Thermal Conductivity and Porosity of Ryugu's Boulders from In-Situ Measurements of MARA - the MASCOT Radiometer. M. Hamm[1], M. Grott[1], J. Knollenberg[1], H. Miyamoto[2], J. Biele[9], A. Hagermann[3], N. Müller[1], W. Neumann[1,4], K. Ogawa[5], T. Okada[6], K. Otto[1], N. Sakatani[6], H. Senshu[7], M. Zolensky[8]. [1]German Aerospace Center, Institute of Planetary Research, Berlin, Germany, maximilian.hamm@dlr.de, [2]University of Tokyo, Department of System Innovation, Tokyo, Japan, [4]Institut für Planetologie, University of Münster, Münster, Germany,[5]Department of Planetology, Graduate School of Science, Kobe University, Kobe, Hyogo, Japan, [6]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Japan,[7]Chiba Institute of Technology, Planetary Exploration Research Center, Narashino, Japan, [8]XI2 NASA Johnson Space Center, Houston, TX, USA, 9 German Aerospace Center, Microgravity Support Center, Cologne, Germany

Introduction: The Hayabusa2 sample-return mission [1] reached the Near-Earth Asteroid (162173) Ryugu and deployed the MASCOT lander [2], which carried the MARA infrared radiometer [3]. 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 $\mathrm{J\,K^{-1}m^{-2}s^{-1/2}}$ [4]. While this value is low when compared to measurements of meteorites, it is consistent with data of the Hayabusa2 thermal infrared mapper (TIR) [5] and ground based observations. Furthermore, it appears to be representative for the majority of boulders on the surface of Ryugu.

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 [6]. However, Ryugu's surface is covered by a surprisingly large number of decimeter to meter sized cobbles and boulders with thermal properties similar to the ones observed by MARA [7] and little or no fine regolith. Therefore, it seems likely that the boulders themselves have low thermal conductivity, which may be associated with a relatively high porosity.

Methods: We derive the thermal conductivity and porosity of the boulder observed by MARA $k_{obs}(\phi)$ from its thermal inertia Γ and a model for the thermal conductivity as a function of porosity $k(\phi)$. Given typical grain densities ρ_g for CI meteorites, and a parameterization for the temperature-dependent heat capacity $c_p(T)$ [8], observed thermal conductivity is then given by

$$k_{obs}(\phi) = \frac{\Gamma^2}{c_p \rho_g (1-\phi)}$$

c_p was calculated for a temperature of 230 K, corresponding to the average nighttime temperature observed by MARA.

We use three different models of $k(\phi)$ to constrain the boulder's bulk porosity and thermal conductivity by setting $k_{obs}(\phi) = k(\phi)$.

The first model fits experimental data for H and L chondrites and can be interpreted in terms of cracks being the dominating conductivity reducing mechanism [8]:

$$k_1(\phi) = \frac{0.11(1-\phi)}{\phi}$$

A second similar model fits the same dataset, but uses a different functional dependence for $k(\phi)$. This model has the advantage of not diverging at low porosities [9]:

$$k_2(\phi) = 4.3\, e^{-\phi/0.08}$$

A third model [9] has been proposed based on theoretical considerations for partially sintered granular material:

$$k_3(\phi) = k_0(1 - a\,\phi)$$

Here k_0 is thermal conductivity at zero porosity and the parameters $k_0$and a were scaled to fit the thermal conductivity of CV3 chondrite Leoville and CK4 chondrite Northwest Africa 5515, which follow a different trend in $k(\phi)$ than the H and L chondrites.

All of the above models suffer from the fact that thermal conductivity data at high porosity is missing, and consequently, models are poorly constrained at high ϕ. To start filling this data gap we performed laboratory measurements of samples at high porosities. We have used a transient hot strip (THS) method [10] to measure thermal conductivity of a CI2 Tagish Lake based analogue material which was produced by crushing constituents mixing them wet condition, and finally drying them [11]. This material was developed at the University of Tokyo as a mechanical analogue for Phobos regolith (UTPS). A block of the material was cut and the THS was placed between two slabs of the analogue material. Measurements were performed under vacuum conditions < 10^{-6} mbar at temperatures ranging from -150°C to +50°C.

Results: The CI2 Tagish Lake analogue (UTPS) is a highly porous sample. The measured bulk density of the material was 1.4 $\mathrm{g/cm^3}$, while the grain density is 2.81 $\mathrm{g/cm^3}$ implying a porosity of ~50%. We found a very low bulk thermal conductivity of 0.04 W/mK at -150°C and 0.1 W/mK at +50°C. and results are shown in Figure 1. For -50°C, representative for nighttime temperatures on Ryugu, we measure a thermal conductivity of 0.07 W/mK.

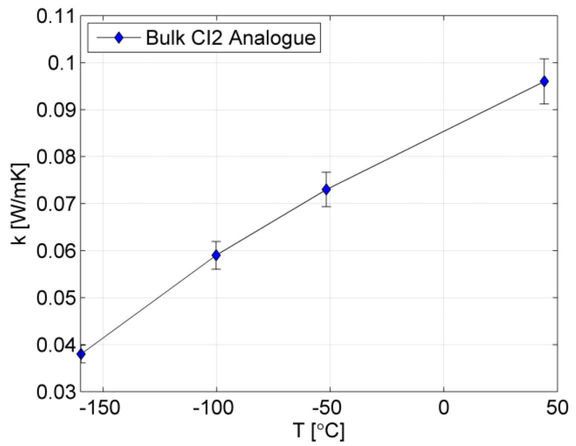

Figure 1: *Thermal conductivity of the UTPS Tagish Lake analogue material as a function of temperature.*

Figure 2 shows the results of the UTPS measurements in comparison to the H, L and C-chondrite measurements from the literature. Published measurements of k were found for three C chondrites, i.e. the CM2 Cold Bokkeveld [12], CK4 NWA 5515 [13], and CV3 Leoville [14]. Figure 2 also shows the three models of $k(\phi)$ extrapolated to the high porosity of UTPS. The figure also shows estimates of k and ϕ of the boulder observed by MARA on Ryugu. While all three models result in similar k between 0.06 and 0.16 W/mK the estimated porosity varies significantly. Applying the k_2 model results in porosities between 28 and 34%, k_1 results in porosities between 43 and 55%, and k_3 in porosities of 44 to 46 %.

Discussion: The large, model dependent uncertainty of the porosity of the boulder on Ryugu is due to the lack of thermal conductivity data at high porosities. As shown in Fig. 2 the models for $k(\phi)$ diverge rapidly at high porosities. The measurement of the UTPS indicates that $k_1$and k_3 are more suitable at high porosities than k_2. Thus we estimate the porosity of the observed boulder on Ryugu to be between 43 and 55%.

The thermal conductivity of the CM seems to agree with those of the H and L chondrites and is well described by the crack-dominated models k_1 and k_2. Microscopic cracks were observed in CM and CI chondrites which could be the result of dehydration [15]. Contrarily, the thermal conductivity of the CK and CV seem to follow a different trend that can be fitted with the model for partially sintered granular material where pores between the grains dominate the reduction of k.

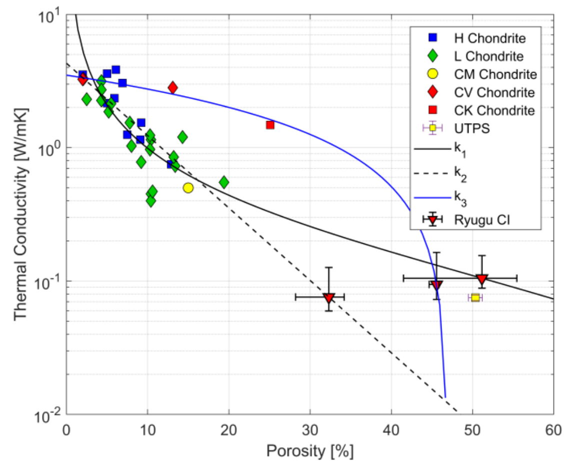

Figure 2: *Thermal conductivity as a function of porosity showing measurements of chondrites, UTPS, $k(\phi)$ models, and the corresponding estimates of the thermal conductivity and porosity of the boulder observed by MARA.*

For Ryugu it remains unknown if cracks or pores govern $k(\phi)$. In order to find a proper model for the thermal conductivity of chondrites with high porosities, it is essential to measure the thermal conductivity of more C chondrites with porosities higher than 30%. CI chondrites would be of particular interest as they seem to be the best representation of Ryugu's surface material. With more data at hand and a suitable model for $k(\phi)$ it would be possible to estimate the porosity of the boulder on Ryugu observed by MARA more accurately.

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