YARKOVSKY-DRIVEN ORBITAL MIGRATION OF ASTEROID RYUGU: IMPLICATIONS FOR THE RETURNED SAMPLE ANALYSES. M. Kanamaru[1] (kanamaru.masanori@jaxa.jp), R. Hyodo[1], T. Okada[1], T. Usui[1], S. Sasaki[2], E. Tatsumi[3,4], Y. Cho[4], T. Morota[4], and S. Sugita[4,5], [1]ISAS/JAXA, [2]Osaka University, [3]Instituto de Astrofísica de Canarias, [4]The University of Tokyo, [5]Chiba Institute of Technology.

Introduction: Orbital evolution of asteroids is an important process responsible for mass transport in the solar system. In particular, C-type asteroids, which are rich in organics and hydrous minerals, may have transported a large amount of volatiles inward beyond the snowline. Dynamical evolution of an asteroid is governed by perturbations due to non-gravitational effects, in addition to gravitational interactions with planets and collision events. Orbital and rotational evolutions of the asteroid caused by anisotropic thermal radiation are called Yarkovsky and YORP effects, respectively [e.g., 1].

Hayabusa2 spacecraft mission successfully returned samples from C-type asteroid Ryugu [2, 3]. In this study, we aim to constrain a planetary geological context of the returned sample and identify an asteroid family from which Ryugu originated by clarifying the dynamical evolution based on the observed physical properties.

Thermophysical Modeling: The orbit calculation in this study is based on thermophysical modeling. The surface temperature of an asteroid is determined by energy balance between heating by sunlight, heat conduction to underground, and cooling by thermal radiation. Using Ryugu's orbital elements, rotation parameters, and a 3-D shape model derived from Hayabusa2 mission, we calculated the temperature distribution on the surface and its time variation over a cycle of orbit. We used a dynamical and thermophysical calculation library for an asteroid, *Astroshaper**. This library was originally developed to investigate the spin evolution of asteroid Ryugu [4]. At present, the model can consider the effects of facet-based shadow detection, 1-D heat conduction, scattering of sunlight, and reabsorption of thermal radiation on the surface. The infrared beaming effect due to surface roughness [e.g., 5) will be implemented in the future.

Yarkovsky Drift at Near-Earth Orbit: To investigate how the Yarkovsky effect causes the orbital evolution of Ryugu at the near-Earth orbit, we performed a thermophysical simulation with the current orbital elements and spin parameters: The orbital semi-major axis $a = 1.19$ au, eccentricity $e = 0.19$, rotation period $P = 7.63262$ h, and obliquity of the spin pole with respect to the orbital plane $\varepsilon = 171.64°$ [6]. The thermophysical properties used in this study correspond

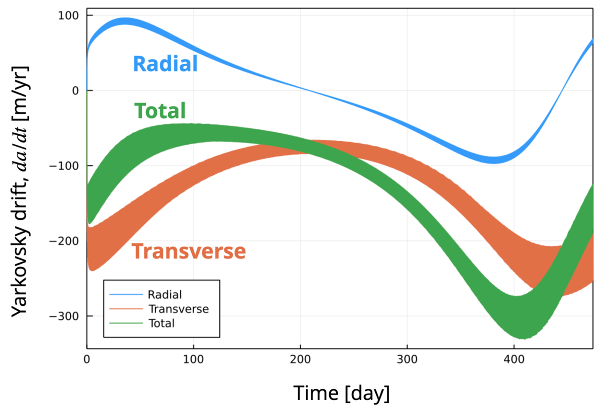

Figure 1. Radial and transverse components of Yarkovsky drift rates and the sum of them over a cycle of orbit.

to the global average values estimated from the observation by the thermal infrared imager (TIR) onboard Hayabusa2 and the Mobile Asteroid Surface Scout (MASCOT) lander: The thermal conductivity $k = 0.1\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$, thermal inertia $\Gamma = 276\ \mathrm{J \cdot m^{-2} \cdot K^{-1} \cdot s^{-0.5}}$ (tiu), bond albedo $A_\mathrm{B} = 0.04$, and emissivity $\epsilon = 1.0$ [7–9]. In this simulation, we used a shape model with resolution reduced to 5,932 facets, which does not significantly affect the Yarkovsky drift rate.

The above simulation yielded thermally induced acceleration $(a_\mathrm{R}, a_\mathrm{T}, a_\mathrm{N})$ on the asteroid at every time step or true anomaly f. The perturbation of the orbital elements can be obtained by using the components of the acceleration: the radial (Sun-to-asteroid direction) component a_R, transverse component along the orbital plane a_T, and normal component perpendicular to the orbital plane a_N. In the later analyses, we focus on the time variation of the orbital semi-major axis as follows [10]:

$$\frac{da}{dt} = \frac{2}{n\sqrt{1-e^2}}\left[e \sin f\, a_\mathrm{R} + \frac{a(1-e^2)}{r} a_\mathrm{T}\right]$$

where n denotes the orbital mean motion, and r the heliocentric distance.

Figure 1 shows the Yarkovsky drift rates derived from the radial and transverse components of the acceleration as functions of time over a cycle of orbit.

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*Astroshaper: Julia-based toolkit for dynamical simulations of planets and small solar system bodies. https://github.com/MasanoriKanamaru/Astroshaper

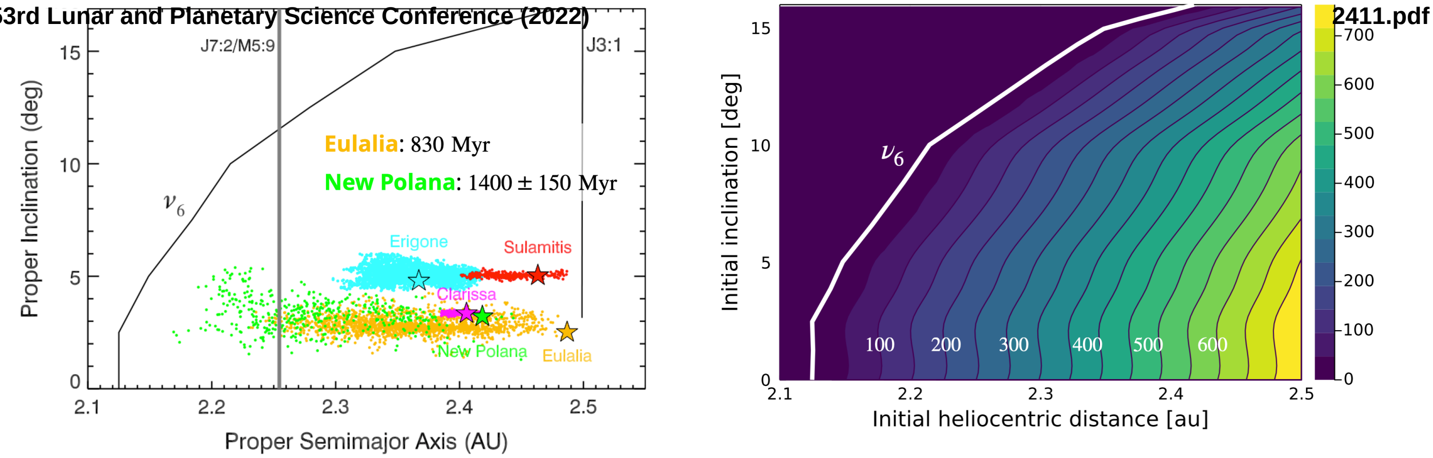

Figure 2. (*Left*) Potential source family of asteroid Ryugu such as Eulalia and New Polana. The figure from [11] is modified. (*Right*) Time needed for a Ryugu-like asteroid to reach the $\boldsymbol{\nu_6}$ resonance by the Yarkovsky drift.

The radial component (blue curve) mostly cancels out in one cycle, while the transverse component (orange curve) always works at a negative rate of change in the semi-major axis. The sum of these two components (green curve) also decreases the semi-major axis. Because asteroid Ryugu is a retrograde rotator with an obliquity close to 180°, the Yarkovsky effect causes it to move radially inward. The orbitally averaged rate was calculated to be $da/dt = -139$ m/yr, which is equivalent to half of the moving speed for asteroid Bennu, $da/dt = -284.6 \pm 0.2$ m/yr [10]. This difference is consistent with the difference in size between Ryugu and Bennu.

Yarkovsky Drift at Inner Main Belt: We also simulated the orbital migration of asteroid Ryugu by the Yarkovsky effect in the inner main belt (a = 2.1–2.5 au). Ryugu is considered to have reached the current near-Earth orbit via a secular resonance with the Saturn called ν_6 [11]. Based on the similarity of the reflectance spectra, Ryugu is thought to originate from Eulalia or New Polana family [11–13] (Left panel of Figure 2).

For simplicity, we hereby assumed a circular orbit ($e = 0$) and a spin axis perpendicular to the orbital plane ($\varepsilon = 180°$). For Ryugu, the approximation of the fixed spin pole should work because torque by thermal radiation, that is, the YORP effect keeps the spin pole perpendicular [4]. Although the rotation period may vary according to YORP cycles, we hereby fixed it to the current period $P = 7.63262$.

The right panel of Figure 2 shows time needed for a Ryugu-like object to reach the ν_6 resonance from each initial orbital element (a_0, i_0). It takes approximately 700 million years for the asteroid with the equivalent diameter of 898 m to travel through the inner main belt only by Yarkovsky (See the yellow region).

Discussions: The oldest geological unit on Ryugu is the equatorial ridge that has a formation age of 23–30 million years [14]. This geological time scale is much shorter than the time scale for Ryugu to travel through the inner main belt. On the other hand, the formation ages of Ryugu's possible source families, e.g., 830 Ma for Eulalia and 1400 Ma for New Polana [11] are comparable or longer than the time scale of Yarkovsky drift. If Ryugu originated from Eulalia family, it could have formed as large as a kilometer when the family members formed. In this case, it is thought that the formation of the top shape is due to a subsequent spin-up by the YORP effect [15]. On the other hand, if Ryugu originated from New Polana, it would have to spend millions of years as a parent body several times larger to stay longer in the main belt. If this is true, it is also possible for Ryugu to directly form the top shape when it accumulated from fragments of the larger parent body [16]. These scenarios will be validated in the future by comparing with a cosmic-ray exposure age and an impact age of the returned sample.

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