Earth and Planetary Science Letters 434 (2016) 117–128

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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Ancient stardust in fine-grained chondrule dust rims from carbonaceous chondrites

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ARTICLE INFO

Article history:
Received 5 May 2015
Received in revised form 9 November 2015
Accepted 17 November 2015
Available online 3 December 2015
Editor: T.A. Mather

Keywords:
carbonaceous chondrites
chondrule rims
Solar Nebula
NanoSIMS
circumstellar matter

ABSTRACT

Carbonaceous chondrites are fragments from primitive parent asteroids, which represent some of the most primitive meteorites accessible for laboratory analysis and offer therefore the best opportunity to explore the chemical and physical conditions in the early Solar System. Here, we report the identification of presolar grains, which are circumstellar condensates that date back from before the formation of our Solar System, in fine-grained dust rims around chondrules in carbonaceous chondrites. Average presolar grain abundances in the rims of aqueously altered chondrites (petrologic type 2) are three times higher than in the respective interchondrule matrices, while for the most pristine specimens (petrologic type 3), the opposite is observed. The presence of these grains implies a nebular origin of the rim material, and gives evidence for differing alteration pathways for different reservoirs of fine-grained material found in primitive meteorites. Moreover, our findings indicate formation of the fine-grained rims in the solar nebula prior to parent-body accretion, giving support to accretionary scenarios for parent-bodies in the presence of dust-rimmed chondrules.

1. Introduction

Primitive meteorites, interplanetary dust particles (IDPs), and cometary matter contain small but significant amounts of refractory dust grains with highly anomalous isotopic compositions. The observed isotopic anomalies cannot be explained by chemical or physical processes occurring in the solar system, but are the result of nucleosynthetic reactions in stellar environments. These grains formed in the winds of evolved stars and in the ejecta of stellar explosions, were incorporated in the protosolar nebula and survived alteration and homogenization processes during the formation of the solar system. They represent samples of ancient stardust available for laboratory analysis (e.g., Zinner, 2014). Investigation of the isotopic compositions and mineralogies of these grains provides valuable information on stellar nucleosynthesis and evolution, grain growth in circumstellar environments, the types of stars that contributed material to our planetary system, and chemical and physical processes in the interstellar medium and in the early Solar System. Moreover, parent body (i.e., asteroidal) alteration processes can be studied by using presolar grain abundances as tracers, as is the case for the present study.

Refractory silicates are the most abundant presolar grain type, if nanodiamonds, whose abundances and origins are a matter of ongoing discussion, are neglected (Zinner, 2014). Matrix-normalized abundances depend on the degree of secondary alteration experienced by the host material, but can exceed 200 ppm in the most primitive meteorites (e.g., Nguyen et al., 2007; Floss and Stadermann, 2009; Vollmer et al., 2009a; Nittler et al., 2013). Presolar oxides are somewhat less abundant, with abundances of up to tens of ppm in meteorites (e.g., Vollmer et al., 2009a; Leitner et al., 2012). The majority of presolar O-rich grains are divided into four distinct groups, according to their oxygen isotopic compositions (Nittler et al., 1997, 2008). These groups reflect different stellar origins, with major contributions from low-mass red giant stars and smaller but still significant contributions from supernovae.

In past investigations, the fine-grained matrix material hosting the larger meteorite components (ICM – interchondrule matrix – hereafter) has been targeted for presolar grain searches. However, further fine-grained components are also present in primitive meteorites, such as fine-grained rims (FGR) around chondrules and fine-grained lithic clasts with distinct boundaries embedded in surrounding material. The origin and nature of fine-grained

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http://dx.doi.org/10.1016/j.epsl.2015.11.028
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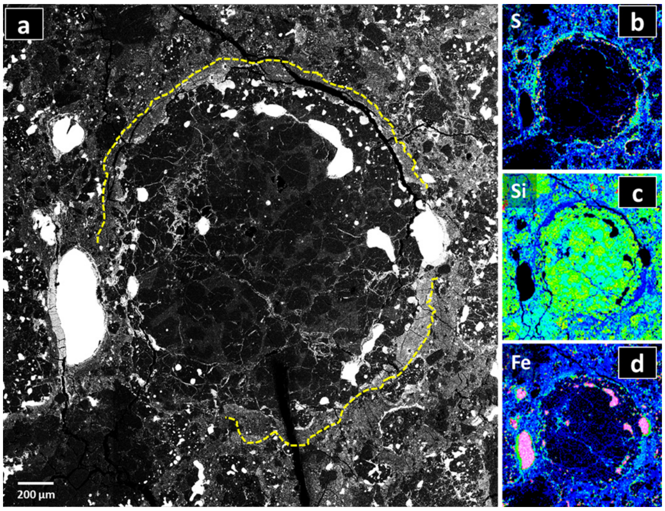

Fig. 1. (a) BSE- and X-ray elemental maps of (b) S, (c) Si and (d) Fe of a rimmed chondrule in GRA 95229. The FGR contains the presolar grains GR9513_6, GR95_13_22, GR95_13_24, GR95_13_27, GR95_13_29, and GR95_14_13 (Table 2). The dashed yellow line in panel (a) marks the outline of the FGR, which can also be identified from the elemental maps in (b–d). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

rims around chondrules has been and is still discussed controversially. Both nebular (e.g., Allen et al., 1980; Metzler et al., 1992; Ciesla et al., 2003; Chizmadia and Brearley, 2008; Bland et al., 2011) and parent body (e.g., Sears et al., 1993; Tomeoka and Tanimura, 2000; Trigo-Rodriguez et al., 2006) formation processes have been suggested, based on a wide variety of observations. If the FGRs accreted in a nebular setting, relatively pristine material like stardust grains or isotopically anomalous organic material could have been preserved there, possibly modified by parent body alteration. Parent body scenarios include chondrule erosion or accretion in the regolith. However, not all structures described as "fine-grained rims" are alike. The FGRs studied in this paper (Fig. 1, Table S1), as well as those investigated in CO (Davidson, 2009; Haenecour and Floss, 2012; Davidson et al., 2012; Haenecour et al., 2014) and CM chondrites (e.g., Metzler et al., 1992; Chizmadia and Brearley, 2008; Leitner et al., 2013) share certain properties like the co-existence of primitive, nearly unaltered components with constituents that have undergone aqueous alteration, on small scales (micrometer to sub-micrometer range). In contrast, the rims described by Tomeoka and Tanimura (2000) and Takayama and Tomeoka (2012) in several CV chondrites and the Tagish Lake meteorite, have been affected heavily by aqueous alteration and may well have a different origin.

The CR (Renazzo-type) group of carbonaceous chondrites is considered to be among the most primitive meteorites (Krot et al., 2002). They exhibit bulk ^{15}N enrichments with δ^{15}N between $+20‰$ and $+230‰$ (depending on weathering grade and state of alteration), hosted in isotopically anomalous organic matter found in these meteorites. Individual isotopic hotspots display ^{15}N enrichments of up to a factor of three (Busemann et al., 2006; Alexander et al., 2007). The degree of aqueous alteration observed within the CR group varies from heavily altered to very little alteration. There is an ongoing debate whether the least altered CR chondrites (MET 00426, QUE 99177) are of petrologic type 2 or 3; however, recently found evidence for aqueous alteration (Le Guillou and Brearley, 2014) would speak against a classification as type 3. A more sensitive scale for the degree of aqueous alteration experienced by CR chondrites is desirable, since such information would ultimately allow differences in the presolar grain abundances due to differing degrees of alteration to be disentangled from inherent heterogeneities. Several approaches have been undertaken to establish more refined classification schemes (Alexander et al., 2013; Harju et al., 2014; Howard et al., 2015). However, these approaches have not yet provided a petrological classification that reflects the vast differences in presolar grain abundances and distributions observed for the CR chondrites (Fig. S2). For more extensively altered meteorites, the scale devised by Harju et al. (2014) is consistent with the significantly lower presolar silicate and oxide abundances observed for Renazzo. However, Alexander et al. (2013) assigned a subtype to Renazzo which puts it in line with the most pristine CR chondrites, indicating less aqueous metamorphism than in QUE 99177. Similar problems are encountered with the scheme by Howard et al. (2015). Here, MET 00426 is assigned 2.6, while QUE 99177, GRA 95229 and even GRA 06100 are classified as 2.8. There are several possible explanations for this apparent discrepancy. First of all, heterogeneous alteration within the CRs might be an important issue. Second, variations of the alteration temperatures could have affected the fraction of surviving presolar silicates and oxides (Alexander et al., 2013). Finally, TEM studies have found that the amorphous silicates in the minimally altered CR chondrite MET 00426 contain water (Le Guillou and Brearley, 2014). These authors ascribe their findings to the simultaneous accretion of dust and ice. The latter produced localized centers of aqueous alteration on sublimation, offering an explanation for the survival of larger amounts of presolar grains in MET 00426 than in the CR2 chondrites (which therefore might have experienced alteration at higher temperatures).

Bulk O-isotopic data for the fine-grained matrix of a set of CR chondrites (Schrader et al., 2014) seem to correlate quite well with both the degree of alteration of the respective meteorite and the abundances of presolar O-anomalous grains from the current study (Fig. S3). However, there is (yet) only small overlap between the sample sets, and heterogeneous alteration also has to be taken into account, as can be seen from differing results for individual samples from the same specimen. Therefore, we refrained from adopting any of these classification schemes for the meteorites studied here.

Early studies of CR chondrites indicated only low presolar O-anomalous dust abundances (Nagashima et al., 2004; Floss and Stadermann, 2005). However, more recent investigations (Floss and Stadermann, 2009; Leitner et al., 2012; Nguyen et al., 2010; Zhao et al., 2013) have revealed much higher oxygen-rich presolar dust concentrations in several of these meteorites. CR chondrites offer the opportunity to study the effects of alteration on primitive meteoritic material from a common reservoir in the early solar nebula. It has been suggested that the range of presolar silicate concentrations among different meteorites is due to secondary alteration processes (e.g., Floss and Stadermann, 2009), which destroy presolar silicate grains preferentially over more refractory presolar phases such as oxides or carbonaceous grains, as has been earlier discussed by Huss et al. (2003).

Here, we report the identification of oxygen-rich presolar grains in fine-grained chondrule rims of several CR chondrites, as well as the ungrouped carbonaceous chondrite Acfer 094. The presence of stardust, together with other primitive materials, indicates a nebular origin of the fine-grained material of which the chondrule rims are comprised. Moreover, formation of these rims must have occurred prior to the formation of the respective meteorite parent bodies. Thus, our findings give strong support to nebular formation scenarios.

2. Materials and methods/experimental

2.1. Sample characterization

All investigated samples (Table 1) were characterized by backscatter electron (BSE) imaging and X-ray elemental mapping with