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Invited review

Chondrule size and related physical properties: A compilation and evaluation of current data across all meteorite groups

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ABSTRACT

The examination of the physical properties of chondrules has generally received less emphasis than other properties of meteorites such as their mineralogy, petrology, and chemical and isotopic compositions. Among the various physical properties of chondrules, chondrule size is especially important for the classification of chondrites into chemical groups, since each chemical group possesses a distinct size-frequency distribution of chondrules. Knowledge of the physical properties of chondrules is also vital for the development of astrophysical models for chondrule formation, and for understanding how to utilize asteroidal resources in space exploration. To examine our current knowledge of chondrule sizes, we have compiled and provide commentary on available chondrule dimension literature data. We include all chondrite chemical groups as well as the acapulcoite primitive achondrites, some of which contain relict chondrules. We also compile and review current literature data for other astrophysically-relevant physical properties (chondrule mass and density). Finally, we briefly examine some additional physical aspects of chondrules such as the frequencies of compound and "cratered" chondrules. A purpose of this compilation is to provide a useful resource for meteoriticists and astrophysicists alike.

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1. Introduction

Early solid components of the Solar System included calcium–aluminum-rich inclusions (CAIs), chondrules, and Fe–Ni metal and sulfide (primarily troilite, FeS) grains. The dimensions of each of those components generally fall in the μm to mm size range (Brearley and Jones, 1998; Ebel et al., submitted). Other silicate materials – materials that would become chondrite matrix – were also present, but their size ranges lie at the lesser end of or below the size distributions of the previously mentioned materials (Brearley and Jones, 1998; Ebel et al., submitted). Chondrules, or spherical objects of predominately silicate composition found in chondrites, contain essential information needed to elucidate chemical and astrophysical processes operating at the time of their formation during the early evolution of the solar system. Numerous mechanisms for chondrule formation have been proposed, and there is general agreement that they formed from the rapid heating of predominantly silicate precursor materials followed by fast (10–1000 °C/h) cooling (Hewins et al., 1996). Most chondrules are dominated by Fe- and Mg silicates in quenched silicate liquid (mesostasis), but many also contain reduced metal (Fe–Ni) and troilite (FeS). Chondrules typically make up between 20 and 80% of a chondrite by volume and their apparent diameters generally range from ~100 to ~2000 μm (Weisberg et al., 2006).

The diameters of chondrules provide a convenient criterion for chondrite classification and, more importantly, provide fundamental constraints necessary for the development and testing of astrophysical models for chondrule formation. Average chondrule sizes vary among (and possibly to a lesser extent, within) different chemical groups of chondrites, and the average apparent diameters of chondrules are considered a valid criterion for establishing the classification of a chondrite (Van Schmus and Wood, 1967; Weisberg et al., 2006). The size distributions of chondrules among the different chondrite groups could be a result of their mechanism of formation, a result of post-solidification nebular sorting, the result of a process on the parent body, or a combination of factors (e.g., Shu et al., 1996; Weidenschilling, 2000; Cuzzi et al., 2001; Cuzzi and Weidenschilling, 2006; Chiang and Youdin, 2010; Wurm et al., 2010). Whatever the case, the dimensions of chondrules provide substantive limits on their natal astrophysical environments.

In this work we compile historical data on the sizes and densities of chondrules. Chondrule dimensions (generally diameters measured in thin section—see Section 2) have been the most frequently reported. Dedicated studies of chondrule densities (a more difficult measurement) are sparser, but because of its astrophysical significance, we also compile literature data on density. Finally, we discuss the current knowledge and examine the prospects for future data refinement. One goal of this compilation is to provide a useful resource for meteoriticists, astrophysicists, and those contemplating exploration and exploitation of chondritic asteroids.

2. Notes on sources and compiled data

The majority of the data compiled and evaluated here are chondrule diameters, mainly apparent diameters measured on a two dimensional surface (i.e., petrographic thin sections). For ease of discussion and presentation of chondrule diameter data, we examine each chondrite chemical group separately and within each we proceed in order of publication date, from oldest to most recent so the evolution of data is apparent over time. We primarily consider data only on whole chondrules, but have occasionally included historically important data that included combined size data on the silicate grains and/or chondrule fragments which can be found in most chondrites (e.g., Stakheav et al., 1973; Dodd, 1976). Since chondrule diameter data based on studies that included chondrule fragments are inherently biased, when such data are included, it is noted in the narrative, tables, and figures. Petrographic studies on small numbers ($n < \sim 10$) of chondrules have generally been omitted because of the small sample size and specific (and generally unusual) chondrules studied (e.g., Krot and Rubin, 1994). Likewise, diameters for chondrules specifically isolated for isotopic or compositional studies have generally been excluded, because those studies also examined small numbers of chondrules and the sizes are biased because collecting instrumental data is easier with larger specimens. When such data are included, it too is noted in the narrative and tables. At times, it was easy to extract non-tabular or graphical data for inclusion in our compilation. Other times, it was more difficult. We only present data derived from graphical sources when we can do so with high confidence.

We do not address sizes of the fine grained rims that can be found on many chondrules, but again note in the narrative