SURFACE ROUGHNESS AND THERMAL INERTIA OF ASTEROID RYUGU INFERRED FROM TIR ON HAYABUSA2. Y. Shimaki[1], H. Senshu[2], N. Sakatani[1], T. Fukuhara[3], S. Tanaka[1], T. Arai[4], H. Demura[5], K. Suko[5] and T. Okada[1], [1]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (3-1-1 Yoshinodai, Chuo, Sagamihara, Kanagawa 252-5210, Japan, shimaki@planeta.sci.isas.jaxa.jp), [2]Chiba Institute of Technology, Japan, [3]Rikkyo University, Japan, [4]Ashikaga University, Japan, [5]University of Aizu, Japan.

Introduction: Thermal inertia ($\Gamma = \sqrt{\rho C_\mathrm{p} \kappa}$, where ρ, C_p, and κ are density, heat capacity, and thermal conductivity) is a key parameter to investigate surface physical state of asteroids. In general, thermal inertia values of fine sand, pebbles, and monolithic rocks are 50, 200-400, and larger than 2000 [$\mathrm{Jm^{-2}s^{-0.5}K^{-1}}$ $\equiv$ tiu], respectively [1]. The thermal inertia of the asteroid 162173 Ryugu is estimated to be from 150 to 300 tiu based on the ground observations [2]. The thermal inertia of asteroids shows negative correlation with their sizes based on ground and in-situ observations, while there are large errors on the km-sized bodies due to lack of precise measurements [3]. Besides the thermal inertia, recent studies on the thermal calculations have pointed out that surface roughness of atomosphereless body affects on the thermal emission of the body [4].

The thermal infrared imager TIR has been developed for the Hayabusa2 spacecraft to image the thermal emission from the surface of Ryugu. It is based on a two-dimensional uncooled micro-bolometer array, inherited from the Longwave Infrared Camera LIR on the Akatsuki, and obtains thermal infrared radiation in wavelength of 8-12 μm [5]. During the proximity phase of the Hayabusa2 in 2018, TIR has carried out several observations for one asteroid rotation [6]. In this study, we report results of a one-rotational thermal imaging of Ryugu during Mid-Altitude operation at August 1, 2018 (altitude of around 5 km with resolution about 5 m/pixel), a thermal calculation on a rough surface, and an investigation on global distribution of surface roughness and thermal inertia of Ryugu.

Methods: TIR has taken thermal images of Ryugu in the same manner as the imaging of the Earth and the moon during the Earth swing-by on December 3, 2015 [7]. Besides the temperature calibration of TIR, we performed a thermal calculation on a rough surface and slope corrections to improve estimation of surface roughness and thermal inertia of Ryugu.

TIR data processing. Level 1 (L1) TIR data is an infrared radiation image from a target body in digital numbers. With a TIR temperature calibration tool HEAT [8, 9] and dedicated calibrations based on the pre-flight ground tests, L1 images are converted to brightness temperature images (L2a product). With a shape model of Ryugu, SPICE kernels derived from SPC shape model based on optical images acquired by ONC-T, and the alignment of TIR precisely determined by adjusting the observed shape of Ryugu and the shape model [10], L2a data are projected on the shape model as a brightness temperature map on a shape model L3b. A diurnal temperature profile on a surface (a polygon on the shape model) of Ryugu is obtained from a series of the L3b during a one-rotational observation. The temperature data of a polygon is sorted by local time with consideration of local EW (East to West) slope of the shape model.

Thermal calculation on rough surface. ONC-T images revealed that the surface of Ryugu is covered by numerous boulders. On a rough surface, apparent brightness temperature of a surface of asteroid depends not only on the heliocentric distance, sub-Solar latitude, and thermal inertia, but also on the directions of the sun and observer and local slopes [11]. To have reference temperature profiles for estimation of thermophysical properties of Ryugu, we carried out a thermal calculation on fractal rough surface based on [11, 12]. In the calculation, a random rough surface was constructed numerically. The surface is composed of normal and reverse triangles, and the height of each vertex is determined by the normal distribution function with the variance of σL, where L is the horizontal length of the triangles sides and parameter σ represents a degree of roughness. Under orbital configurations for Mid-Altitude operation, of which the sub-Solar and the sub-spacecraft latitudes were -8.4 and -5.4 degree, we varied thermal inertia Γ from 10, 100 to 800 by 100 tiu, roughness σ from 0.0 to 0.5 by 0.1, and latitude θ from -88 to 88 by 4 degree, respectively. After the calculation, the three parameters were interpolated by smooth spline or polynomial functions.

Multiple linear regression analysis. To characterize the effect of σ and Γ on the temperature profile for each θ, the temperature profiles are fitted by 4-order function as follows,

$$T = ax^4 + bx^3 + cx^2 + dx + e, \tag{1}$$

where T and x are temperature and local time, respectively. A multiple linear regression analysis on Γ and σ was performed for each θ and we obtained empirical equations as follows,

$$\Gamma_\theta = f_\theta(a, b, c, d, e), \tag{2}$$

$$\sigma_\theta = g_\theta(a, b, c, d, e). \tag{3}$$

From coefficients of 4-order function obtained by fitting on an observed temperature profile and Eqs. (2, 3), Γ and σ of a surface of Ryugu were estimated.

Slope corrections. Slopes on a surface of a small body have an important role to determine diurnal temperature profile, because NS (North to South) slope affects on the maximum temperature and EW slope defines the local noon. However, in general, a shape model makes a local slope on the surface narrower than the actual. To improve estimation of Γ and σ for a polygon on the shape model, we carried out slope corrections for both NS and EW directions. To evaluate estimations for both parameters, we examined root mean square (RMS) of temperature difference between observed and calculated. We varied correction angles from -45 to 45 degree to find minimum RMS values.

Results and Discussion: Temperature profiles by the thermal calculation for σ = 0.0 (plane surface) showed good agreement with those by one without roughness [13]. With the increase of Γ, maximum temperature decreased and its local time shifted from the local noon. With the increase of σ, temperature at mooning and evening increased while that at noon decreased, which results in a flat temperature profile relative to plane surface. Temperature profiles showed twin peaks at σ = 0.5. With the increase of the difference of latitude from the sub-Solar latitude, maximum temperature decreased. Diurnal temperature profile of a polygon at $>$64 N became narrower than that at lower latitudes due to lack of sunlight.

Figure 1 shows an example of the slope correction for a polygon located on the equatorial ridge of Ryugu. We found that the correction is sensitive to EW slope rather than NS slope, indicating that our estimation on surface roughness and thermal inertia is more sensitive to the local time. As expected by the thermal calculation, diurnal temperature profile of the polygon shows flat at noon and high at morning and evening. The estimated thermal inertia Γ and roughness σ of this polygon are 188 tiu and 0.39, respectively.

To evaluate the estimation of thermal inertia and roughness, we defined a threshold RMS value as 3 K. Large RMS values are appeared in facets of boulder. For the dataset with RMS less than the threshold, the global surface roughness was 0.40$\pm$0.05 with small regional variation, consistent with the boulder-riched surface of Ryugu as observed by ONC-T. On the other hand, the global thermal inertia of Ryugu was estimated to be 327$\pm$137 tiu, a little bit higher but still consistent with the ground-based observations within errors [2], with regional heterogeneity. The thermal inertia of low latitude in the northern hemisphere is higher than that in the southern, implying existence of denser materials.

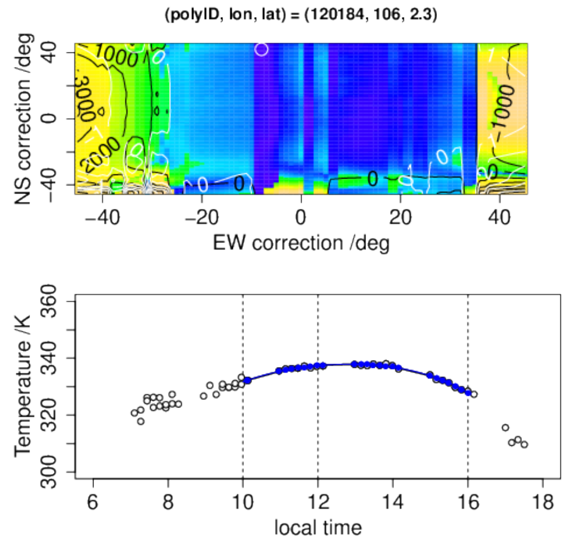

Figure 1: A slope correction for the diurnal temperature profile. (top) Color map of RMS values for slope corrections in EW (longitude) and NS (latitude) directions. Least RMS is shown by white circle. (bottom) Temperature profile of a polygon with slope corrections. White and blue circles are observed and estimated temperatures, respectively. Fitting were performed in slope-corrected local time from 10 to 16 hour.

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