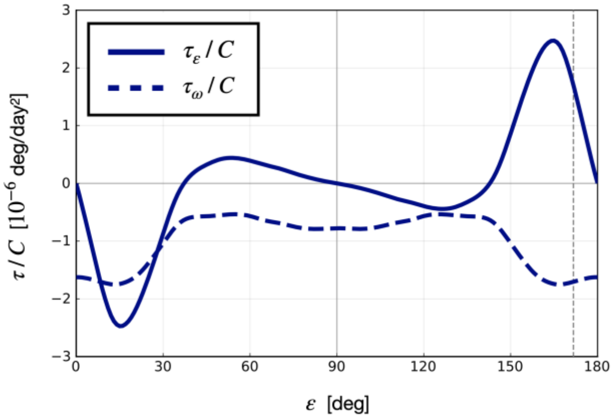

**Figure 1.** Obliquity dependence of YORP effect on Ryugu, derived from our nominal case of the SPC-based model (Shape ID: SPC_49k_v20190802).

In general, the numerical calculation of the YORP effect is known to be strongly dependent on slight differences in input geometry [5]. Therefore, we performed a survey for 20 shape models with different release dates and methods of reconstruction: Stereo photoclinometry (SPC) and structure-from-motion (SFM). The shape models used in this study consist of about 50,000 surface meshes (mean mesh size ~ 8.4 m).

**Results:** We averaged the thermal torque $\tau$ on Ryugu over the orbital period to obtain the net rates of change in angular velocity of rotation $\omega$ and obliquity $\varepsilon$ (i.e., tilt angle of the spin pole with respect to the normal vector to the orbital plane).

*Obliquity dependence of YORP.* Figure 1 shows the year-averaged torque divided by moment of inertia $C$ as function of obliquity. $\tau_\omega$ and $\tau_\varepsilon$ denote torque components to change spin velocity (dashed) and obliquity (solid), respectively. Figure 1 is a typical example of the 20 shape models we examined. The vertical gray dashed line at $172^\circ$ marks the current obliquity of Ryugu.

In the above nominal case, it is indicated that Ryugu spins down with a negative rate of change in the rotation velocity $\omega\ (>0)$ at every obliquity

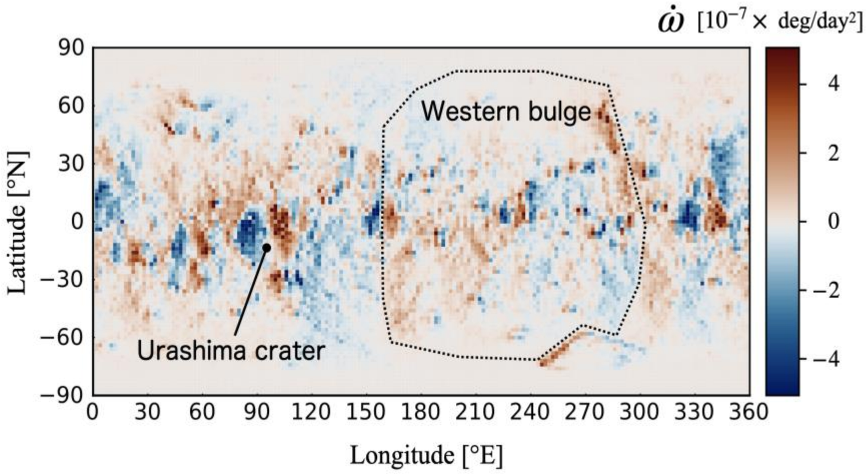

**Figure 2.** Spatial distribution of thermal torque to contribute to acceleration (red) or deceleration (blue).

$\varepsilon$ (0° to 180°) (see dashed curve). On the other hand, the thermal torque changes the spin pole direction for obliquity to approach one of three asymptotic states: $\varepsilon = 0^\circ, 90^\circ$, and $180^\circ$, depending the initial obliquity (see solid curve).

Given the current obliquity of Ryugu, the body is expected to be spinning down at a rate of $-1.71 \times 10^{-6}$ deg/day$^2$, which corresponds to 2.15 million years for rotation period to change from 3.5 h to 7.6 h. Asteroid Ryugu is a retrograde rotator with an obliquity of $172^\circ$. The YORP effect is working to bring the obliquity to $180^\circ$ because of a positive rate of change.

*Summary of 20 cases.* In all 20 shape models, we confirmed that Ryugu is spinning down at the current obliquity regardless of meter-scaled differences in topography. The rates of change in spin velocity ranged from $-0.42 \times 10^{-6}$ to $-6.3 \times 10^{-6}$ deg/day$^2$ depending on the input shape models. The corresponding time scale of the spin down is 0.58 – 8.7 million years. The states of the upright spin pole, that is, $\varepsilon = 0^\circ$ and $180^\circ$ are stable obliquities for all cases.

**Discussion:** Despite the sensitivity of the YORP modeling to slight differences in the shape models, it is suggested that Ryugu is spinning down at the currently observed shape. The YORP effect can be a dominant mechanism to bridge the gap between the fast rotation in the past and the current spin state.

Figure 2 shows the spatial distribution of the rate of acceleration. The east-facing slope contributes to the slowdown, while the west-facing one contributes to acceleration. The sum of them over the entire surface is the net acceleration rate shown earlier. Whether the thermal torque accelerates or decelerates rotation depends on tens of meters scale topography such as a crater or convex terrain with east-west asymmetry.

The above time scale of rotational deceleration corresponds to timing of major change in topography on asteroid Ryugu. The deceleration time scale we estimated (0.58 – 8.7 million years) corresponds to the formation ages of Urashima crater (the largest crater on Ryugu, 5–11 Ma) and the western bulge (2–8 Ma), for example, which are derived from the crater statistics in each geological unit [6, 7]. It is considered that Ryugu was spinning at a period of ~3.5 h millions of years ago and the rotation of the body has slowed down in the wake of the large crater formation or the resurfacing event on the western hemisphere.

Our YORP simulation also suggested that the spin pole of Ryugu has been upright with respect to the orbital plane for the last several million years. Hayabusa2 observed the latitudinal patterns in albedo and spectral slope from b- to x-bands [8]. The upright spin pole may have protected the polar regions from solar heating, which were observed to have bluer spectra than the rest of the surface.

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**References:** [1] Rubincam D. P. (2000) *Icarus*, *148*(1), 2–11. [2] Watanabe S. et al. (2019) *Science*, *364*(6437), 268–272. [3] Hirabayashi M. et al. (2019) *The Astrophysical Journal*, *874*(1), L10. [4] Takita et al. (2017) *Space Science Reviews*, *208*(1–4) 287–315. [5] Statler T. S. (2009) *Icarus*, *202*(2), 502–513. [6] Morota T. et al. (2020) *Science*, *368*(6491), 654–659. [7] Cho Y. et al. (submitted). [8] Sugita S. et al. (2019) *Science*, *364*(6437), eaaw0422.