Petrography and Oxygen isotopic compositions of Ca-Al-rich inclusions from Asuka-9003 and 09535

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Introduction:

The current model explaining the whole-rock isotope dichotomy is the accretion of non-carbonaceous chondrites (NCs) and carbonaceous chondrites (CCs) parent asteroids inside and outside, respectively, of the early formed proto-Jupiter (Desch et al., 2018). It is observed that the largest, centimeter-sized Calcium-aluminum-rich inclusions (CAIs) are predominately found in CV and CK chondrites, with CAI sizes in all other chondrites being smaller (e.g., MacPherson et al., 2005). CAIs typically comprise 0.5–3 vol% in CCs that formed far from the Sun, but only < 0.1 vol% in enstatite and ordinary chondrites, collectively known as NCs, that formed closer to the Sun (Desch et al., 2018). Because CAIs are generally thought to have formed in the inner solar system, the fact that they were preferentially incorporated into CCs is puzzling.

Asuka (A)-9003 and A-09535 represent a new type of carbonaceous chondrite, designated CA (Kimura et al., 2021). These CA chondrites have unique features: they share similarly high chondrule/matrix ratios with ordinary chondrites but resemble CO and CV chondrites in terms of the abundances of refractory inclusions (4−6 vol%) and oxygen isotopic compositions (Kimura et al., 2021). With characteristic features of both NCs and CCs, the CA chondrites are in some sense transitional between materials that accreted in the inner solar system and those from the outer solar system. In addition, they could help shed light on complex histories of material transport before their accretion into the parent bodies. Here we present the results of petrological characterizations and oxygen isotopic compositions of CAIs in CA chondrites.

Methods:

CAIs studied were identified in polished thin sections of Asuka-9003 and 09535, on loan from the National Institute of Polar Research. The petrographic observation and chemical analysis were performed by scanning electron microscopy (SEM, Tescan Vega) equipped with an energy dispersive spectrometer (EDS) at UCLA. The oxygen isotope analysis was carried out on the UCLA CAMECA ims-1290 ion microprobe in multicollection mode.

Result and discussion:

CAIs in both A-9003 and A-09535 are typically fine-grained inclusions (FGIs). Based on mineralogy, the FGIs can be classified into four groups: (1) spinel-melilite-pyroxene inclusions, (2) spinel-hibonite-melilite inclusions, (3) spinel-hibonite-melilite-grossite inclusions, and (4) pyroxene-rich inclusions.

Spinel-melilite-pyroxene inclusions are irregularly-shaped. These inclusions have a spinel-rich core enclosed in melilite, both of which are rimmed by a complete or discontinuous layer of Ca-pyroxene. The inclusions contain fine-grained mixtures of Na-rich minerals which appear to be alteration products replacing melilite. Spinel-hibonite-melilite inclusions can be further divided into two types based on the morphologies. One has lath-shaped hibonite grains that are embedded in spinel and are subparallel to one another. Melilite occurs on the exterior of the inclusions. This morphology is similar to hibonite-spinel CAIs in the ALHA77307 (CO3.0) chondrite (Han et al., 2015). The other type is characterized by a layered structure of irregularly shaped nodules in the center composed of spinel that encloses hibonite and melilite. In some cases, melilite in the nodules has been partially converted into alteration products. Spinel-hibonite-melilite-grossite inclusions are either irregularly-shaped or round. These inclusions have similar mineralogy and textures to spinel-hibonite-melilite inclusions. MgO-rich and FeO-rich (Fe# (100 × molar Fe/(Mg + Fe) > 75) spinel are both present in this type of inclusions. FeO-rich spinel shows a porous texture, while MgO-rich spinel does not. This type of inclusion has been found in the Kainsaz (CO3.2) chondrite (e.g., Itoh et al., 2004). Pyroxene-rich inclusions are irregularly-shaped. They consist of Ca-rich pyroxene and often contain spinel, olivine, low-Ca pyroxene, melilite, and anorthite as accessory minerals. The first two groups of CAIs are much more abundant than the last two in both A-9003 and A-09535 samples. The observed mineralogic features in CA CAIs are similar to those in CAIs from both C (CO and CV) and O chondrites (e.g., Russel et al., 1998; MacPherson, 2014; Krot, 2019; Han et al., 2019).

Spinel-melilite-pyroxene inclusions and pyroxene-rich inclusions are up to ~600 μm in size, while spinel-hibonite-melilite inclusions and spinel-hibonite-melilite-grossite inclusions are relatively smaller (< 200 μm). The lack of millimeter- or centimeter-sized CAIs found in this study makes CA chondrites more similar to CO chondrites than to CV in terms of the CAI sizes (e.g., Russell et al., 1998; Itoh et al., 2004; Han et al., 2019)

Spinel and Ca-pyroxene in spinel-melilite-pyroxene inclusions have a narrow range of $\Delta^{17}O$ from −24 to −20‰. In comparison, melilite shows a large range of $\Delta^{17}O$ from −24 to −5‰. Spinel and hibonite in both spinel-hibonite-melilite and spinel-hibonite-melilite-grossite inclusions have ^{16}O-rich compositions from −24 to −21‰ in Δ^{17}O. Melilite in these two types of CAIs has variable Δ^{17}O values, which range from −21 to −14‰. Hercynite and grossite are ^{16}O-poor compared to spinel, hibonite and melilite. Spinel, Ca-pyroxene, and hibonite in CA CAIs have ^{16}O-rich compositions similar to the isotopic composition of the Sun (McKeegan et al., 2011), suggesting that they still preserve the Δ^{17}O values of the nebular gas, and secondary processes either in the nebula or on their parent bodies did not affect these minerals. In contrast, melilite, grossite, and hercynite seem to have undergone isotope exchange with ^{16}O-poor components (e.g., matrix materials or water) during fluid-rock interactions, which have been invoked to explain the oxygen isotope compositions of CAI minerals from CO chondrites of type 3.1 and above (e.g., Brearley and Krot, 2013; Krot, 2019). This inference is supported by our petrologic observations which show that CA CAIs contain fine-grained nepheline, a product of fluid-assisted metasomatism on the parent bodies. From the petrological observations and oxygen isotope compositions, we conclude that CAIs from CA chondrites closely resemble those of CO chondrites. With CA chondrites having high chondrule/matrix ratios, CA chondrite-forming regions would need to be either a dust-poor or chondrule-rich environment like those in the inner solar system in which ordinary chondrites accreted but this reservoir should be in the CC region to best explain the CAI properties. Further studies of CA-chondrite components, including chondrules and matrix, are needed to shed more light on the origins of these unusual meteorites.

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