Revisiting the Analysis of the MARA Measurements on Ryugu's Surface with a Multi-Scale Shape Model

M. Hamm[1,2], M. Grott[1], J. DeWiljes[2], J. Knollenberg[1], F. Scholten[1], K.-D. Matz[1], F. Preusker[1], J. Biele[3], S. Elgner[1], K. Ogawa[4], N. Sakatani[5], H. Senshu[6], T Okada[5], R. Jaumann[1], S. Sugita[7], S. Tanaka[5]

[1]German Aerospace Center, Institute of Planetary Research, Berlin, Germany, (Maximilian.hamm@dlr.de), [2]Univerisity of Potsdam, Institute of Mathematics, Potsdam, Germany, [3]German Aerospace Center, Microgravity User Support Center, Cologne, Germany ,[4]Department of Planetology, Graduate School of Science, Kobe University, Kobe, Hyogo, Japan, [5]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Japan,[6]Chiba Institute of Technology, Planetary Exploration Research Center, Narashino, Japan, [7]Dept. of Earth and Planetary Science, School of Science, University of Tokyo, Tokyo, Japan

Introduction: The Japanese sample-return mission Hayabusa2 [1] reached the Near-Earth Asteroid (162173) Ryugu on June 27 and observed the surface of Ryugu with various instruments including a thermal infrared mapper (TIR) [2]. Hayabusa2 released the lander MASCOT [3] which carried, among other instruments, an infrared radiometer (MARA) [4]. MARA measured brightness temperatures of a single boulder for a full diurnal cycle, and the thermal inertia of this boulder was estimated to be 247-375 $\mathrm{J\,K^{-1}m^{-2}s^{-1/2}}$ [5]. While this value is low for competent rock, it is consistent with TIR and ground based observations, and appears to be representative for the majority of boulders on the surface [6].

Prior to the visit of Hayabusa2, the low thermal inertia of Ryugu was interpreted in terms of a regolith cover with dominant grainsizes in the millimeter to centimeter range [7]. However, Ryugu's surface is covered by a surprisingly large number of decimeter to meter sized boulders with thermal properties similar to the ones observed by MARA [6]. The low thermal inertia was interpreted as the consequence of a high intrinsic boulder porosity of 28 – 55 % [5].

The large uncertainty of the thermal inertia estimate was mainly driven by the lack of information about the surface orientation that determines the insolation. In the first analysis of the MARA data, the surface orientation was varied as a free parameter in the thermal model. Now, by constraining the 3D shape of the observed boulder and its surroundings, the illumination and observation geometries are fixed and should allow for a more precise estimate of the boulders bulk thermal inertia.

Methods: From the MASCOT Camera (MasCam) images [8], a detailed 3D shape model of the observed boulder was derived [9]. It was integrated into a reduced regional shape model of the landing site of MASCOT [10]. The illumination and shadowing on this multi-scale shape model determines the upper boundary condition of the 1D heat-conduction equation which is solved for each facet of the combined shape model as described in [11] and [5].

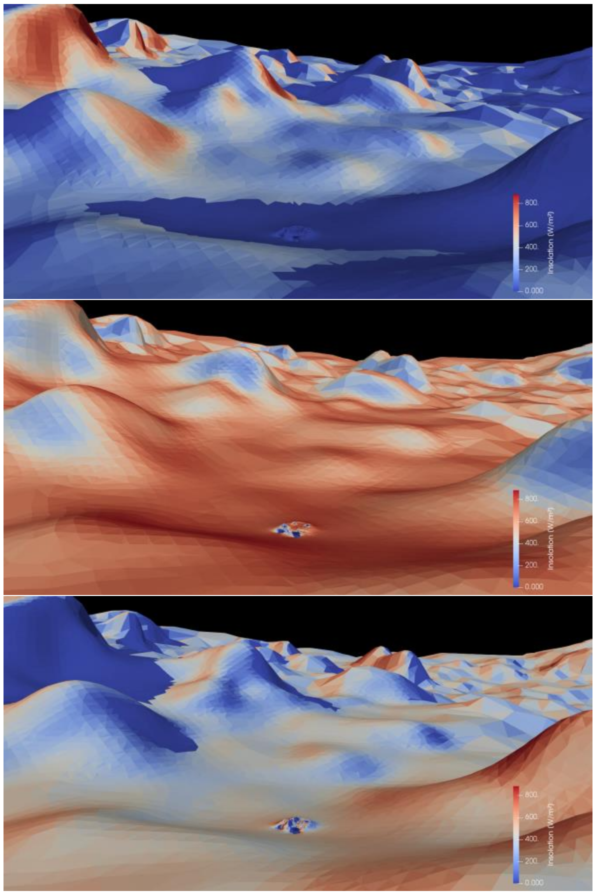

Figure 1: Combination of the shape models of the region around the MASCOT landing site and the boulder observed by MASCOT. Color indicates the insolation for three local times: sunrise observed by MARA (top), noon (center), and sunset (bottom)

Results: The modeled insolation is shown figure 1 for the times when the MARA instrument observed local sunset, noon, and sunrise. The modeled sunrise and sunset are delayed with respect to the MARA observation. These differences in the timing are likely caused by smoothing effects within the shape model.

Around noon, the facets within the field of view of MARA show a maximum insolation around 800 W $\mathrm{m^{-2}}$ which corresponds to intermediate values compared to the initial analysis of the MARA data where the surface orientation was a free parameter of the thermal model, and the results of which are shown in figure 2. Here, the retrieved thermal inertia is plotted as a function of surface orientation, parametrized by the maximum insolation, with color indicating the goodness of fit. Further free model parameters were the emissivity and the heat exchange between the observed spot on the boulder and the environment (methods of [5]).

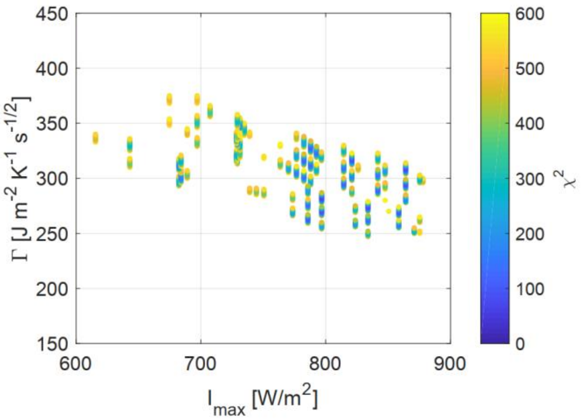

Figure 2: Thermal inertia estimates derived from MARA brightness temperature measurements as a function of maximum insolation [5]. Each spot corresponds to an individual model assuming a specific emissivity, thermal radiation from the environment, and surface orientation. The latter is parametrized by the maximum illumination.

Discussion: As apparent in figure 2, the main spread of the thermal inertia estimate is due to the unknown orientation of the surface. By fixing the illumination condition through the use of a 3D shape model, we expect to reduce the uncertainty of the thermal inertia estimate significantly. Since the shape model also fixes the heat exchange between the spot on the boulder observed by MARA and its surroundings, the only free parameter left is the emissivity of the surface, which adds little to the uncertainty of the thermal inertia.

Furthermore, the 3D shape model fixes the observation geometry and a consistent implementation of a roughness model becomes feasible. This allows for the analysis of the daytime observations of the four narrow-band filters of MARA. With such an analysis the emissivity of the surface could be estimated at wavelength of 6, 9, 10 and 13 µm and a spectral slope could be determined.

Currently, the thermal model calculating the surface temperatures for each face of the shape model is being implemented. We expect that the new upper limit of the thermal inertia estimate will be below 350 $\mathrm{J\,K^{-1}m^{-2}s^{-1/2}}$ compared to the initial upper estimates of 375 $\mathrm{J\,K^{-1}m^{-2}s^{-1/2}}$.

Acknowledgements: The authors thank the Hayabusa2 and MASCOT operation and instrument teams for their great work and support.

References: [1] Tsuda, Y. et al. (2013), *Acta Astronautica* 91: 356-362. [2] Okada, T. et al. (2016), *Space Science Reviews* 208(1-4): 255-286. [3] Ho, T.M. et al. (2017), *Space Sci, Rev* 208: 339. [4] Grott, M. et al. (2016), *Space Science Reviews* 208(1-4): 413-431. [5] Grott, M. et al. (2019), *Nature Astronomy*. [6] Sugita, S. et al. (2019), *Science*, 364, 252. [7] Müller, T. G. et al. (2017), *Astronomy & Astrophysics* 599. [8] Jaumann, R. et al. (2019), *Science*, 365, 6455, 817-820. [9] Scholten, F. et al. (2019), *Astronomy & Astrophysics* (submitted). [10] Preusker, F. et al. (2019), *Astronomy & Astrophysics* (submitted). [11] Hamm, M. et al. (2018) *Planetary and Space Science*, 159, 1-10.