CONTRIBUTION OF THE REGOLITH ROUGHNESS TO THE TANGENTIAL YORP EFFECT OF ASTEROID (162173) RYUGU. O. Golubov[1] and V. Lipatova[1], [1]Institute for Astronomy, V.N.Karazin Kharkiv National University, Sumska Street 35, Kharkiv 61022, Ukraine.

Introduction: Rotational dynamics of asteroids is strongly affected by the YORP effect, which is a torque caused by an asymmetric scattering and re-emission of light by the asteroid. It consists of the normal YORP (or NYORP) produced by the global shape asymmetry of the asteroid, and the tangential YORP (or TYORP), produced by uneven heat conduction on small-scale structures on the surface of the asteroid [1]. Boulders of different shapes have been considered as examples of such irregularities of the surface (see [2] and references therein). Still, roughness of the surface does not always manifest itself in the form of individual boulders, as it is clearly exemplified by the *in situ* photos of the surface of asteroid (162173) Ryugu, which were obtained by the *MASCOT* lander [3]. Such kind of roughness requires for its description a new theory, which considers TYORP not of individual boulders, but of a rough surface as a whole. Here we construct an approximate analytic theory for TYORP produced by a curved asteroid surface ans apply it to estimate TYORP of asteroid Ryugu.

Analytic model of the tangential YORP produced by a sinusoidal wave: Consider a surface of asteroid regolith having a shape of sinusoidal wave with the wavelength L and amplitude $kL/2\pi$ (so that the maximum slope is k). Let the crests and troughs of the wave be oriented at the azimuthal angle β. Let they be positioned at the latitude ψ on the asteroid surface.

We linearize the 2-dimensional heat conduction problem under the sinusoidal surface, find the approximate solution for the temperature, and use it to compute the tangential YORP force. It is convenient to express the force F_x acting on the surface area S in terms of the dimensionless pressure $p = F_x c/((1-A)\Phi S)$, where c is the speed of light, A is the albedo of the asteroid surface, and Φ is the solar constant at the asteroid's orbit. For the dimensionless pressure of tangential YORP we derive the following expression:

$$p = \frac{k^2\pi\tau_0^2\theta^2\left(4\tau_0^3+\mu\theta\right)}{2\sqrt{2}\left(2l\tau_0^3+\pi\theta\right)\left(16\tau_0^6+4\sqrt{2}\tau_0^3\theta+\theta^2\right)}\times$$
$$\times\frac{\cos\psi\cos^2\beta}{16\tau_0^6+8\mu\tau_0^3\theta+(\mu^2+\nu^2)\theta^2}$$

Here $\tau_0=(\cos(\psi)/\pi)^{1/4}$, whereas constants μ and ν are defined as

$$\mu = \frac{1}{\sqrt{2}}\left(\sqrt{1+\left(\frac{2\pi}{l}\right)^4}+\left(\frac{2\pi}{l}\right)^2\right)^{\frac{1}{2}}$$
$$\nu = \frac{1}{\sqrt{2}}\left(\sqrt{1+\left(\frac{2\pi}{l}\right)^4}-\left(\frac{2\pi}{l}\right)^2\right)^{\frac{1}{2}}$$

The non-dimensional wavelength l is connected to the physical wavelength L as $l = L/L_{\text{wave}}$, with L_{wave} being the thermal wavelength [4]. The thermal parameter θ is determined in the same way as in [4].

Surface roughness of asteroid Ryugu: Asteroid Ryugu presents a nice opportunity to test our theory, as its surface has been investigated at a small scale by the MASCOT lander of the Hayabusa2 space mission [5], giving us a good opportunity to measure the values needed to apply the derived equations for the tangential YORP.

We used the cross-section of the surface presented in [6], which has the length 40 cm and the spacial resolution 3 mm, and determined the surface slopes corresponding to sinusoidal waves of different wavelengths. For the wavelengths in the range 1 cm to 10 cm, the maximum slope of the sinusoidal waves was nearly the same, $k \approx 0.5$.

Taking the asteroid parameters from [7] and assuming the heat conductivity 700 TIU, which is typical for chondrite material [8], we arrive at the thermal parameter θ=1.4 and the thermal wavelength L_{wave} = 1.7 cm. At this thermal parameter, the maximum $p/k^2 \approx 0.0048$ is attained at $l \approx 4$ (see Fig. 1). With L_{wave} = 1.7 cm and $k \approx 0.5$ this corresponds to the maximal non-dimentional TYORP pressure $p_0 \approx 0.0012$ at the wavelength $L \approx 7$ cm.

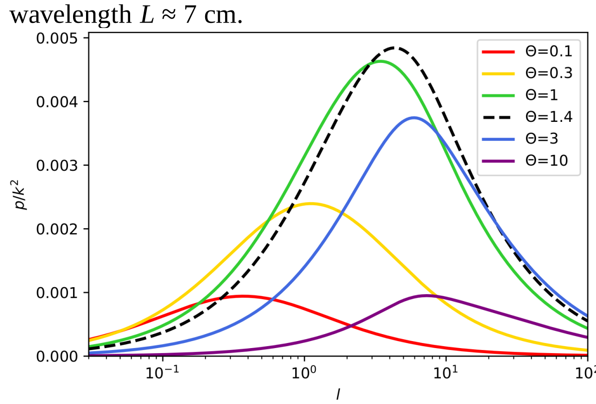

Fig. 1. Non-dimensional tangential YORP pressure p as a function of wavelengths l for different values of the thermal parameter θ. The other values are β=0 and ψ=0.

This p_0 is attained at the equator, whereas at other latitudes p should be multiplied by the factor $\cos(\psi)$. We integrate p over the surface of a near-spherical asteroid and obtain the total tangential YORP torque T. The corresponding non-dimensional torque $\tau = Tc/(\Phi R^3)$ is

$$\tau = (1 - A)p_0\frac{8\pi}{3}$$

Substituting parameters of Ryugu, we get $\tau \approx 0.01$ for the non-dimensional tangential YORP torque exerted on Ryugu by the roughness of its regolith.

Conclusions: Based on the shape model of Ryugu, [9] predict the negative normal YORP effect lying in the range $-0.42\cdot10^{-6}$ deg/day^2 to $-6.3\cdot10^{-6}$ deg/day^2. It corresponds to the non-dimentional torque of the normal YORP between −0.00014 and −0.0021. We see that the tangential YORP can surpass the normal YORP, causing a positive total acceleration.

The theory created for TYORP produced by the regolith of asteroid Ryugu is equally applicable to other asteroids, whose surface is rough at the centimeter scale, although the tangential YORP torque for other asteroids is harder to evaluate because of the lack of reliable information about their small-scale surface roughness. The same theory can also be used to describe TYORP caused by surface roughness of boulders on the surface of asteroids. The TYORP torques created by the boulders themselves [4] and by the roughness on the surface of these boulders are complementary to each other, and there is no distinct boundary between them. Both components can contribute to the overall TYORP at comparable magnitudes, and a more accurate evaluation of them would enable a more reliable prediction of dynamic evolution of asteroids.

References: [1] Vokrouhlický D. et al. (2015) *Asteroids IV* (P. Michel et al., eds.), Univ. of Arizona, Tucson, 509–531. [2] Golubov O. (2017) *AJ*, *154*, 238. [3] Scholten F. et al. (2019) *A&A*, *632*, L5. [4] Golubov O., Krugly, Y. N. (2012) *ApJL*, *752*, L11. [5] Preusker F. et al. (2019) *A&A*, *632*, L4. [6] Otto K. A. et al. (2021) *MNRAS*, *500*, 3178–3193. [7] Watanabe S. et al. (2019) *Science*, *364*, 268–272. [8] Szurgot M. (2011) *LPSC XLII*, *1608*, 1150. [9] Kanamaru M. et al. (2021) *Journal of Geophysical Research: Planets*, *126*, e2021JE006863.