bonaceous chondrites with properties that are between the CM and CO meteorite groups, though they are more closely related to the latter [1,2].

One hundred seventy CAIs were observed in a 102-mm^2 thin section of MAC 87300, all <500 µm and most <300 µm in size. Most are composed of pyroxene and spinel, with textures similar to spinel-pyroxene inclusions in CM meteorites [3]. Melilite-bearing inclusions are uncommon. One unusual hibonite-bearing inclusion, #43, is composed of three large (≤75 µm) hibonite laths surrounded by thin rims of hibonite + spinel + (outermost) diopside. The hibonite has low TiO_2 (1.8 wt%) and MgO (0.8 wt%), reminiscent of Murchison PLACS [4]. Hibonite in #43 has an unusual smoothly fractionated concave-upward REE pattern, with Lu enriched ~3× relative to the light REE, a small negative Eu anomaly, and a much larger negative Yb anomaly. The largest inclusion (480 µm across) in this section, #44, is a type A consisting of melilite ($Åk_{7-17}$) enclosing 1–5-µm-sized grains of spinel. The inclusion has a well-defined diopside rim and an accretionary mantle. REE in #44 are unfractionated, ~10–30× C1, with a small negative Yb anomaly. No excess ^{26}Mg was detected in either #43 or #44: for #43, inferred initial $^{26}Al/^{27}Al < 1 \times 10^{-5}$ at $^{27}Al/^{24}Mg \sim 105–125$; for #44, initial $^{26}Al/^{27}Al = (0.5 \pm 2.0) \times 10^{-5}$ (±2σ) at $^{27}Al/^{24}Mg$ up to 32 (see Fig. 1).

One hundred sixty-two CAIs were located in a 172-mm^2 thin section of MAC 88107, similar in size distribution to those in MAC 87300. The most common CAIs are again spinel- and pyroxene-rich, but irregularly shaped melilite-rich type-A inclusions ($Åk_{3-19}$; FeO in spinel ≤0.6 wt%) similar to those in the least-metamorphosed CO3 chondrites [5] are more common than in MAC 87300. Inclusion #14 is a compact intergrowth of melilite, spinel, perovskite, and hibonite laths, with an incomplete diopside rim. Inclusion #16 is unrimmed and extensively cracked, consisting of melilite enclosing spinel and perovskite. Inclusion #20 consists of melilite, spinel, and perovskite (the latter two phases rimmed with Ti-rich pyroxene), and has numerous round voids. The inclusion has a complete diopside rim. Inclusion #35 is a compact, unrimmed intergrowth of melilite and spinel only. Apart from pyroxene, no secondary minerals were detected in these four inclusions. Each contains an excess of ^{26}Mg that corresponds to an initial $^{26}Al/^{27}Al$ of $\sim 4.5 \times 10^{-5}$. REE patterns for #14, #16, and #20 are unfractionated with REE ~50× CI (#14, #16) and ~10× CI (#20). Inclusion #35 has a modified group II REE pattern.

Differences in CAI populations from MAC 87300 and MAC 88107 suggest that the two meteorites are not paired. The CAIs from MAC 87300 and MAC 88107 are most closely related to those from the lowest petrologic type CO3s, and demonstrate that these two meteorites are extremely primitive carbonaceous chondrites. The canonical initial $^{26}Al/^{27}Al$ of CAIs ($4–5 \times 10^{-5}$), defined by the major carbonaceous chondrite groups [6], also applies to inclusions from MAC 88107, whereas no evidence for ^{26}Al in MAC 87300 has yet been found.

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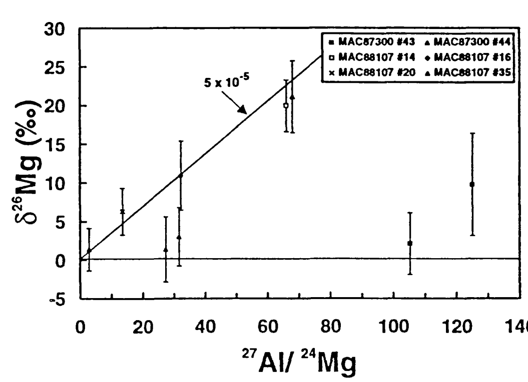

Fig. 1.

QUANTITATIVE MODELS OF CAI RIM LAYER GROWTH. A. Ruzicka and W. V. Boynton, University of Arizona, Tucson AZ 85721, USA.

Many hypotheses have been proposed to account for the ~50-µm-thick layer sequences (Wark-Lovering rims) that typically surround coarse-grained CAIs, but to date no consensus has emerged on how these rims formed. A two-step process— flash heating of CAIs to produce a refractory residue on the margins of CAIs [1–3], followed by reaction and diffusion between CAIs or the refractory residue and an external medium rich in Mg, Si, and other ferromagnesian and volatile elements to form the layers [3–5]— may have formed the rims.

We have tested the second step of this process quantitatively, and show that many, but not all, of the layering characteristics of CAI rims in the Vigarano, Leoville, and Efremovka CV3 chondrites can be explained by steady-state reaction and diffusion between CAIs and an external medium rich in Mg and Si. Moreover, observed variations in the details of the layering from one CAI to another can be explained primarily by differences in the identity and composition of the external medium, which appears to have included vapor alone, vapor + olivine, and olivine ± clinopyroxene ± vapor.

An idealized layer sequence for CAI rims in Vigarano, Leoville, and Efremovka can be represented as MSF | S | AM | D | O, where MSF = melilite (M) + spinel (S) + fassaite (F) in the interior of CAIs; S = spinel-rich layer; AM = a layer consisting either of anorthite (A) alone, or M alone, or both A and M; D = a clinopyroxene layer consisting mainly of aluminous diopside (D) that is zoned to fassaite toward the CAI; and O = olivine-rich layer, composed mainly of individually zoned olivine grains that apparently preexisted layer formation [3]. A or M are absent between the S and D layers in roughly half the rims. The O layer varies considerably in thickness (0–60 µm thick) and in porosity from rim to rim, with olivine grains either tightly intergrown to form a compact layer or arranged loosely on the outer surfaces of the CAIs. None of these variations in rim layers are correlated with the modal compositions of the CAIs.

In our models, we investigated the reaction of CAI interiors (containing M + S + F) with various proportions of vapor (V), O, and D in the five-component system $MgO-AlO_{3/2}-CaO-SiO_2-TiO_2$. Representative compositions were assumed for the solids. Most likely, a vapor reacting with CAIs would have small (e.g., solar) or trivial abundances of Al, Ca, and Ti compared to Si and Mg, and such Al-, Ca-, and Ti-poor compositions were assumed for the vapor. The model zone sequence MSF | S | A | D | V can form when Mg/(Mg + Si) = 0.28–0.47 in the vapor, and is consistent with rims that contain an A layer but lack an O layer. The zone sequence MSF | S | D | VO, which can form when Mg/(Mg + Si) = 0–0.47 in the vapor, may explain rims that lack an A (and M) layer and that have a porous (or poorly compacted) O layer. Finally, the model zone sequence MSF | S | A | D | O ± D is consistent with rims that contain both an A layer and a compact O layer, but this sequence can form only if the system experienced open-system loss of Ca at the D-O contact, with Ca-poor vapor being a possible open-system sink for Ca. The occasional presence of M in a mono- or bimineralic layer within rims apparently cannot be explained by the models, possibly indicating that the rims did not fully attain a steady-state condition.

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OBSERVATION OF CORRELATED CALCIUM-41 AND ALUMINUM-26 IN CV3 HIBONITES. S. Sahijpal[1], G. Srinivasan[1], G. J. Wasserburg[2], and J. N. Goswami[1], [1]Physical Research Laboratory, Ahmedabad 380 009, India, [2]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena CA 91125, USA.

The demonstration of the presence of ^{41}Ca in the early solar system, based on the observation of excess ^{41}K in Efremovka CAIs [1,2], has led to several attempts that sought to identify plausible stellar sites and processes that could have produced and subsequently injected a host of short-lived radionuclides (e.g., ^{41}Ca, ^{26}Al, ^{60}Fe, ^{53}Mn, and ^{107}Pd) into the protosolar cloud [3–5]. Radiogenic excess of ^{26}Mg (from ^{26}Al decay) was also found in the Efremovka CAIs where excess ^{41}K was present [6,7]. This association suggests possible coproduction and subsequent injection of these two short-lived nuclides to the solar nebula. We have measured K and Mg isotopic composition in a single mineral phase (hibonite), having contrasting ^{26}Mg excesses to further substantiate this hypothesis.

We have chosen hibonites from two CV3 meteorites, Efremovka and Allende, for the present study. The Efremovka hibonite is from a CAI (E50) having a well-behaved Mg-Al isotopic systematics with initial $^{26}Al/^{27}Al$ of $(4.87 \pm 0.87) \times 10^{-5}$ [6]. The Allende sample (HAL hibonite), on the other hand, has a very low initial $^{26}Al/^{27}Al$ of $(5.2 \pm 1.7) \times 10^{-8}$ [8]. We have carried out K and Mg isotopic studies of E50 hibonite and K isotopic study of HAL hibonite using procedures described previously [1,2,6]. Because of the small size of E50 hibonites, K isotopic composition could be measured in only a few hibonite grains, where the contribution from the neighboring K-rich phase (melilite) toward the measured K signal was negligible. In the case of HAL hibonite there is a large variation in K content, and the signal at ^{39}K is often close to the system background, while the signal at mass 41 is dominated by the $(^{40}Ca^{42}Ca)^{++}$ interference. The magnitude of this interference was estimated by measuring the $(^{40}Ca^{43}Ca)^{++}/^{43}Ca^{+}$ ratio in terrestrial (Madagascar) hibonite as well as in the HAL hibonite. We obtained a value of $(7.3 \pm 0.6) \times 10^{-6}$, which is about 4× lower than the corresponding value for pyroxene [1,2].

Definite excess of ^{41}K has been found in E50 hibonites with Ca/K ratio exceeding 5×10^5. A forced linear fit of the data through the solar system $^{41}K/^{39}K$ ratio (0.072) yields an initial $^{41}Ca/^{40}Ca$ of about 1.4×10^{-8}, which is close to the value reported for Efremovka pyroxene [1]. The Al-Mg isotopic data for the E50 hibonites reveal ^{26}Mg excess, consistent with the results reported earlier [6]. In contrast, no excess ^{41}K was found (within the limits of our experimental uncertainties) in HAL hibonite, even though its Ca/K ratio is much higher than in Efremovka hibonite. Our data provide an upper limit of 3×10^{-9} for initial $^{41}Ca/^{40}Ca$ in HAL hibonite. These results and data obtained from studies of other Efremovka CAIs [1,2,6,7] show that (1) ^{41}Ca and ^{26}Al are present at the same level ($^{41}Ca/^{40}Ca \sim 1.4 \times 10^{-8}$ and $^{26}Al/^{27}Al \sim 5 \times 10^{-5}$) in several Efremovka CAIs and (2) ^{41}Ca is very low or absent when ^{26}Al is at very low levels (HAL hibonite). It therefore appears that ^{41}Ca and ^{26}Al are coupled either in their original stellar source(s) or were well mixed in some parcels of interstellar material before they were injected to the solar nebula. The lower initials in HAL hibonite may reflect either a heterogeneity of ^{26}Al and ^{41}Ca in the solar nebula (due to variable mixing of the source material with nebular material) or processing of material and/or redistribution of Mg and K isotopes at a later time. Although we cannot decide between these alternatives based on our data, extensive studies of HAL and other refractory objects indicate that many CAIs evolved through multiple events in the early solar system, spreading over a significant time interval [e.g., 9–12].

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ORDINARY CHONDRITES VIEWED AS REASSEMBLED "SPLASH EJECTA."

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A case has already been made favoring chondrites as reassembled "splash ejecta" following low-velocity collisions between molten planetesimals [1]. Here I briefly review this hypothesis, then develop further arguments in its support.

The scenario envisaged may be summarized as follows. Planetesimals grew to radii greater than 30 km in less than 1 Ma after the formation of CAIs, and they were heated rapidly by the decay of ^{26}Al. By 2 Ma each planetesimal, had a molten interior insulated by a cool, dusty carapace. Low-velocity collisions at this stage released enormous, turbulent, expanding clouds of incandescent spray mixed with dust and solid grains from the carapace. The cloud constituted a rather special, transient nebular environment; as it cooled, the melt droplets became chondrules. Much of the cloud's contents reassembled under gravity onto the surface of the hot, residual planetesimal, and the accumulated debris became reheated and metamorphosed. Collisions recurred over the few million years that relative velocities remained low and planetesimals remained molten. Thus, the cumulative debris contained many recycled and broken chondrules. This scenario is apparently reconcilable with chondrule cooling rates, the preservation of clasts of "planetary" rock in chondrites, the retention of volatiles in chondrules, the preservation of solar chemistry, and more than a dozen other features.

Is it reasonable to claim that 30-km-radius bodies existed by 1 Ma, and were substantially molten by 2 Ma? Cameron [2] argued that CAIs were saved from drifting into the Sun by their incorporation, soon after formation, into planetesimals whose mass was sufficient to hold them in orbits, decoupled from the drag of nebular gas. Wetherill's models [3] show that many bodies >100 km radius may have formed on a timescale of 10^5 yr. In these terms, the proposed 30 km by 1 Ma is quite conservative. Regarding ^{26}Al heating, the remarkably constant initial ratio of $^{26}Al/^{27}Al$ (5×10^{-5}) in CAIs from different classes of meteorite [4] suggests that ^{26}Al was uniformly distributed in the dust that eventually formed the chondrite parent bodies. This amount of ^{26}Al translates to some 7000 J g^{-1}. A simple finite element calculation was made to assess the likely thermal evolution of planetesimals of different sizes, starting from 300K at different times. The proposed body of 30 km radius at 1 Ma was found to be a limit for substantial internal melting. Its interior would have remained molten for several million years. Earlier accretion, or larger planetesimals, would have generated even more melt. It seems, therefore, that molten planetesimals were abundant in the early solar system. Moreover, they evidently suffered collision and accretion. If their collision products were not chondrules, then what were they?

Two further arguments favoring the proposed scenario concern the age difference of CAIs and chondrules and the existence of macrochondrules. Cameron's Leonard Award address [2] was stimulated by the inferred time interval of several million years between the formation of CAIs and chondrules. Chondrules were interpreted as dust melted by solar flare activity, the dust having been produced by late collisions between planetesimals. If, as is argued here, the planetesimals were already internally molten, chondrules would have been produced directly, without needing to invoke a solar flare heat source. A separate issue is the existence of porphyritic olivine macrochondrules up to 4 cm across [5]. Macrochondrules are not easily reconcilable with chondrule formation by radiative heating in a nebular setting. Such a mechanism predicts an inverse relationship between chondrule diameter and temperature rise, which is not observed. However, in the present scenario, macrochondrules are interpreted simply as examples of large blobs of frozen melt.

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OXYGEN ISOTOPES IN FORSTERITE GRAINS FROM JULESBURG AND ALLENDE: OXYGEN-16-RICH MATERIAL IN AN ORDINARY CHONDRITE.

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Grains of forsterite form a significant fraction of the matrices of the CM, CV, CO, and UOC meteorites; some of them consist of nearly pure forsterite ($Fa < 1$) and display blue cathodoluminescence. Steele [1] has made a comprehensive study of the minor elements in these grains, and found that the most Fe poor ($< Fa_{0.7}$) display blue CL and seem to be common to all the aforementioned chondrite groups. Bulk samples of, and chondrules from, the UOCs and the carbonaceous chondrites have different O isotopic signatures [2,3]. It is therefore desirable to determine the O isotopic signatures of the forsterite grains from the different meteorite groups to determine whether