SIZE ANALYSIS OF CHONDRULES AND THEIR RIMS IN CM CARBONACEOUS CHONDRITES

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Introduction: The CM carbonaceous chondrites represent the most pristine solar system material available for study and therefore, provide an excellent opportunity to improve our understanding of the evolution of solids in the Solar System. Chondrules and the fine-grained rims (FGR's) which surround them represent ~20 vol%. of the CM chondrites [1] and can provide vital clues as to these processes.

Despite the significance of chondrules, a conclusive mechanism of chondrule formation, the formation of their FGR's and how they mixed remains elusive [2]. Many of the physical characteristics of chondrules and FGR's such as size, shape, long axis orientation and density may aid our understanding of these issues. However, many these characteristics lack detailed investigation [3-4]. This problem is perhaps best demonstrated by the poorly constrained average size of chondrules within the CM chondrite group which is frequently reported in the literature as being ~300 μm [1,5].

This study sets out to begin an improved analysis of the physical characteristics of chondrules within CM chondrites, particularly with respect to different petrologic sub-types. Findings aim to improve our understanding of the evolution of chondrules and the CM chondrite parent body as well as aid our interpretation of the recently returned samples from Ryugu and future returned samples from Bennu.

Methods: Chondrules from three CM carbonaceous chondrites were examined by Backscattered Electron imaging (BSE) and Energy-Dispersive X-ray Spectroscopy (EDS) using a Zeiss Sigma SEM: two sections of Aguas Zarcas (CM2.2) [6], two sections of Murchison (CM2.5) [7] and one section of Lewis Cliff (LEW) 85311 (CM2.7) [8]. Similarly to [4], only whole chondrules were considered during this work. A whole chondrule was defined here based on criteria discussed in the literature and included chondrules and irregular chondrules as defined by [9]. The definition used in study for a whole chondrule was: polymineralic, has a rounded or spherical shape over >50% of the outline and an intact FGR which surrounds the entire grain [10-12].

Whole chondrules identified in SEM images were extracted manually using GIMP-2.10 image processing software. The parameters of each chondrule were then analysed and best fit ellipsoids produced in the image processing software Fiji (version 2.10/1.53c). A maximum and minimum FGR thickness was also measured in Fiji.

Results: During this study a total of 173 chondrules from the three samples were measured, with analysis of the best fit ellipsoids showing an average major axis length of 190 µm ($\sigma = 0.150$, 95% CI = 0.0224). The maximum size observed was 900 µm and a minimum size 35 µm. No clear correlation was detected between major axis length and the petrologic sub-type of the sample. In common with previous work by [10], a linear relationship between major axis lengths and FGR thickness was found (Fig. 1). In addition to this, a relationship between the average FGR thickness and petrological sub-type was observed (Fig. 1), with the least aqueously altered CM chondrites observed to have thicker FGR's surrounding their chondrules.

A total of ten clasts in Aguas Zarcas and Murchison were identified during this work from BSE images and EDS maps using the criteria set out by [10,13]. Three of the clasts are believed to be examples of primary accretionary rock [10] and displayed significantly higher chondrule densities than the surrounding material. Chondrules within these high-density clasts were observed to have smaller major axis lengths, an average of 106 µm. Within three of the clasts, very similar average FGR thicknesses were measured.

Discussion: Comparing the findings above to those by [5, 1] a smaller average chondrule size was recorded which is closer to the average chondrule sizes recorded in CO chondrites (148 µm as reported by [14]). Thus, the commonly used ~300 μm value should be reconsidered. Explanations for the smaller chondrule size recorded here could include multiple petrological subtypes being examined in this study, although from this data no clear correlation with subtype was shown and, that the clastic nature of CM chondrites results in variability between and within samples. The difference between the values reported in the literature and here may also be the consequence of a sampling bias resulting from large chondrule fragments being excluded from this study due to truncation during section preparation. Future work seeks to use X-ray computed tomography (XCT) on larger sample chips to circumvent this issue and allow investigation of the differences between 2D and 3D observations. [15] found that 2D measured values in ordinary chondrites yielded an 8-18% underestimate in mean chondrule size.

The linear relationship between FGR thickness and chondrule size has been observed previously and used by [10] as evidence for a nebular origin of FGR's and lack of aqueous alteration on the CM parent body. This is disputed by [16]. The relationship observed here between FGR thickness and petrological subtype has not to the author's knowledge been previously recorded and could provide evidence of aqueous alteration occurring on a CM chondrite parent body. [17] examined the implications of parent body processing for FGR material showing that FGR's can be highly susceptible to aqueous alteration.

Similarities in chondrule size and average FGR thicknesses between clasts could also provide evidence of a relationship between physical chondrule characteristics and petrological sub-type, provided the clasts were of similar petrological sub-type. Clasts containing chondrules of similar characteristics raise the possibility for detecting shared histories between the clasts of different CM chondrite samples with implications for our understanding of the CM chondrite parent body(ies).

Conclusions: This study has revealed a smaller average chondrule size for the CMs than often reported, and a relationship between FGR thickness and petrologic subtype. Alongside the numerous uncertainties within the literature, these results demonstrate the need for a more thorough study of the physical characteristics of chondrules. This should include considering the petrological variability between and within samples as well as applying robust statistical analysis to findings. In doing this it may be possible to investigate similarities in chondrule characteristics between the clasts of different CM chondrites improving our understanding of processes, such as brecciation, occurring on the CM chondrite parent body.

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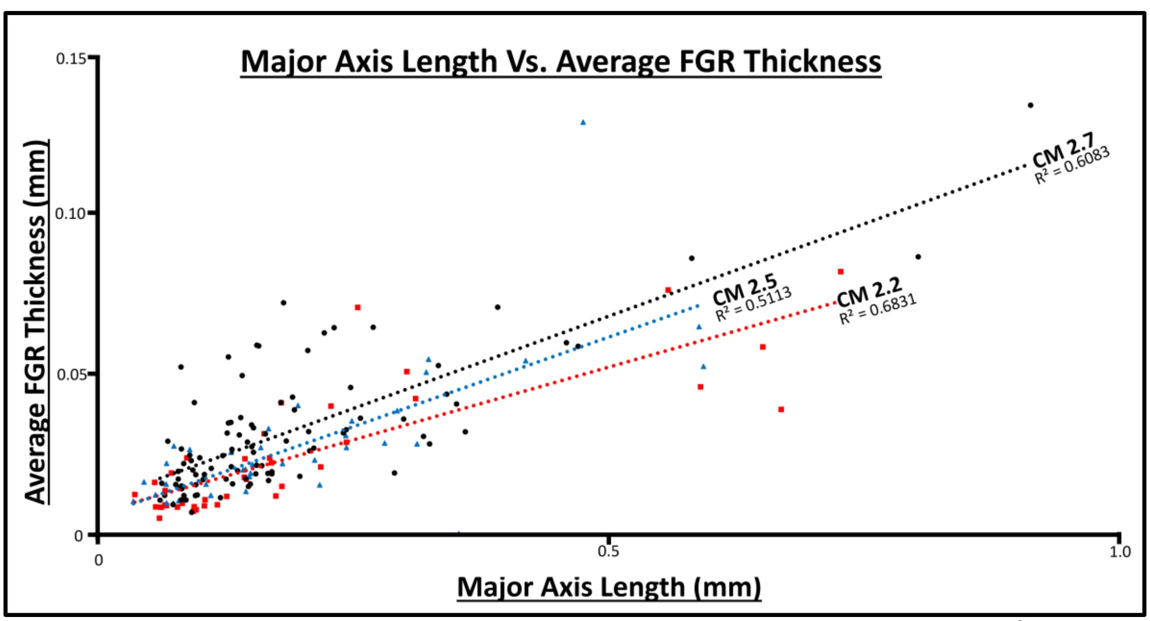

Figure 1. Graph showing the relationship between the major axis length and the average FGR thickness for the three CM chondrites examined