THERMAL PROPERTIES OF BOULDERS ON C-TYPE ASTEROID 162173 RYUGU OBSERVED BY HAYABUSA2 TIR DURING LOW ALTITUDE OPERATIONS. A. Ohsugi[1,2], N. Sakatani[3], Y. Shimaki[2], T. Arai[4], H. Senshu[5], T. Kouyama[6], H. Demura[7], T. Sekiguchi[8], S. Tanaka[2], and T. Okada[1,2], [1]Graduate School of Science, the University of Tokyo, Japan, [2]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Japan, [3]Rikkyo University, Tokyo, Japan, [4]Ashikaga University, Japan, [5]Chiba Institute of Technology, Narashino, Japan, [6]National Institute of Advanced Industrial Science and Technology, Tokyo, Japan, [7]University of Aizu, Aizu-Wakamatsu, Japan, [8]Hokkaido University of Education, Asahikawa, Japan.

Introduction: The Hayabusa2 mission is one of the primitive body exploration missions led by the Japan Aerospace Exploration Agency (JAXA), to investigate the origin and evolution of the Solar System and the clues to building blocks of life, as well as to challenge a cutting-edge space technologies to achieve them. In this mission, a multi-scale analysis of primitive body has been planned through remote sensing from the spacecraft, *in situ* observations using small surface landers, and sample return from the surface of C-type asteroid 162173 Ryugu [1]. C-type asteroids are considered to be parent bodies of carbonaceous chondrite meteorites and formed by accretion of interplanetary dust, pebbles, or fragments of undifferentiated celestial bodies. Carbonaceous chondrites are enriched in volatile species such as water and organics, so that they are thought to be primitive materials in the Solar System.

After arrival at Ryugu, the asteroid explorer Hayabusa2 has performed a variety of science observations and experiments using remote sensing instruments to characterize Ryugu [1]. From June 2018 to November 2019, the Hayabusa2 has accomplished its asteroid proximity phase operations, unveiling poorly known characteristics of C-type asteroid, in connection with carbonaceous chondrites.

Especially, Thermal Infrared Imager (TIR) [2,3], a mid-infrared thermographic two-dimensional imager mounted for the first time for solid planetary missions, allows us to obtain the digital thermal images of the surface, which indicate the thermal radiation from Ryugu and to determine the thermophysical state of the asteroid surface. The recent study has been clarified that close-up thermal images of Ryugu taken during the descent operations showed that most of the surface was covered with highly porous rocks and boulders, but some rocks and boulders were apparently consolidated compared with their surroundings, like typical carbonaceous chondrite meteorites [3].

In this study, so as to obtain further information about the thermophysical properties of boulders at Ryugu, we analyzed TIR images taken below the altitude of 500 m and investigated temperature variations of boulders and their physical state in the specific regions.

Methods: Instruments, observation conditions and analysis: TIR is a thermal infrared imager based on an uncooled micro-bolometer array. TIR has a field of view (FOV) of 16.7˚ x 12.7˚ and the effective pixels of the detector of 328 x 248, resulting in the spatial resolution about of 0.051˚ per pixel [2]. A temperature range which TIR covers is 150 to 460 K and the well-calibrated temperature range is 230 to 420 K.

We used the high-resolution thermal images taken below the altitude from 500 m down to about 50 m during the pass for the release of MINERVA-II rovers (MNRV), with the 32 thermal images on 21st September 2018, and during the pass for the release of MASCOT lander (MSCT), with the 43 thermal images on 3rd October 2018.

In this study, we identified each boulder imaged with 100 pixels or larger and catalogued them with the equivalent size of boulders and the calculated average, maximum and minimum values of the temperature of the boulders using the image analysis software Image j.

Identifications of boulders and temperature distributions: Total numbers of the boulders exceeding the size of 100 pixels or larger were 355 (MNRV) and 312 (MSCT), and the detection errors were obtained as ±5.2 % and ±5.5 % by Wald inequality [4], respectively. In MNRV, the average of minimum, average and maximum temperatures were 286 K, 314 K, and 332 K, respectively. Their standard deviations σ were 11.2 K, 5.65 K, and 5.74 K, respectively. In MSCT, the average of minimum, average, and maximum temperatures were 287 K, 313 K, and 332 K, respectively. The standard deviations σ were 11.0 K, 5.53 K, and 5.99 K, respectively. One of the reasons why the values of σ at T_{min} were larger than others was probably due to the influences of shadows of the boulders. From the normal Q-Q plots, where the horizontal axis is the observed value and the vertical axis is the expected value, assuming that the detected value follows a normal distribution, it was found that each plot tends to be distributed in a straight line. Thus, it was considered that the temperatures of detected boulders are in line with the normal distribution.

Size-Frequency of boulders: We also investigated that the size-frequency distributions (SFD) of boulders were divided by imaging average altitudes and calculated the values of the slopes of SFD.

Accordingly, the values of the slopes were in the range of 0.30 to 4.0, larger slope for the larger boulders. The obtained slopes of SFD were consistent with the boulder distributions investigated [5], which was suggested the larger boulders were formed when the parent body of Ryugu was destroyed catastrophically and the smaller boulders covered with regolith layers are formed by impact cratering process, by thermal fatigue, or by fractured during granular flow.

Thermophysical properties and surface state: Thermal inertia is a physical property which allows us to obtain lots of information on the grain size, porosity, or surface roughness. At both MNRV and MSCT, the range of thermal inertias [6] of 34.6-385 J m^{-2} $s^{-0.5}$ K^{-1} (tiu) was calculated using the one-dimensional heat transfer equation [7]. This value implies that boulders on Ryugu investigated in this study are considered as porous and fluffy material with lower thermal inertia, in comparison with typical carbonaceous chondrite meteorites. These results are also consistent with the thermal inertia of the global average of Ryugu, estimated as an apparent range of 300 ± 100 tiu [3], and as the range of 225 ± 45 (tiu), best fit to the diurnal temperature profiles considering the surface roughness of assuming the surface roughness [8]. In this study, we assumed that the surfaces of boulders were confronted to the images so that further detailed study considering the surface local slopes is needed to estimate them more accurately.

Summary: Thermal properties of boulders on the surface of C-type asteroid Ryugu were investigated using the close-up thermal images by TIR at the altitude below 500 m. The total numbers of boulders identified with the size exceeding 100 pixels were 355 (MNRV) and 312 (MSCT), respectively. The normal Q-Q plots suggested that the average temperature distributions of boulders observed in both regions were close to the normal distribution. Moreover, in the observation areas, the SFD slopes and thermal inertias suggested the formation of boulders mainly by a single catastrophic impact event of a porous parent body for larger boulders, and partly by the events like impact cratering, thermal fatigue or fracture by granular flow on the current asteroid for the smaller size. In the future, we will investigate the boulders in the areas observed at other low-altitude operations, such as the descent operations during the touchdown rehearsals, the first and the second touchdowns.

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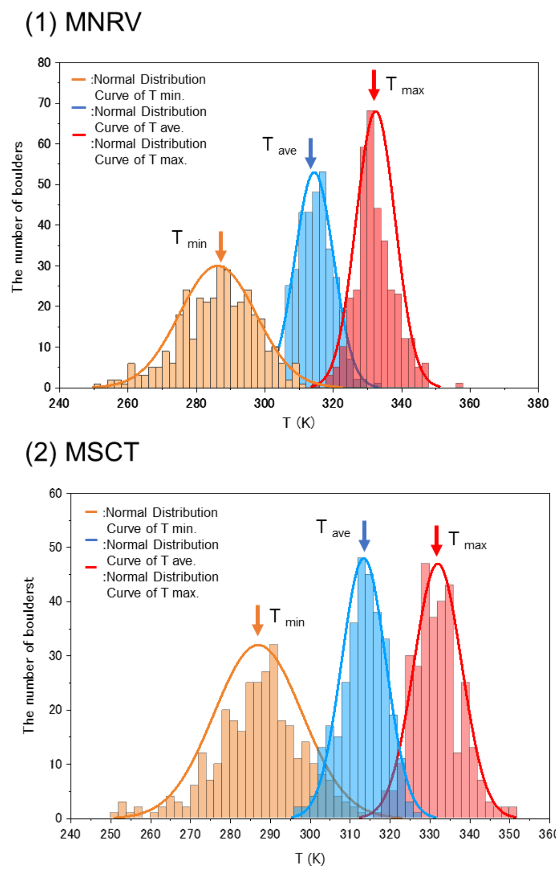

Fig.1 Temperature distributions of boulders at MNRV (a) and MSCT (b)