Comparison of Thermal Diffusivity between Ryugu grains and Carbonaceous Chondrites

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Introduction: According to the general planetary formation scenario, the Solar System bodies evolved over a long period of time through repeated collision, fragmentation, and aggregation of planetesimals formed in the solar nebula. Thermal evolution, which induces various physicochemical reactions such as aqueous alteration, thermal metamorphism, and volcanism, is important for the evolution of planets. The temperature history inside the planetesimals followed in thermal evolution can vary greatly depending on when and how large they agglomerate and their effective thermal conductivity. Therefore, it is essential for the theory of planetary system formation to know the thermal conductivity of asteroids and meteorites, especially those that are thought to have existed since the early stages of planetary system formation.

The Ryugu sample brought back in 2020 by Hayabusa2 was found to be a primitive Ivuna-type carbonaceous chondrite, which is close to the average chemical composition of the Solar System [1]. Additionally, the elastic properties of the Ryugu grains were found to be similar to those of the Tagish Lake meteorite [2]. On the other hand, the thermophysical properties of Ryugu grains were found to vary widely from grain to grain [3]. Although this is the most important parameter in understanding the thermal history of asteroidal parent bodies, the cause of this variation has not been clarified. In this study, we measured the thermal diffusivities of Ryugu particles and carbonaceous chondrites using the lock-in thermography (LIT) periodic heating method [3], which was also used for the initial analysis of Ryugu grains to evaluate how the thermal properties of Ryugu grains are related to those of other carbonaceous chondrites.

Samples and Methodology: In this study, the thermal diffusivities of Ryugu and the carbonaceous chondrites were measured. A breakdown of the samples is as follows: three grains of Ryugu (A0172, A0038, and C0054), three grains of Ivuna (CI), one grain of Murchison (CM2), one grain of Tarda (C2-ungrouped), three grains of Tagish Lake (C2-ungrouped), and two grains of Allende (CV3). Bulk densities of the sample were also measured by obtaining weights and volumes of the sample. The volume was obtained by using an X-ray computed tomography (X-CT) device (SKYSCAN 1272). The X-CT images were also utilized to avoid cracks inside the sample, because the cracks may specifically affect to the results of the thermal diffusivity measurements.

In the measurement by the LIT periodic heating method, a spot on the sample is periodically heated using a laser, and the temperature response is measured by LIT to obtain the phase lag distribution on the sample surface. Then, the thermal diffusivity is analyzed from the gradient of the phase lag according to this equation; $D = \pi f / (d\theta/dr)^2$. Here, D is thermal diffusivity, f is heating frequency, θ is phase lag and r is distance from heating point. A measurement apparatus was originally constructed by combining a LIT (InfraTec ImageIR® 8350hp) with InSb cooled detector and 3x objective lens which provides a spatial resolution of 5 μm, optics, and a diode laser (633 nm, less than 10 μm of focus diameter). The laser beam was modulated according to the synchronized periodic signal from LIT, and an average power was estimated to be less than 10 mW. The schematic of the measurement is shown in Figure 1.

Figure 1 Schematic of the measurement.

The heating frequency was selected according to the sample size to avoid the influence of reflected temperature waves at the sample edge, and then measurements were performed at 20 Hz. The samples were measured under vacuum conditions of a pressure less than 10^{-4} Pa to refrain the effect of the surrounding air because the air causes the overestimate of the thermal diffusivity in the case of the low thermal diffusivity material.

Results and Discussion: The average value of the measured directional distribution of the thermal diffusivities of the Ryugu grains were (1.5–3.7) × 10^{-7} m^2/s. The thermal diffusivity of A0308 was particularly low, averaging 1.5 × 10^{-7} m^2/s, which is the lowest value among all the Ryugu grains ever measured. The thermal diffusivities of the ten grains of carbonaceous chondrites were (1.5–5.1) × 10^{-7} m^2/s, with the Allende meteorite having a definitely higher value and the Tagish Lake meteorite having a definitely lower value than that of the others. The results for the other meteorites coincided within the margin of error.

Figure 2 shows the relationship of the thermal diffusivity and bulk density for each sample. Figure 1 also includes the results of the initial analysis of Ryugu [3], and reference values of Allende (CV3) measured by Soini et al. [4], and Murchison (CM2), Murray (CM2), Cold Bokkeveld (CM2), Jbilet Winselwan (CM2) and NWA 7309 (CM2) by Opeil et al. [5] are also shown as square plots. The results show a positive correlation between thermal diffusivity and bulk density, which is in agreement with reference values, except for Jbilet Winselwan and NWA 7309. Tagish Lake and Ryugu have the smallest thermal diffusivity and density among the groups that experienced the aqueous alteration, including Ryugu. On the other hand, the density and thermal diffusivity of Allende are confidentially larger than the other carbonaceous chondrites and Ryugu. There are several possible causes explaining the variation: (i) thermal diffusivities and densities of Ca- and Al-rich inclusions and chondrules are possibly larger than those of the matrix and Allende has a larger volume fraction of them [6]; (ii) the thermal diffusivity of the matrix possibly to be larger when olivine content is higher; (iii) the thermal diffusivity may be reduced by pores and cracks in the matrix developed during an aqueous alteration. We still have no clear conclusion for the cause of variation. Nevertheless, the variation of the thermal diffusivity and relationship with the density is critical for the thermal evolution of the planetesimals.

Also, Ryugu grains show a thermal diffusivity-bulk density relationship more similar to the Tagish Lake than to the Ivuna sample, which has a similar elemental composition to Ryugu. This result is in agreement with the elastic properties measured by Onodera et al. [2] and suggests that in carbonaceous chondrites with petrological classifications 1 or 2, thermo-mechanical properties may be dominated by mechanical and structural features consisting of the matrix, inclusions, and voids inside the grain. The grain of the lowest thermal diffusivity in Ryugu samples do not have a smaller bulk density than that of other Ryugu grains. Furthermore, the results of the thermal diffusivity distribution analysis indicate that the decrease in thermal diffusivity is unlikely due to cracking because the angular distribution of the thermal diffusivity seemed almost isotropic. In other words, this suggests the possibility that there is a heterogeneous distribution of the pore structure or tiny inclusions that reduce the thermal diffusivity while maintaining the bulk density.

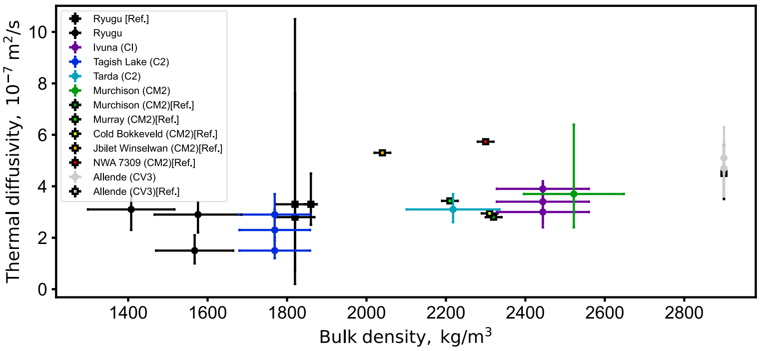

Figure 2 Thermal diffusivity vs. bulk density of Ryugu and carbonaceous chondrites.

To investigate the relationship between elastic wave velocity and thermal diffusivity, we additionally measured the primary elastic wave (P-wave) velocities of some samples as follows: one grain of Ivuna (CI), one grain of Murchison (CM2), one grain of Tarda (C2-ungrouped), and three grains of Tagish Lake (C2-ungrouped). The pulse transmission method was used for the measurements. Details of the measurements of the P-wave velocity are described in a previous report [7]. The result is shown in Figure 3, and the reference value of Ryugu is from Ref. [3, 5]. Figure 3 shows that there is a positive correlation between thermal diffusivity at the range of 0–2 km/s for the P-wave velocities. However, for P-wave velocities above 2.0 km/s, the thermal diffusivity tends to approach a constant value for P-wave velocity. Although the number of measurements is insufficient to clearly understand the cause of this trend, since the thermal diffusivity is more susceptible for the structural factors than the elastic wave velocity, it is possible that the structural factors in the grain may differ around the P-wave velocity of 2.0 km/s (e.g., whether the cracks are in a contact or non-contact at interface). The relationship between thermal diffusivity and elastic wave velocity will be able to provide an effective basis for understanding the internal structure of Ryugu and chondrite grains, by increasing sampling numbers for the carbonaceous chondrites in petrological classifications 1 or 2 and 3.

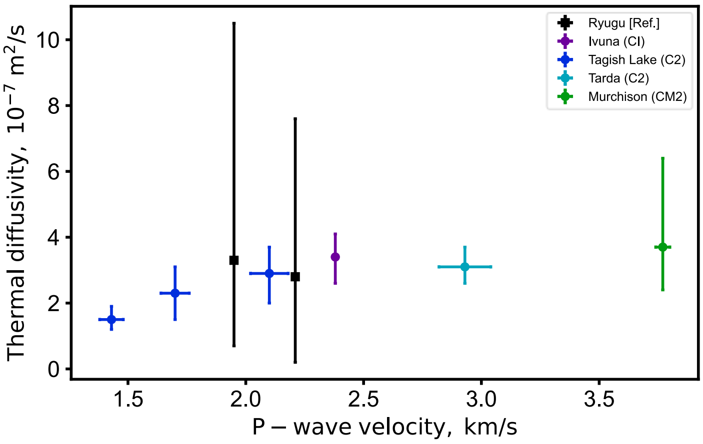

Figure 3 Thermal diffusivity vs. P-wave velocity of Ryugu and carbonaceous chondrites.

References

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