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The nature, origin and modification of insoluble organic matter in chondrites, the major source of Earth's C and N

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ABSTRACT

All chondrites accreted ~3.5 wt.% C in their matrices, the bulk of which was in a macromolecular solvent and acid insoluble organic material (IOM). Similar material to IOM is found in interplanetary dust particles (IDPs) and comets. The IOM accounts for almost all of the C and N in chondrites, and a significant fraction of the H. Chondrites and, to a lesser extent, comets were probably the major sources of volatiles for the Earth and the other terrestrial planets. Hence, IOM was both the major source of Earth's volatiles and a potential source of complex prebiotic molecules.

Large enrichments in D and ^{15}N, relative to the bulk solar isotopic compositions, suggest that IOM or its precursors formed in very cold, radiation-rich environments. Whether these environments were in the interstellar medium (ISM) or the outer Solar System is unresolved. Nevertheless, the elemental and isotopic compositions and functional group chemistry of IOM provide important clues to the origin(s) of organic matter in protoplanetary disks. IOM is modified relatively easily by thermal and aqueous processes, so that it can also be used to constrain the conditions in the solar nebula prior to chondrite accretion and the conditions in the chondrite parent bodies after accretion.

Here we review what is known about the abundances, compositions and physical nature of IOM in the most primitive chondrites. We also discuss how the IOM has been modified by thermal metamorphism and aqueous alteration in the chondrite parent bodies, and how these changes may be used both as petrologic indicators of the intensity of parent body processing and as tools for classification. Finally, we critically assess the various proposed mechanisms for the formation of IOM in the ISM or Solar System.

Contents

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1. Introduction

The study of the organic material in chondritic meteorites aims to establish where and how it formed – either the interstellar medium (ISM) and/or the solar protoplanetary disk (nebula) – and to determine how it was subsequently modified by nebular and parent body processes. Here we focus on the dominant organic component, the so-called insoluble organic matter (IOM), that is the major carrier of C, N and noble gases in chondrites, and second only to water/OH as a carrier of H. How and where the organic material in chondrites formed will have even wider significance if, as some have speculated, it played a role in the origin of life on Earth (e.g., Ehrenfreund and Charnley, 2000). At the very least, the IOM was probably the ultimate source of most of the C, N and noble gases, as well as much of the H, accreted by the terrestrial planets (e.g., Alexander et al., 2012; Marty, 2012; Marty et al., 2013). Because the organics can be modified by heating at relatively modest temperatures, they can also provide information about dust evolution in the solar nebula, and presumably disks around other low mass stars. This complements what can be inferred about high temperature processing and dust transport from the abundance and properties of crystalline silicates (e.g., Ciesla, 2009; Watson et al., 2009).

There have been a number of fairly recent reviews of the organic matter in meteorites (Botta and Bada, 2002; Sephton, 2002, 2005; Gilmour, 2003; Pizzarello et al., 2006). However, with the renewed interest in the subject, the introduction of new techniques, and the availability of new samples from Antarctica and Comet 81P/Wild 2, the field is evolving rapidly. Traditionally, studies of the organic and inorganic components of chondrites have been treated as essentially separate disciplines, with little attempt to use the one to inform the other. Recently, it has become increasingly apparent that the organic material has great utility as a petrologic tool, both for classification purposes (Quirico et al., 2003; Bonal et al., 2006, 2007, 2016) and potentially for thermometry (Busemann et al., 2007a; Cody et al., 2008c). Here we try to link the organic chemistry with the petrology of the chondrites to show how the organic material can provide important constraints on the origin and evolution of chondrites, comets and, ultimately, our Solar System.

The three basic types of extraterrestrial material that are accreted by the Earth and survive atmospheric entry are classified in order of increasing size into: interplanetary dust particles (IDPs), micrometeorites and meteorites. Because of their small sizes, the organics in IDPs/micrometeorites are not as well characterized as in meteorites, so they are only considered briefly here. With a few exceptions (i.e., those that come from the Moon and Mars) meteorites are fragments of main-belt asteroids (2–4 AU), with a strong bias towards inner belt asteroidal sources (Morbidelli et al., 2002). While there is an overall radial gradient of spectral classes amongst the larger objects in the asteroid belt (Gradie et al., 1989), there has been considerable radial mixing of smaller bodies that are largely collisional fragments (DeMeo and Carry, 2014). As a result, it is likely that the meteorite collection has sampled many asteroid types that formed over a wide range of radial distances (Burbine et al., 2002). Only the most primitive types of meteorite, the chondrites, contain abundant indigenous organic material. This is because non-chondrites come from parent bodies that experienced extensive melting, and even wholesale differentiation into silicate mantles and iron cores.

IDPs almost certainly come from the Zodiacal Cloud and have both cometary and asteroidal sources. The proportions of cometary and asteroidal particles accreted by the Earth is a matter of debate (Dermott et al., 2002; Nesvorný et al., 2010), but recent dynamical arguments suggest that most come from Jupiter family comets that probably formed at about the same distance from the Sun as Neptune (Nesvorný et al., 2010).

The presence of organic material in chondrites, along with presolar circumstellar grains (e.g., Nittler and Ciesla, 2016), demonstrates that they contain a primitive, low temperature component. The organic materials in primitive chondrites often have large D and ^{15}N enrichments, relative to bulk Solar System H and N isotopic compositions, including extreme enrichments in so-called hotspots (Busemann et al., 2006c; Nakamura-Messenger et al., 2006). The large isotopic anomalies in bulk and in hotspots point to formation of the IOM or its precursors in cold, radiation-rich environments, most likely the outer Solar System and/or the ISM (Charnley and Rodgers, 2008). Very similar hotspots are seen in IDPs (Messenger, 2000; Floss et al., 2006). Since at least some IDPs come from comets (Nesvorný et al., 2010; Bradley, 2014), the similarities in their isotopic properties suggests that there is a genetic relationship between chondritic and IDP/cometary organic matter. This is supported by the similar elemental compositions of the most primitive (most aliphatic and isotopically anomalous) chondritic IOM, $C_{100}H_{75-79}O_{11-17}N_{3-4}S_{1-3}$ (Alexander et al., 2007b) and comet Halley CHON particles, $\sim C_{100}H_{80}O_{20}N_4S_2$ (Kissel and Krueger, 1987). Recent in situ measurements of comet 67P/Churyumov-Gerasimenko also suggest that the dominant carbonaceous component of the dust resembles IOM, although with a higher H/C ratio (Fray et al., 2016). The organic materials found in comet 81P/Wild 2 samples returned by the Stardust mission are very variable but share some functional group similarities with