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ScienceDirect

Geochimica et Cosmochimica Acta 226 (2018) 107–131

Geochimica et Cosmochimica Acta

www.elsevier.com/locate/gca

High abundances of presolar grains and ^{15}N-rich organic matter in CO3.0 chondrite Dominion Range 08006

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Received 1 November 2017; accepted in revised form 30 January 2018; available online 10 February 2018

Abstract

NanoSIMS C-, N-, and O-isotopic mapping of matrix in CO3.0 chondrite Dominion Range (DOM) 08006 revealed it to have in its matrix the highest abundance of presolar O-rich grains (257 +76/−96 ppm, 2σ) of any meteorite. It also has a matrix abundance of presolar SiC of 35 (+25/−17, 2σ) ppm, similar to that seen across primitive chondrite classes. This provides additional support to bulk isotopic and petrologic evidence that DOM 08006 is the most primitive known CO meteorite. Transmission electron microscopy of five presolar silicate grains revealed one to have a composite mineralogy similar to larger amoeboid olivine aggregates and consistent with equilibrium condensation, two non-stoichiometric amorphous grains, and two olivine grains, though one is identified as such solely based on its composition. We also found insoluble organic matter (IOM) to be present primarily as sub-micron inclusions with ranges of C- and N-isotopic anomalies similar to those seen in primitive CR chondrites and interplanetary dust particles. In contrast to other primitive extraterrestrial materials, H isotopic imaging showed normal and homogeneous D/H. Most likely, DOM 08006 and other CO chondrites accreted a similar complement of primitive and isotopically anomalous organic matter to that found in other chondrite classes and IDPs, but the very limited amount of thermal metamorphism experienced by DOM 08006 has caused loss of D-rich organic moieties, while not substantially affecting either the molecular carriers of C and N anomalies or most inorganic phases in the meteorite. One C-rich grain that was highly depleted in ^{13}C and ^{15}N was identified; we propose it originated in the Sun's parental molecular cloud.

Keywords: Carbonaceous chondrites; Early solar system history; NanoSIMS; Nebular processes; Organic matter; Isotopic anomalies; Presolar grains Stardust; Solar Nebula

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1. INTRODUCTION

Chondritic meteorites and micrometeorites, stratospheric interplanetary dust particles (IDPs) and dust from comet Wild 2 brought to Earth by NASA's Stardust spacecraft all contain traces of materials that pre-date the formation of the Sun's protoplanetary disk. Presolar stardust grains originated as condensates in the outflows and ejecta of evolved stars. They are recognized by their highly anomalous isotopic compositions, which largely reflect nuclear processes that occurred in the grains' parent stars (Zinner, 2014; Nittler and Ciesla, 2016). Additionally, a large fraction of the C present in primitive meteoritic materials is in the form of a macromolecular organic matter ("insoluble organic matter" or IOM) that shows isotopic anomalies (typically high D/H and/or ^{15}N/^{14}N ratios relative to terrestrial values) strongly indicative of an origin

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https://doi.org/10.1016/j.gca.2018.01.038
0016-7037/

in either the Sun's parental molecular cloud, or in the outer reaches of the nascent Solar System, where conditions were similar to those in molecular clouds (Messenger, 2000; Busemann et al., 2006).

A large number of presolar stardust phases have been identified, the most abundant being crystalline and amorphous silicates, Al_2O_3, $MgAl_2O_4$, and SiC, but also including graphitic grains (often containing sub-grains of metal and carbides), Si_3N_4, and other minor phases (Zinner, 2014). Nanometer-sized diamonds (nanodiamonds) carrying isotopically anomalous noble gases are also abundant, but their small sizes make their identification as presolar grains ambiguous (Dai et al., 2002; Stroud et al., 2011; Heck et al., 2014). Presolar grains are essentially fossil remnants of stars that survived interstellar and solar nebular processing, and as such they have been used as tools to probe a wide variety of astrophysical processes. Because they encompass such a wide range of chemical forms, they also can serve as sensitive probes of processes that affected materials in the interstellar medium (e.g., shocks and irradiation, Vollmer et al., 2007), the protoplanetary disk (e.g., heating, Huss and Lewis, 1995), and in asteroidal and cometary parent bodies (e.g., aqueous alteration, thermal metamorphism: Floss and Stadermann, 2012; Leitner et al., 2012b). In particular, detailed analyses of presolar grain abundances in meteorites suggest that the different chondrite groups accreted a similar mix of presolar materials and abundance variations observed today reflect that different phases respond differently to parent-body processes. For example, the low-temperature aqueous alteration that has affected many carbonaceous chondrites has little or no obvious impact on SiC abundances (Davidson et al., 2014a), but can be very destructive of presolar silicates (Leitner et al., 2012b). Thermal metamorphism destroys all presolar grains, but at different rates. For instance, presolar $MgAl_2O_4$ is in much higher abundance in meteorites that have seen lower degrees of heating, like CM chondrites (Zinner et al., 2003) and the LL3 Krymka (Nittler et al., 2008), than in the more heated Tieschitz (H/L3.6) ordinary chondrite (Nittler et al., 1997). Of the known stardust phases, silicates are the most susceptible to destruction by parent-body processing and their abundances (and the ratio of their abundances to those of the more resistant oxide phases) are thus highly sensitive indicators of the degree to which the material they are embedded in has been processed.

The highest presolar silicate abundances have been observed in anhydrous fine-grained IDPs collected in Earth's stratosphere and micrometeorites collected in Antarctica, with reported abundances ranging from a few hundred ppm to percent levels (e.g., Floss et al., 2006; Busemann et al., 2009; Davidson et al., 2012; Alexander et al., 2017b). Floss et al. (2006) calculated an average presolar silicate abundance of 375 ppm for a sub-set of ^{15}N-rich IDPs, termed "isotopically primitive." Anhydrous IDPs are suspected to have originated from comets and the high abundance of presolar grains supports this hypothesis, as comets are expected to be more primitive than the asteroidal parent bodies of chondritic meteorites. Prior to the present study, the highest presolar silicate abundances in meteorites have been reported for the highly primitive ungrouped carbonaceous chondrite Acfer 094 (150–200 ppm; Nguyen et al., 2007; Vollmer et al., 2009b; Hoppe et al., 2015), the CO 3.0 chondrite Allan Hills (ALH) 77307 (190 ppm; Nguyen et al., 2010), and the relatively unaltered CR2 chondrites Queen Alexandra Range (QUE) 99177 and Meteorite Hills (MET) 00426 (160–220 ppm; Floss and Stadermann, 2009a; Nguyen et al., 2010). Because presolar grains reside in the fine-grained matrix between chondrules and other inclusions in chondrites, these quoted abundances are all matrix-normalized, but are still lower than the average abundance reported for IDPs. These lower abundances indicate that there has been significant destruction of presolar silicates either in the nebular regions where the chondrites accreted or during the very minor degrees of alteration that petrographic studies indicate occurred in the parent bodies of these four meteorites (Brearley, 1993; Greshake, 1997; Harju et al., 2014).

An additional type of primitive, possibly presolar, material found in meteorites and IDPs is isotopically anomalous organic matter (Messenger, 2000; Busemann et al., 2006; Alexander et al., 2007, 2017a; Davidson et al., 2012). Macromolecular insoluble organic matter (IOM) is the dominant form of C in primitive chondrites and IDPs. Large isotopic variations, most notably enrichments in D and ^{15}N, relative to terrestrial D/H and $^{15}N/^{14}N$ ratios, are commonly observed in the bulk isotope compositions for organic matter from different parent bodies, and even greater variations often occur at the μm to sub-μm scale in the most primitive samples (Messenger, 2000; Keller et al., 2004; Busemann et al., 2006; Alexander et al., 2007; Davidson et al., 2012; De Gregorio et al., 2013). Carbon-isotopic anomalies are also seen occasionally in IOM from IDPs and primitive meteorites (Floss et al., 2004; Busemann et al., 2006; Floss and Stadermann, 2009b). *In situ* studies (e.g., Busemann et al., 2006; Remusat et al., 2010; Bose et al., 2014; Le Guillou and Brearley, 2014) of chondrites indicate that IOM is generally present as discrete, typically sub-μm, grains, including "nanoglobules," which are spherical and often hollow solid organic grains (Nakamura-Messenger et al., 2006; De Gregorio et al., 2013). How the meteoritic IOM formed is still an open question. The large D and ^{15}N enrichments as well as infrared spectral similarities with dust in the diffuse interstellar medium have long been interpreted to indicate an interstellar heritage for the IOM (Robert and Epstein, 1982; Yang and Epstein, 1983; Pendleton et al., 1994), or that it formed in parent bodies from originally interstellar material (Cody et al., 2011; Vollmer et al., 2014). Alternatively, it has been suggested that the IOM may have formed in the solar nebula, e.g., by irradiation of simpler molecular ice precursors or by Fischer–Tropsch type processes (Gourier et al., 2008; Nuth et al., 2008; Ciesla and Sandford, 2012). Complementary to presolar grain abundances, the nature of IOM, e.g. abundance, isotopic composition, and chemical structure, can also be a sensitive indicator of thermal metamorphism and aqueous alteration in meteorite parent asteroids (Quirico et al., 2003; Alexander et al., 2007, 2013, 2018; Busemann et al., 2007; Cody et al., 2008; Bonal et al., 2016).