CAIs, DUSTBALLS AND REFRACTORY LITHOPHILE ABUNDANCES IN CHONDRITE GROUPS.
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Chondrite groups can be distinguished on the basis of their abundances of refractory lithophile elements (RLE). These abundances are, in part, functions of the mass fraction of CAIs within the chondrites. Estimates derived from mass-balance calculations indicate that a significantly greater proportion of bulk RLE occurs in CAIs in carbonaceous chondrites than in ordinary chondrites (OC): e.g., in CV3 Allende ~14% of bulk Ca resides in CAIs and ~21% in CAIs plus AOIs; in LL3 Semarkona, ~8% of bulk Ca resides in CAIs and ~9% in CAIs plus AOIs.

Enstatite chondrites, OC and R chondrites have only very rare CAIs; thus, their relatively low CI- and Mg-normalized RLE abundance ratios (0.87-0.97) reflect the concentrations of these elements in chondrules and matrix. In contrast, the abundance ratio of RLE in carbonaceous chondrites tends to increase with the abundance of CAIs (in vol.%): CI (1.00, 0.0), CR (1.02, 0.6), CO (1.11, 1.0), CM (1.13, 1.2), CV (1.35, 3.0), CK (1.24, 4). The nebular mechanism responsible for incorporating CAIs into chondrites determined the chondrites' bulk RLE abundances.

When the abundance of matrix is plotted against that of RLE, chondrite groups form two clusters – a tight cluster consisting of OC and enstatite chondrites (groups with few CAIs and low RLE) and a broad cluster containing R chondrites and carbonaceous chondrites (groups with more matrix and higher RLE). R chondrites have few CAIs and fall at the low RLE end of the carbonaceous-chondrite cluster. In general, matrix-rich chondrites tend to have higher abundance ratios of RLE than matrix-poor chondrites.

Matrix-rich chondrite groups tend to have higher modal abundances of CAIs. (R and CI chondrites are exceptions.) This general trend is consistent with reports that the abundance of CAIs deceases in the order: carbonaceous chondrites > R chondrites > OC > enstatite chondrites [1,2]. It is apparent that the same local nebular environments that allowed carbonaceous-chondrite groups to acquire abundant matrix permitted them to incorporate relatively large numbers of CAIs.

Different chondrite groups formed under different nebular conditions and it seems likely that heliocentric distance was the dominant factor in determining chondrite properties: (1) Kurahashi et al. [3] found that the formation ages of some CO chondrules were the same as those of L and LL chondrules and inferred that the distinctive properties of OC and CO chondrite whole-rocks arose at different nebular locations. (2) The enstatite chondrites are similar in O-isotopic composition to the Earth and Moon [4] and are likely to have formed in gross proximity to the Earth. Other chondrite groups presumably formed elsewhere within different O-isotopic reservoirs. (3) The high abundance of OC falls (74%) suggests that these rocks formed near an orbital resonance that could deliver samples efficiently into Earth-crossing orbits; this is plausibly the 3:1 resonance with Jupiter [5] located at ~2.5 AU. Less-abundant chondrite groups formed elsewhere. (4) Organic-rich asteroids (e.g., C , P, D) occur mainly in the outer belt where cooler ambient temperatures permit the survival of organics. By analogy, carbonaceous chondrites (which are richer in organics than OC and enstatite chondrites [6]) probably formed farther from the Sun than other chondrite groups [7].

Compositional relationships among chondrite groups and comparisons to the bulk properties of the terrestrial planets suggest that, with increasing heliocentric distance, the groups can be ordered as: EH-EL, H-L-LL, R, CR, CV-CK, CO-CM, CI [5,8]. The groups that accreted closest to the Sun (enstatite chondrites and OC) have small amounts of matrix and probably formed in regions with relatively little nebular dust. R chondrites formed farther from the Sun in a zone with substantially more dust.

The amount of ambient dust probably peaked in the CV-CK region. These matrix-rich chondrites have few RP and C chondrules; they have the largest average chondrule sizes among chondrite groups, the highest percentages of enveloping compound chondrules, the highest proportion of chondrules with igneous rims, and the thickest igneous rims. These are all properties that appear to have resulted from multiple chondrule melting events in dusty nebular environments [8].

The modal abundances of CAIs and the bulk abundances of RLE also peaked in the CV-CK region and diminished with increasing heliocentric distance.

The similarities in O-isotopic composition among CAIs in different chondrite groups and the occurrence of the decay products of ^{10}Be in some CAIs suggest that CAIs formed close together in the nebula (probably relatively near the Sun) and were transported to different nebular locations [9].

CAIs seem to be ~1-2 Ma older than chondrules [10,11]. In a laminar, dust-free nebula, the CAIs would experience gas drag and inward radial drift. Cuzzi et al. [12] proposed that weak turbulence in the nebula would inhibit radial drift of CAIs on timescales on the order of 1 Ma, thereby allowing chondrules and CAIs to accrete together into chondrites.

It is likely that dust was present in the nebula when CAIs were formed. The innermost layer of fine-grained accretionary rims around some CV CAIs [13] contains ^{16}O-rich magnesian olivine grains [14,15]. It seems reasonable to infer that these refractory, ^{16}O-rich dust rims are roughly contemporaneous with the refractory, ^{16}O-rich CAIs they surround. The accretionary rims on CAIs are probably altered remnants of collapsed refractory dustballs.

Why did CAIs concentrate in nebular regions that contained substantial dust? The aerodynamic behavior of a particle is a function of the product of its size and density [16,17]. Isolated sub-µm-size nebular dust grains would experience very different rates of radial drift than mm-size CAIs; these sets of objects are unlikely to be concentrated in the same nebular regions. It therefore seems plausible that much of the dust existed in larger structures. Random aggregates of dust grains can form highly porous structures resembling IDPs [18]. Experimental and theoretical studies [19,20] have demonstrated that nebular fines would tend to agglomerate into dustballs with ~90% porosity. These dustballs would likely be in the mm-to-cm size range: T Tauri and Herbig Ae star-disk systems appear to contain abundant mm-size particles near their midplanes [21,22]. Particle collisions at relative velocities >~1 m s^{-1} would cause shattering rather than clumping [22]; the maximum particle size expected under such conditions is ~1 cm [21,23-25].

A 1-cm-diameter porous spherical dustball with a density of 0.32 g cm^{-3} would respond to aerodynamic forces in the same manner as a compact 1-mm-diameter CAI with a density of 3.2 g cm^{-3}. The mass of the dustball would be 100 times that of the CAI.

It is likely that such dustballs actually existed in the nebula – chondritic meteorites contain altered remnants of dustballs. The remnants survive as (1) matrix lumps in OC and CV chondrites, (2) dark inclusions in carbonaceous chondrites, (3) microchondrule-bearing fine-grained rims around normal-size chondrules in OC, (4) igneous rims around chondrules in every chondrite group except CI, and (5) secondary shells of enveloping compound chondrules.

This scenario in which substantial amounts of dust occurred in mm-to-cm-size dustballs differs from a commonly held view that fine-grained chondrule rims were constructed grain by grain while individual chondrules moved through the nebula and swept up dust particles that stuck to the chondrule surface [26]. However, the presence of microchondrule-bearing rims around some OC chondrules and the high abundances of igneous rims around CV, CK and CR chondrules suggest that fine-grained chondrule rims were instead generally derived from large dustballs.

I propose that porous dustballs, on the order of 100 times more massive than CAIs, were common in the solar nebula. Refractory ^{16}O-rich dustballs were quasi-contemporaneous with CAIs. Aerodynamic radial drift processes affected dustballs to approximately the same degree as CAIs; both types of objects were concentrated at relatively large heliocentric distances where the carbonaceous chondrites formed. The peak concentrations of dustballs and CAIs were in the CV-CK region of the nebula. Over time, as the nebula cooled, more-oxidized materials condensed and parcels of gas and dust with distinct O-isotopic compositions fell into the nebula from the surrounding molecular cloud [27]. Existing dustballs incorporated and reacted with some of this material and became more ferroan and relatively depleted in ^{16}O.

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