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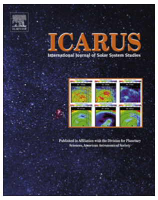

Growth of calcium–aluminum-rich inclusions by coagulation and fragmentation in a turbulent protoplanetary disk: Observations and simulations

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ABSTRACT

Whereas it is generally accepted that calcium–aluminum-rich inclusions (CAIs) from chondritic meteorites formed in a hot environment in the solar protoplanetary disk, the conditions of their formation remain debated. Recent laboratory studies of CAIs have provided new kind of data: their size distributions. We report that size distributions of CAIs measured in laboratory from sections of carbonaceous chondrites have a power law size distribution with cumulative size exponent between −1.7 and −1.9, which translates into cumulative size exponent between −2.5 and −2.8 after correction for sectioning. To explain these observations, numerical simulations were run to explore the growth of CAIs from micrometer to centimeter sizes, in a hot and turbulent protoplanetary disk through the competition of coagulation and fragmentation. We show that the size distributions obtained in growth simulations are in agreement with CAIs size distributions in meteorites. We explain the CAI sharp cut-off of their size distribution at centimeter sizes as the direct result from the famous fragmentation barrier, provided that CAI fragment for impact velocities larger than 10 m/s. The growth/destruction timescales of millimeter- and centimeter-sized CAIs is inversely proportional to the local dust/gas ratio and is about 10 years at 1300 K and up to 10^4 years at 1670 K. This implies that the most refractory CAIs are expected to be smaller in size owing to their long growth timescale compared to less refractory CAIs. Conversely, the least refractory CAIs could have been recycled many times during the CAI production era which may have profound consequences for their radiometric age.

1. Introduction

Calcium–aluminum-rich inclusions (CAIs) from chondritic meteorites are the oldest objects formed in the Solar System as indicated by their absolute radiometric ages using the U–Pb chronometer (e.g. Amelin et al., 2010; Bouvier and Wadhwa, 2010; Connelly et al., 2012). Understanding their conditions of formation is thus key to unravel the astrophysical conditions in the nascent Solar System. They are widely thought to have formed by gas–solid condensation of a gas of chondritic (i.e. solar) composition, notably for the rock-forming elements (e.g. Grossman, 1972; Ebel, 2006), but numerous such objects have experienced complex thermal histories, including in some cases multiple partial melting events (e.g. MacPherson, 2003; and references therein). Their astrophysical environment of formation has been investigated and it is widely thought they have formed at high pressure ($P > 0.1$ Pa) and high temperature ($T > 1300$ K) in the hot inner region of the solar protoplanetary disk (e.g. Shu et al., 1997; Ciesla, 2010). In spite of their common refractory chemistry and isotopic anomalies indicative of formation in a common reservoir, they present a wide diversity of petrographic types and sizes. Their sizes notably span four orders of magnitude from less than 1 μm to ~2 cm, for the smallest corundum (Al_2O_3) grains found in meteorite matrices (e.g. Nakamura et al., 2007; Makide et al., 2009) to the largest so-called type B CAIs (e.g. MacPherson and Grossman, 1981; MacPherson et al., 1989), respectively. How CAIs reached such large sizes remains mostly unknown since their growth mechanism has never been investigated in detail. Large rounded

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cm-sized CAIs have phase relationships indicative of extensive partial melting (e.g. type A and B CAIs, MacPherson and Grossman, 1981; Simon et al., 1999; Kita et al., 2012), which obscured their growth mechanism, while other CAIs are aggregates of 10–50 μm nodules (such as the fine-grained spinel-rich CAIs; e.g. Krot et al., 2004) and thus may not have been completely melted since they were assembled (see examples on Fig. 1). Once partially molten CAIs are also designated as igneous, i.e., crystallized from a silicate melt, or coarse-grained CAIs (designated as CG-CAIs hereafter) and fine-grained aggregates are commonly referred to as fine-grained CAIs (designated as FG-CAIs hereafter). Although nodules from FG-CAIs are thought to have best preserved condensation evidence (e.g. Krot et al., 2004) and may be direct condensates from the gas, laboratory condensation experiments have only produced sub-μm to ⩽5 μm grains to date (Toppani et al., 2006; Takigawa et al., 2012; Tachibana et al., 2014). In addition to the aggregate nature of the FG-CAIs, it was recently realized that several CG-CAIs were in fact compound inclusions made of several lithological units that were initially individual CAIs aggregated to each other before being partially molten to some extent (e.g. El Goresy et al., 2002; Aléon et al., 2007; MacPherson et al., 2012; Ivanova et al., 2012). These observations suggest that coagulation of refractory precursors is a potential mechanism to produce large cm-sized CAIs from initially sub-μm to μm-sized condensates. Conversely, the growth of dust to cm-sized objects in the planet formation regions of protoplanetary disks has been investigated for long (see e.g. Brauer et al., 2008; Birnstiel et al., 2010; Charnoz and Taillifet, 2012) and is known to be a rapid mechanism. Dust grains grow from micrometer to millimeter size through surface sticking in a few 10 to 100 years at 1 AU (Brauer et al., 2008; Charnoz and Taillifet, 2012). In the present paper, we first report the measurement of size distributions obtained from 4 meteorites from the CAI-rich CV–CK chondrite clan. Then we describe and apply a numerical simulation of grain growth in protoplanetary disks to the case of CAIs growth to determine whether growth by coagulation competing with fragmentation (starting from small precursors) in a hot and turbulent inner disk region (where the pressure and temperature conditions are favorable for CAI formation) is a viable mechanism to produce cm-sized CAIs and the resulting size distribution are compared to laboratory measurements. We also investigate the typical growth time and collisional lifetime of CAIs. The paper is organized as follows: we present laboratory measurements of CAI size distributions and the dust-growth numerical model in Sections 2 and 3, respectively. In Section 4, we present our results from numerical simulations, compare them to laboratory measurements and discuss their implications in the context of planet formation. Our findings are summarized in Section 5.

2. CAIs size distributions in CV–CK carbonaceous chondrites

Each chondrite group has its own population of CAIs, in terms of size and petrography (e.g. Krot et al. 2001). We focused our study to the CV and CV-related CK carbonaceous chondrites, because CAIs in these meteorites are (1) more abundant (up to approximately 15 vol%; e.g. Chaumard et al., 2014), (2) span the full size range from μm- (e.g. Kunihiro et al., 2005) to cm-sizes, and (3) have been extensively studied in the past. To our knowledge, only two studies investigated in details the size distribution of CAIs in CV chondrites (Chaumard et al., 2014; Fisher et al., 2014). Data from Chaumard et al. (2014) were used here to produce new size distributions. The samples investigated here are classified as follows with increasing metamorphic grade: Allende (CV3 Ox.), Northwest Africa (NWA) 779 (CV3), NWA 2900 (classified as a

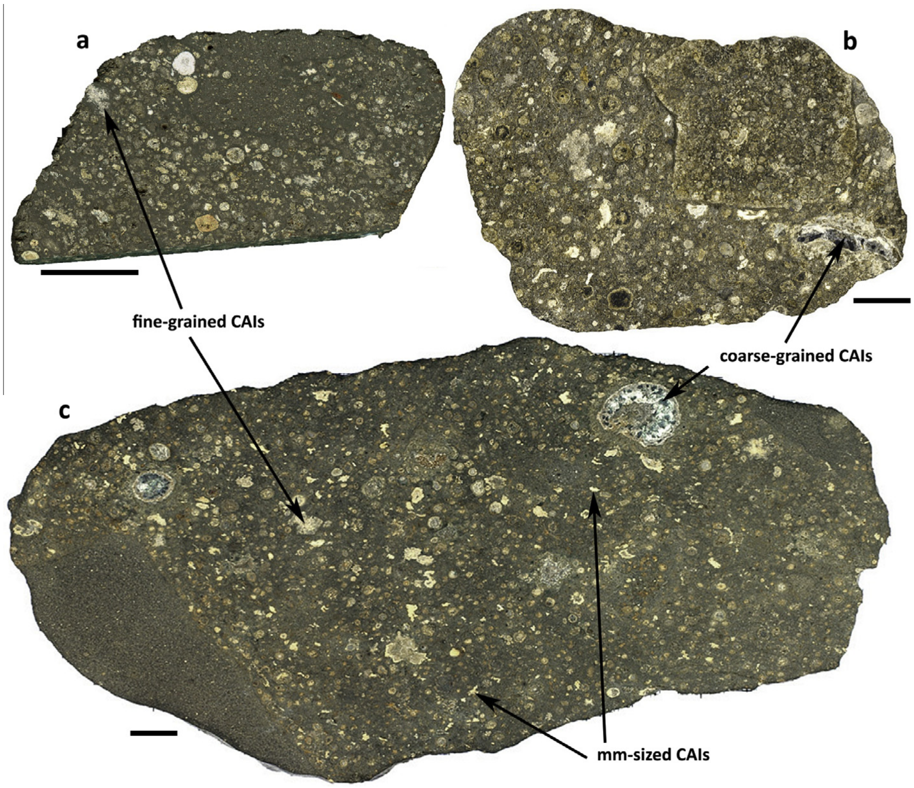

Fig. 1. Representative scanned slabs of CV and CK carbonaceous chondrites used to establish the CAI size distributions in Chaumard et al. (2014) and the present study. (a) Allende, (b) NWA 2900, and (c) TNZ 057. Scale bars are 1 cm. Numerous CAIs are visible as whitish inclusions, with several examples of cm-sized and mm-sized CAIs labeled with arrows. Dark mm-sized grains of pyroxene are visible within coarse-grained CAIs, whereas grains are indistinguishable in fine-grained CAIs.