THERMAL IMAGING OF C-TYPE NEAR EARTH ASTEROID 162173 RYUGU BY THERMAL INFRARED IMAGER TIR 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], Maximiliam Hamm[11], Marco Delbo[14], 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 Thermal-Infrared Imager (TIR) 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]Observatoire de la Côte d'Azur, CNRS, France, [15]Kobe University, Japan, [16]Nagoya University, Japan.

Introduction: Global, local and close-up thermal images taken by the Thermal Infrared Imager TIR [1] on Hayabusa2 have revealed thermophysical properties of C-type asteroid 162173 Ryugu. TIR is a two-dimensional thermographic camera developed to investigate the nature of Ryugu and its origin and evolution in terms of thermophysical properties of the asteroid. Outlines of the TIR experiments during the asteroid proximity phase are briefly described.

Hayabusa2 and Ryugu: Hayabusa2 is a JAXA asteroid mission to explore C-type near-earth asteroid Ryugu [2]. After a 3.5 year-long cruise, Hayabusa2 arrived at Ryugu and started remote sensing to characterize the asteroid including its shape, spin state, geomorphology, spectral and thermal properties, and gravity. Such information implies that the nature of the asteroid and the proper landing sites are studied. *In situ* surface experiments have been conducted on the asteroid using the robotic landers Minerva-II and Mascot. Mascot [3] was developed by DLR in collaboration with CNES and JAXA and carried four scientific instruments: a camera, a hyperspectral microscope, a magnetometer, and a radiometer MARA. *In situ* radiometry by MARA was conducted during a day-night cycle to derive the thermal inertia of a boulder [4]. After the first sampling from Ryugu, an impact experiment using the Small Carry-on Impactor (SCI) will take place to expose the subsurface materials, and the ejecta will be collected. Hayabusa2 will return those samples to Earth in 2020.

Ground-based observations [5] showed that Ryugu is a C-type near-earth asteroid, is about 0.9 km in diameter and has a roughly rotational symmetric shape. It rotates in 7.63 hours. Its geometric albedo is about 0.05 or lower, and the globally averaged thermal inertia is 150 to 300 [tiu = J m^{-2} $s^{-0.5}$ K^{-1}]. This is consistent with a surface covered with coarse regolith about cm-size. These features of Ryugu that have remained unknown were basically verified by Hayabusa2.

TIR performances: TIR is the same design as the LIR imager on Akatsuki Venus climate orbiter [6]. It has 328 x 248 effective pixels and covers the 8 to 12 μm range. Its measurable temperature range has been proven from 150 to 460 K by the pre-flight and in-flight tests [1]. This implies that not only the sunlit areas of Ryugu but even the nighttime areas could be observed (except for shadowed regions) if the thermal inertia is larger than 50 tiu. The TIR FOV and IFOV are 16.7° x 12.7° and 0.051° per pixel, respectively. This corresponds to ca. 18 m per pixel from the Home Position (20 km altitude earthward from the asteroid; hereafter, HP) and to ca. 0.9 m per pixel from 1 km altitude. Closest views of the asteroid surface by TIR are ca. 9 mm per pixel when observed from 10 m altitude, just before the final free fall to touchdown.

TIR Observations in Proximity Phase: Outline of the TIR observation plan during the asteroid proximity phase is shown in Table 1.

1) Light curves and Moon Searches: During the approach phase, TIR successfully detected Ryugu as a point source smaller than 1 pixel at the distance of 2300 km on 6 June 2018, as was previously predicted [7]. One-shot images were taken almost every day, which showed the brightness temperature of Ryugu was increasing inversely proportional to the square of distance. Light curves were measured and compared with ground observations, consistent with the ground-based observations. No moons larger than 0.3 m in diameter orbiting Ryugu have been detected so far in the TIR images during the Approach, Box-A and C.

2) Global Thermal Images of Ryugu: Thermal images of Ryugu have been taken from the HP. The surface temperature (mainly sunlit side, SPE angle < 20°) has been measured at 300 to 370K at about 1AU from the Sun, and gradually decreased inversely proportional to the solar distance. Comparison with thermal modeling shows that the surface of Ryugu is colder than expected for fine-grained regolith but hotter than expected for base rocks. Most large boulders of several 10s of meters on Ryugu show temperatures almost the same as the surrounding surfaces. Diurnal temperature profiles of Ryugu are rather flatter than expected for sandy layers like lunar regolith. Representative thermal inertia is ~300 tiu or large. These facts are consistent with a very rough and porous surface where boulders have high porosity (~35 ± 10 %) [8] and the surface is dominated by porous rocks larger than several centimeters (larger than the thermal skin depth).

Higher resolved global thermal images of Ryugu obtained from 5 km altitude (Box-C or Mid-Altitude) show basically the same profiles as shown at HP. Oblique views (ca. 22° larger solar phase angle) of Ryugu during Box-B from the south pole side and from the dusk side) showed a remarkable decrease of thermal flux by 10 to 15 % when compared with the results from Box-A, indicating a rough surface.

3) Close-up Thermal Images of Ryugu: During the descent operations for the release of robotic landers and the touchdowns for sample collection, close-up thermal images of the local sites have been taken by TIR at altitudes below 100 m. During these operations, TIR starts to take images below 500 m altitude at 96 second intervals except for 15-minutes for ONC-T multiband imaging, then at 64 second intervals below 160m. At the altitude of 60 m for the release of landers and 24m for touchdowns (including their rehearsals), TIR takes thermal images at 32 sec intervals for several to more than 10 minutes until the spacecraft ascends to the HP.

Close-up thermal images show the surface physical state and a variety of boulders. As seen on optical images by ONC-T and the surface landers Minerva-II and Mascot, the surface of Ryugu is widely covered with centimeter to meter sized rocks and boulders, but not with fine regolith. In the close-up images, meter sized boulders often have a layered or sedimented texture, which might be a result of processes undergone in the parent body of Ryugu. Most of the boulders in close-up images also show a temperature similar to the surroundings on average but with more variations of temperature. This may be due to the different normal direction or local time on each facet of the boulders and also due to the difference of thermal inertia. There is a very small number of boulders that show “Cold Spots”, remarkably colder than the surroundings, indicating a dense rock with lower porosity. There are some areas of “Hot Spots”, where smaller sized particles are gathered from the surrounding, which might be produced by meteoritic impacts, thermal stresses, or something else. Detailed and statistical analyses and discussions are still on-going.

Concluding Remarks: Thermophysical properties of C-type primitive asteroid 162173 Ryugu have been revealed by global, local and close-up thermal images taken by TIR on Hayabusa2. The most striking news is that the surface of Ryugu is dominated by rugged and porous boulders. Those features might be typical for primitive bodies. These thermal image sets of primitive bodies are obtained only by TIR on Hayabsua2, since NASA OSIRIS-REx has only a point spectrometer at the thermal infrared range, so that such information will allow us to understand the formation and evolution processes of Ryugu, its parent body, and the primitive bodies in general.

Table 1: Main plan/results of TIR observations

Date	Alt. [km]	Contents of TIR Observations
2018/06/06	2000	Light curves & search for moons (1)
2018/06/18	200	Light curves & search for moons (2)
2018/06/30	20	Light curves & search for moons (3)
2018/07/10	20	Global mapping (1): Box-A
2018/07/20	5~7	Global mapping (2): Box-C
2018/08/01	5	Global mapping (3): Mid-Altitude
2018/08/06-07	1	HR images (1): gravity measurement
2018/08/24,31	20	Global mapping (4): Box-B (South/dusk)
2018/09/14,24	0.01	Close-up images: TD1-R1, MNRV
2018/10/03-04	3	Close-up + HR images: MASCOT
2018/10/14,24	0.01	Close-up images: TD1-R1-A, TD1-R3
2018/11/23-27	20~60	Global mapping (5): Conjunction
(Tentative Plan)		
In 2019	20	Global mapping (6): Box-A
	20	Global mapping (7): Box-B (low-SPE)
	20	Global mapping (8): Box-B (North)
	0.01	Close-up images: TD1
	0.1	HR images (2): Descent observation
	1.5	HR images (3): Crater search (pre)
	0.5	Tracking of SCI and dust cloud images
	1.5	HR images (4): Crater search (post)
	0.01	Close-up images: Pin-Point TD

Acknowledgments: The authors appreciate all the members of the Hayabusa2 Project and supporting staff for their technical assistance and scientific discussions. This research is partly supported by the JSPS KAKENHI No. J26287108, No. J17H06459 (Aqua Planetology), and the Core-to-Core program “International Network of Planetary Sciences”. MDB acknowledges support from CNES.

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