UNVEILING HIGHLY-POROUS NATURE OF PRIMITIVE ASTEROID 162173 RYUGU BY THERMAL IMAGER ON HAYABUSA2. T. Okada[1,2], T. Fukuhara[3], S. Tanaka[1], M. Taguchi[3], T. Arai[4], N. Sakatani[1], Y. Shimaki[1], H. Senshu[5], Y. Ogawa[6], H. Demura[6], K. Suko[6], K. Kitazato[6], T. Kouyama[7], T. Sekiguchi[8], J. Takita[1,9], S. Hasegawa[1], T. Matsunaga[10], T. Wada[1], T. Imamura[2], J. Helbert[11], T.G. Mueller[12], A. Hagermann[13], Jens Biele[11], Matthias Grott[11], Maximilian Hamm[11,14], Marco Delbo[15], Y. Yamamoto[1], N. Hirata[6], N. Hirata[15], F. Terui[1], T. Saiki[1], S. Nakazawa[1], M. Yoshikawa[1], S. Watanabe[16], Y. Tsuda[1], and Hayabusa2 Joint Science Team[1], [1]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (ISAS/JAXA), 3-1-1 Yoshinodai, Chuo-Ku, Sagamihara 252-5210, Japan, email: okada@planeta.sci.isas.jaxa.jp, [2]University of Tokyo, Japan, [3]Rikkyo University, Japan, [4]Ashikaga University, Japan, [5]PERC, Chiba Institute of Technology, Japan, [6]University of Aizu, Japan, [7]National Institute of Advanced Industrial Science and Technology (AIST), Japan, [8]Hokkaido University of Education, Asahikawa, Japan, [9]Hokkaido Kitami Hokuto High School, Japan, [10]National Institute for Environmental Studies (NIES), Japan, [11]German Space Research Center (DLR), Germany, [12]Max-Planck Institute for Extraterrestrial Physics (MP-E), Germany, [13]University of Stirling, UK, [14]University of Potsdam, Germany, [15]Observatoire de la Côte d'Azur, CNRS, France, [15]Kobe University, Japan, [16]Nagoya University, Japan.

Introduction: The first high-resolution global thermal images of an asteroid and the close-up very local thermal images from Hayabusa2 has proven that the asteroid has very low thermal inertia compared to that of typical carbonaceous chondrites, indicating highly-porous materials on the surface, as wel as the highly-porous nature of primitive bodies in general. Here we show the asteroid thermal images by TIR, the method of data analysis, the derived results of thermal inerta, and the speculative discussions.

Backgrounds: C-type Near-Earth asteroid 162173 Ryugu is the target of the JAXA Hayabusa2 asteroid sample return mission [1], which was launched in 2014, arrived there in 2018, observed and collected samples there in 2018-2019, and will return sample to Earth in 2020. C-type asteroids are likely analogues to carbonaceous chondrites. Ground-based and space-based remote observations [2] of Ryugu characterized the target asteroid's taxonomy as C-type, its rotation period of 7.63 hours, its diameter of ~0.85 km, and its global thermal inertia from 150 to 300 J m^{-2} $s^{-0.5}$ K^{-1} (tiu, hereafter), having been interpreted as a surface covered with millimeter scale granules. After arrival at Home Position (HP), 20 km from Ryugu, Hayabusa2 globally observed the asteroid [3-6]. Ryugu has a bulk density of 1190 ± 20 kg m^{-3} [3] and its surface is evenly covered with boulders [4], without smooth terrains found on 25143 Itokawa [7]. These facts indicate that Ryugu is a rubble-pile asteroid with bulk porosity of 50 % or higher [3], assuming the asteroid is composed of CI (~2420 kg m^{-3}) or CM (~2960 kg m^{-3}) carbonaceous chondrites [8].

Thermal Imaging by TIR: Thermal imaging was conducted using a thermal infrared imager TIR on Hayabusa2 [9] to investigate the surface physical state of Ryugu, such as particle size, porosity, abundance of boulders and surface small scale roughness, derived from the thermal inertia. The surfaces of the Moon, Mars, and large satellites are predominantly covered with regolith that is formed by hypervelocity meteoritic impacts. On the other hand, the surface of small bodies remains poorly known [10] since a majority of impact ejecta might escape due to low gravity, depending on the physical properties of the surface materials, so that their surface physical state needs in-depth investigation.

Global Thermal Images of Ryugu: The first set of high-resolved global thermal infrared images of an asteroid in history was obtained on 30 June 2018, with ~18 m/pixel, covering its rotation every 6° [6]. Higher resolution one-rotation thermal image sets have been taken from 5 km altitude, with spatial resolution of ~4.5 m/pixel, during the Mid-Altitude Observation Campaign on 1 August 2018. It was surprising that boulders on Ryugu, including the largest one of ~ 160 m size "Otohime", showed similar temperatures to the surroundings while, before arrival, they were expected to be consolidated and observed as "cold spots".

A brightness temperature image is plotted on the shape model (SHAPE_SFM_200k_v20180804) [3] to be compared with simulated images for eight uniform thermal inertia models from 50 to 1000 tiu. Although none of them matches to the observations perfectly, the apparent global thermal inertia of Ryugu is most suitable to ~300 ± 100 tiu [6] (in more detail of the average and the regional variation, 278 ± 138 tiu, by the latest calculation [11]).

Diurnal temperature profiles have been investigated at various sites and geologic features, finding that an extremely high surface porosity and roughness might explain these profiles. Thermal inertia of 225 ± 45 tiu with roughness of 0.41 ± 0.08 are derived for the global average of Ryugu [11].

Close-up Thermal Images of Ryugu: After September 2018, Hayabusa2 started descent operations for sampling and for the release of landers. Every time during descents, close-up thermal images were taken by TIR down to < 60 m for lander releases and < 20 m for samplings, at a few cm/pixel at local sites.

During the touchdown rehearsal TD1-R1-A on 15 October 2018, the close-up thermal images proved that the surface is not covered with soils nor granules but dominantly with boulders. This causes similar temperature profiles between large boulders and the surroundings. Most boulders were from 300 to 310 K, corresponding to highly-porous materials with 200 to 300 tiu, as predicted by global thermal images.

However, We discovered a few boulders below 280 K, corresponding to 600 to 1000 tiu (typical value of carbonaceous chondrites [8]. The surface of Ryugu is dominated by highly-porous boulders, except for some dense boulders similar to carbonaceous chondrite meteorites, which is consistent with the images taken by the camera MasCAM on MASCOT [12], showing that a large majority of boulders have cauliflower-like crumbly surfaces, while a minority have flat surfaces, and the average thermal inertia is consistent with the result derived from *in situ* measurements of a single boulder using the radiometer MARA on MASCOT [13], and consistent with the ground observations [2].

Porous Nature of Primitive Bodies: Accounting for the asteroid's bulk density, Ryugu must have a bulk porosity of 50 to 60 % [3], assuming it consists of materials of CI or CM chondrites. The macro porosity caused by voids between rocks should be below 20 % for micro porosity of 50 %, or 30 ~ 40 % for micro porosity of 30 %. The former is more likely since the boulders of < 200 tiu are identified by detailed analysis [11]. A trend of small asteroids having lower thermal inertia compared with typical carbonaceous chondrites [14] might be caused not by regolith as predicted but by very porous boulders. A similarly low thermal inertia is observed for B-type asteroid 101955 Bennu by the OSIRIS-REx mission [15].

The formation history of Ryugu proposed in the previous study [4] might be constrained [6]. Ryugu could be formed from fragments of a parent body that has experienced a low degree of consolidation of originally porous materials. This is the direct evidence of less consolidated nature of C-type asteroids formed from fluffy dust or pebbles in the early solar system. This discovery also implies that those large asteroids in the main belt with high porosity [16] could be formed in the similar way and they are very common among the C-type asteroids. Those less consolidated materials might have low mechanical strength which cannot survive during atmospheric entry. This might be a reason that the spectra did not match perfectly with the meteorite samples on the Earth [4,5].

Dense boulders might be formed at a consolidated inner core of the parent body, or might be an exogenic origin such as surviving fragments of meteoritic impacts. Highly porous physical state might have been in common with planetesimals that formed from fluffy dust [17] in the early solar system and could have strongly affected planetary formation processes such as cratering and collisional fragmentation by attenuating shock propagation [16]. There still cannot be ruled out that the low thermal inertia and the low density of Ryugu are due to materials different from carbonaceous chondrites such as the organic-rich material discovered on Comet 67P/Churymov-Gerasimenko [18]. These questions will however be resolved upon sample return.

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Data Availability: All the raw thermal images used in the study [6] taken by TIR on Hayabusa2 (Level 1) and their brightness temperature converted images (Level 2) are available at the Hayabusa2 project data archive site: darts.isas.jaxa.jp/pub/hayabusa2/tir_bundle/browse/, with the easy-to-use brightness temperature images in png file (only in Level 2).

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