MACRO-POROSITY AND GRAIN DENSITY OF C-TYPE ASTEROID (162173) RYUGU.

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Introduction: Upon arrival of the Hayabusa2 spacecraft [1] the C-type asteroid (162173) Ryugu was found to be a spinning top-shaped rubble pile [2], whose surface is dominated by large blocks and boulders [3]. A regolith cover of fine particles appears to be absent [4]. Boulders on Ryugu are predominantly dark and rugged [4,5], and these boulders appear to be similar to CI chondritic meteorites [5,6]. Thermal properties a boulder measured in-situ indicate high intrinsic porosities [6], consistent with the overall low bulk density of the asteroid [4]. Assuming typical grain densities for carbonaceous chondrites, bulk porosities close to 50% would be expected [2].

Porosity inside rubble pile asteroid Ryugu can be separated into two contributions: the first one stems from the intrinsic porosity of rocks and boulders and is termed micro-porosity ϕ_m, whereas the second contribution refers to voids in between individual rocks and is termed macro-porosity ϕ_M [7]. Given the size distribution of particles, the macro-porosity of the asteroid can be calculated using semi-empirical mixing models [7,8], assuming the surface distribution of boulders to be representative for the entire asteroid.

Data: Boulder size and shape distributions have been determined by [3] using data from the Hayabusa2 on-board navigation camera (ONC). Images were taken at altitudes between 20 km and 6.5 km with resolutions of up to 0.65 m/pixel, and size-frequency and shape distributions were determined in the 0.02 to 140 m size range (Figure 1). Size-frequency data was fitted using power laws, and power law indices between 1.65 and 2.65 have been obtained [3], with 2.65 being the best fit for the global dataset. Furthermore, particles are generally elongated, and axis ratios for boulders >2m are close to 0.70, consistent with boulder generation by impact processes [3].

We fitted the data provided by [3] to a simple polynomial, and data can be adequately represented by a second order function in log-log coordinates. Results of the fitting are shown together with the uncertainty of the data in Figure 1. It is worth noting that representing the data using a single power law for the entire size range does not adequately represent the data [3].

Modeling: Here we compute the macro-porosity ϕ_M of Ryugu using semi-empirical mixing models [7,8] given the size-frequency distribution of observed boulders [3]. For poly-disperse particles, macro-porosity can be much lower than the canonical 36% for a random close packing or ~42% for a random loose packing of spherical mono-sized particles [7], as smaller particles start filling the gaps between larger ones. Once ϕ_M has been computed, macro-porosity ϕ_M, micro-porosity ϕ_m, and bulk porosity ϕ_B are related by

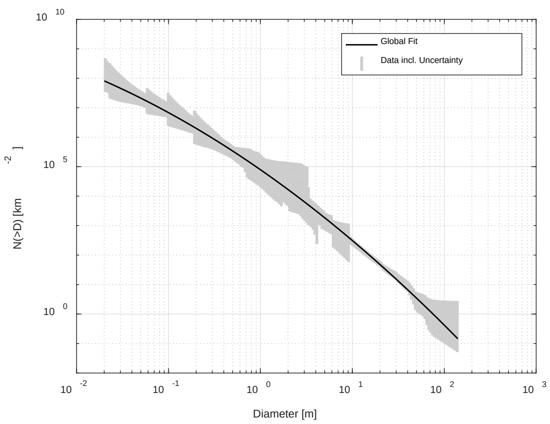

Figure 1: Cumulative size-frequency distribution of boulders observed on Ryugu. The global fit represents the data of [3], spanning the size range between 0.02 and 140 m.

$$\phi_M = 1 - \frac{1-\phi_B}{1-\phi_m} \qquad (1)$$

where $\phi_B = 1 - \rho_b/\rho_s$. Here, ρ_b and ρ_s are Ryugu's bulk and grain density, respectively. While the bulk density of Ryugu has been estimated to be 1190 ± 20 kg/m^3 [4], the boulder's micro-porosity ϕ_m cannot currently be unambiguously constrained due to the difficulties associated with extrapolating meteorite thermal conductivities to porosities in excess of 20% [9]. However, end-member models [10,11] suggest micro-porosities ϕ_m between 28-35% and 41-55% for Ryugu's dark and rugged boulders [6]. Here we use Monte-Carlo simulations to propagate these uncertainties to the uncertainty of Ryugu's grain density ρ_s.

Results: Assuming minimum and maximum particle sizes of 0.02 and 140 m, Ryugu's macro-porosity ϕ_M is calculated to be 15 ± 2.5 %, and results of the Monte-Carlo simulations using 1000000 draws are shown in Figure 2, where a histogram of the grain density ρ_s is shown. Owing to the two different models used to extrapolate boulder micro-porosity, two separate peaks are obtained for the distribution of admissible grain densities. Extrapolation of thermal properties using the porosity model of [11] results in lower micro-porosities, and consequently, obtained grain densities also have to be lower to satisfy the constraint posed by Ryugu's bulk density. On the other hand, the extrapolation using the model of [10] results in higher micro-porosities and higher grain densities. Overall, grain densities ρ_s = 2002 ± 85 kg m^{-3} and ρ_s = 2672 ± 229 kg m^{-3} are obtained for the two different models.

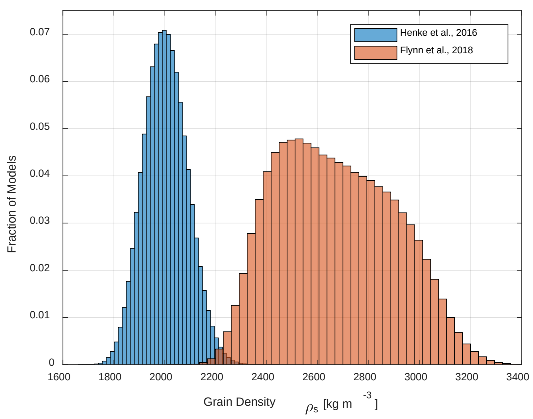

Figure 2: Results of the Monte-Carlo simulations showing the histogram of grain density ρ_s assuming two endmember models for the micro-porosity ϕ_m [6].

Discussion: In the above analysis, we have neglected the influence of particle shape on the porosity. In general, particle sphericity can have a significant effect on the porosity of particle mixtures, but this effect only becomes important for sphericities of less than 0.8. For the Ryugu boulders, axis ratios b/a of close to 0.7 have been reported [3], resulting in sphericities of 0.84. Therefore, particle shape can be considered a second order effect here.

The grain densities obtained here are much lower than typical grain densities of ordinary chondrites, which range from 3520 to 3710 kg m^{-3} [10], and also lower than those of most carbonaceous chondrites, which typically have grain densities in excess of 3360 kg m^{-3}. Only the CM and CI sub-classes show lower grain densities, and $\rho_{s,CM}$ = 2960 ± 40 kg m^{-3} while $\rho_{s,CI}$ = 2420 kg m^{-3} [10]. The Tagish Lake meteorite, an ungrouped carbonaceous chondrite, exhibits similar grain densities in the range between 2430 and 2840 kg m^{-3} [12]. While the larger grain densities obtained here are consistent with the CM, CI, and Tagish Lake results, the lower densities are inconsistent with those of known meteorite samples.

Support for extrapolating boulder porosities using the model by [10] rather than the model by [11] is provided by laboratory measurements of thermal conductivity at high porosities [13]. The UTPS Tagish Lake simulant [14] has a grain density of 2813 kg m^{-3} and a porosity of 47%, while at the same time exhibiting thermal conductivities similar to those obtained for Ryugu's rugged boulders. This falls within the range predicted by the model of [11], favoring grain densities of ρ_s = 2672 ± 229 kg m^{-3}. However, more laboratory measurements at high porosity are needed to confirm these results and reduce uncertainties.

Results presented here assume that the size-frequency distribution observed on the surface is representative for the entire asteroid, but it has been argued that particle size sorting may take place during rubble pile re-accretion, with larger particles accreting first [15]. On the other hand, seismic shaking and the Brazil Nut Effect could lead to an overrepresentation of large particles on the surface [16]. This topic can be addressed once grain density and micro-porosity have been determined from the returned samples.

Summary: Rubble pile asteroid (162173) Ryugu's boulder size-frequency distribution is consistent with a macro-porosity close to 15 ± 2.5 %, provided the observed surface distribution of boulders is representative for the bulk asteroid. In this case, a grain density of ρ_s = 2672 ± 229 kg m^{-3} is best compatible with the available data, consistent with a CI or CM composition.

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