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Particle size distributions in chondritic meteorites: Evidence for pre-planetesimal histories

J.I. Simon [a,*], J.N. Cuzzi [b], K.A. McCain [c,1,2], M.J. Cato [d,1,3], P.A. Christoffersen [e,1,4], K.R. Fisher [f,1,5], P. Srinivasan [g,1,3], A.W. Tait [h,1,6], D.M. Olson [i], J.D. Scargle [b]

[a] *Center for Isotope Cosmochemistry and Geochronology, ARES, EISD-XI3, NASA Johnson Space Center, Houston, TX 77058, USA*
[b] *NASA Ames Research Center, Moffett Field, CA 94035, USA*
[c] *The University of Chicago, Chicago, IL 60637, USA*
[d] *Western Carolina University, Cullowhee, NC, 28723, USA*
[e] *St. Lawrence University, Canton, NY, 13617, USA*
[f] *University of Cincinnati, Cincinnati, OH, 45219, USA*
[g] *Rutgers University, Piscataway, NJ, 08854, USA*
[h] *Monash University, Clayton, 3168, VIC, Australia*
[i] *BAERI, inc., Petaluma, CA 94952, USA*

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ABSTRACT

Magnesium-rich silicate chondrules and calcium-, aluminum-rich refractory inclusions (CAIs) are fundamental components of primitive chondritic meteorites. It has been suggested that concentration of these early-formed particles by nebular sorting processes may lead to accretion of planetesimals, the planetary bodies that represent the building blocks of the terrestrial planets. In this case, the size distributions of the particles may constrain the accretion process. Here we present new particle size distribution data for Northwest Africa 5717, a primitive ordinary chondrite (ungrouped 3.05) and the well-known carbonaceous chondrite Allende (CV3). Instead of the relatively narrow size distributions obtained in previous studies (Ebel et al., 2016; Friedrich et al., 2015; Paque and Cuzzi, 1997, and references therein), we observed broad size distributions for all particle types in both meteorites. Detailed microscopic image analysis of Allende shows differences in the size distributions of chondrule subtypes, but collectively these subpopulations comprise a composite "chondrule" size distribution that is similar to the broad size distribution found for CAIs. Also, we find accretionary 'dust' rims on only a subset (∼15–20%) of the chondrules contained in Allende, which indicates that subpopulations of chondrules experienced distinct histories prior to planetary accretion. For the rimmed subset, we find positive correlation between rim thickness and chondrule size. The remarkable similarity between the size distributions of various subgroups of particles, both with and without fine grained rims, implies a common size sorting process. Chondrite classification schemes, astrophysical disk models that predict a narrow chondrule size population and/or a common localized formation event, and conventional particle analysis methods must all be critically reevaluated. We support the idea that distinct "lithologies" in NWA 5717 are nebular aggregates of chondrules. If $\geq$cm-sized aggregates of chondrules can form it will have implications for planet formation and suggests the sticking stage is where the preferential size physics is operating.

1. Introduction

Largely spherical, magnesium-rich silicate chondrules constitute 30–80% of primitive meteorites and have been reported to be narrowly size-sorted (Ebel et al., 2016, and references therein) as compared to more irregular shaped, refractory CAIs that make up

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[*] Corresponding author.
E-mail address: justin.i.simon@NASA.gov (J.I. Simon).

[1] Former summer interns at JSC through Lunar and Planetary Institute or NASA Co-op Programs.

[2] Now at University of California, Los Angeles, Department of Earth, Planetary, and Space Sciences, Los Angeles, CA, 90095, USA.

[3] Now at University of New Mexico, Department of Earth and Planetary Sciences, Albuquerque, NM, 87131, USA.

[4] Now at Centre for Planetary Science and Exploration, Department of Earth Sciences, University of Western Ontario, London, Ontario, Canada, N6A 3K7.

[5] Now at ARES, NASA Johnson Space Center, Houston, TX, 77058, USA.

[6] Now at University of Stirling, Department of Biological and Environmental Sciences, Stirling, FK9 4LA, Scotland, UK.

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only 1–10% and thought to be less tightly sized-sorted (Hezel et al., 2008, references therein). The high abundances of chondrules in primitive meteorites suggest that chondrule formation and accumulation processes were fundamental to the earliest stages of the accretion of asteroids, which provide the parent bodies for these primitive meteorites. Since terrestrial planets formed from primitive asteroids or analogous planetesimals, understanding these early stages is important for understanding planetary accretion overall.

The mineralogical, chemical, and isotopic composition of chondritic components provide important constraints on their initial formation conditions (*e.g.*, Alexander et al., 2008; Davis et al., 2017; Gooding and Keil, 1981; Huang et al., 2012; Richter et al., 2002; Shahar and Young, 2007; Simon et al., 2017; Yu and Hewin, 1998). However, the characteristic distributions of particle sizes in primitive meteorites likely reflect a combination of how the various subgroups of particles initially formed (*e.g.*, Charnoz et al., 2015), at different times and in different locations in the solar nebula, and how they were preserved and/or were concentrated (*i.e.*, sorted) between formation and parent body assembly.

There are a number of hypotheses for the formation of chondrules. Most postulate that they originated from melting early-formed dust by either localized or nebula scale energetic events in the gas-rich stage of the protoplanetary disk (Boss, 1996; Connolly and Love, 1998; Grossman et al., 1989; Jones et al., 2000), such as magnetic flares (Levy and Araki, 1989), current sheets (Joung et al., 2004), lightning (Desch and Cuzzi, 2000; Johansen and Okuzumi, 2018) or nebular shock waves (Desch and Connolly, 2002; Morris and Desch, 2010; Wood, 1996). Alternative formation models include “melt splash” due to impacts on or between primitive planetary bodies (Johnson et al., 2015; Asphaug et al., 2011), or in planetesimal bow shocks (*e.g.*, Morris et al., 2012).

The more refractory mineralogy of CAIs implies that they formed from precursor materials that condensed out of nebula gas at a high temperature (Grossman et al., 2002), perhaps closer to the protoSun, or at an earlier, hotter nebula stage. There is evidence from radioisotopic age constraints that CAIs might be as much as ∼2 Ma older than chondrules (*e.g.*, Connelly et al., 2012). Given the significant compositional differences (implying that they formed under very different conditions) and their likely age differences, the problem of how CAIs with high-temperature minerals ultimately end up mixed with chondrules and other lower temperature minerals remains a mystery (cf. Ciesla, 2010; Jacquet et al., 2011). These ‘lucky’ CAIs avoided being lost into the Sun or otherwise destroyed in the varied chaotic environments extant in the protosolar disk, including the thermal processes that produced chondrules. Partial overlap of the CAI and chondrule formation environments has been suggested, based on evidence that CAIs interacted with, and possibly some of their rims formed in a chondrule-like environment (Dyl et al., 2011; Simon et al., 2005; Simon and Young, 2011). Finally, the free-floating CAIs must also be ‘selected’ for accretion into the same planetesimal building block(s) as the chondrules.

In principle, size distributions of chondrules (*e.g.*, Ebel et al., 2016) and CAIs (*e.g.*, Hezel et al., 2008) in meteorites can be used to test astrophysical processes. However, with a few exceptions (*e.g.*, Teitler et al., 2010) the differences within and between these distinct particle groups, both of which are made up of diverse subgroups with different minerals and thermal histories, remain poorly quantified. McSween (1977) noted that CV chondrite chondrules ranged in diameter from ∼550 μm to ∼2000 μm. Grossman et al. (1989) reported a compiled mean diameter of ∼1000 μm, but did not cite specific data sources. In abstract form, Paque and Cuzzi (1997) and May et al. (1999) reported mean chondrule diameter for CV chondrites from ∼680 to 850 μm. Teitler et al. (2010) reevaluated the Paque and Cuzzi (1997) data, and along with additional disaggregated materials, reported mean diameters for Allende chondrules of 912 ± 644 μm ($n = 287$) and 917 ± 744 μm ($n = 126$). The available data for CAIs in Allende are more limited, but appear distinct from chondrules. McSween (1977) reported CAIs in terms of modal area fraction ranging from 2.5 to 9.4%. May et al. (1999) obtained a much smaller and narrower range between 0.65 and 1.89%. Hezel et al. (2008) found that CAIs make up 5.02 ± 0.80% ($n = 223$) of the modal area of three Allende thin sections, and based on these and the available literature data report that the modal area of CAIs in Allende is $2.98^{+0.3\%}_{-0.1\%}$. They also report a mean CAI diameter of ∼100 μm with a pronounced peak at the smallest diameters (<100 μm). Their reported size distribution decreases monotonically to slightly larger sizes (∼300 μm in diameter) and then shows a few, exceptionally large (1000’s μm), outliers.

There have been a large number of size distribution studies of chondrules in ordinary chondrites. For a comprehensive view, see the excellent summary by Friedrich et al. (2015). There appears to be variability among the various chondrites (mean diameters differ from ∼300 μm to ∼1200 μm), but with a few exceptions, the data sets are relatively small and, like for the CV chondrites, the smallest and largest particles may have been undercounted, as discussed below.

Here we report a large-area, high-resolution study of the types and sizes of particles in the ordinary chondrite Northwest Africa 5717 ($n = 12{,}966$ particles measured in a photographic mosaic) and the well-studied carbonaceous chondrite Allende ($n = 2339/2555$ particles/particle cores measured in X-ray maps and $n = 6530$ particles in a photographic mosaic). With this extensive data set a number of important observations can be made: (1) The measured particle size distributions are significantly broader than previously reported. This spread in size is inconsistent with previous particle sorting models (Cuzzi et al., 2001) that predict narrow size distributions. In practical terms, the differences among the measured distributions highlight the fact that sampling bias is likely a systemic problem, a problem pointed out recently (*e.g.*, Ebel et al., 2016), and thus there is a need to reevaluate the current data and its use for defining “characteristic” particle sizes for classification purposes. (2) In Allende most (∼85%) particles are unrimmed and in direct contact with meteorite host material (the matrix) whereas rims surround the other ∼15%, often nearby, particles. This diverse behavior strongly argues for pre-accretional rim formation for some particles as they traversed distinct (cooler and/or dustier) nebular environments, *e.g.*, Metzler et al. (1992). (3) When present, fine-grained accretion rim types and thicknesses appear correlated to underlying particle size as recently reported for chondrules contained in the Murchison chondrite (Hanna and Ketcham, 2018). (4) Allende shows differences in the size distributions of chondrule subtypes, but collectively these subpopulations comprise a composite “chondrule” size distribution that is similar to the broad size distribution found for CAIs. And (5) NWA 5717 contains distinct lithologies that appear to be chondrule aggregates.

2. Methods

2.1. Sample materials

Northwest Africa 5717 is an ungrouped (subtype 3.05) ordinary chondrite dominated by chondrules, that contains two apparently distinct lithologies (Bigolski et al., 2016; Bunch et al., 2010). In the studied ∼11 cm × 14 cm slab, the darker of these lithologies seems to host the second, much lighter lithology (Fig. 1). The nature of the boundary between the two is variable and at times uncertain, ranging from abrupt to gradational and not always following particle boundaries. The distinction between the lithologies, beyond the obvious color differences, has been supported by a