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Formation of chondritic refractory inclusions: the astrophysical setting

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Abstract—This study attempts to identify the astrophysical setting in which properties of the Ca,Al-rich inclusions (CAIs) found in chondritic meteorites are best understood. Importance is attached to the short time period in which most or all of the CAIs were formed ($<\sim 0.5$ Myr, corresponding to the observed dispersion of values of initial $^{26}Al/^{27}Al$ about the canonical value of $\sim 5 \times 10^{-5}$), a constraint that has been overlooked. This period is dissimilar to the time scale of evolution of T Tauri stars, ~10 Myr; it corresponds instead to the time scale of Class 0 and Class I young stellar objects, protostars as they exist during the massive infall of interstellar material that creates stars. The innermost portion of the sun's rapidly accreting nebular disk, kept hot during that period by viscous dissipation, is the most plausible site for CAI formation. Once condensed, CAIs must be taken out of that hot zone rather promptly in order to preserve their specialized mineralogical compositions, and they must be transported to the radial distance of the asteroid belt to be available for accretion into the chondrites that contain them today. Though this paper is critical of some aspects of the x-wind model of CAI formation, something akin to the x-wind may be the best way of understanding this extraction and transport of CAIs. *Copyright © 2004 Elsevier Ltd*

1. INTRODUCTION

An important and enigmatic ingredient of chondritic meteorites is the category of objects called refractory inclusions or Ca,Al-rich inclusions (CAIs; Fig. 1). CAIs assumed importance in meteoritics when they were found to be abundant in the Allende, Mexico, chondrite that fell in 1969 (Clarke et al., 1970; Marvin et al., 1970), and when thermodynamic calculations showed that the high-temperature minerals abundant in them (Al oxides, melilite, spinel) would be the first condensates in a cooling solar nebula (Grossman (1972); but see also Lord (1965)). Unlike the most abundant ingredient of chondrites, the chondrules, CAIs are not size-sorted. (Not within a given chondrite class, that is, though there are systematic differences in size between classes.) They range in diameter from several cm down to sizes too small to be definitively recognized as CAIs. They are not evenly distributed among the classes of chondrites, ranging in abundance from ~5% by volume in CV3 carbonaceous chondrites to almost zero in ordinary chondrites. A review of the varied and complex properties of CAIs is beyond the scope of this paper: the reader is referred to MacPherson et al. (1988) and Brearley and Jones (1998) for reviews. A simplified classification of CAIs in the Allende CV3 chondrite is presented in Table 1.

Because CAIs differ greatly in dimension, composition, oxidation state, thermal history, and isotopic properties from the other ingredients of chondrites, it has seemed clear that some special setting or circumstance was required for their production (e.g., Guan et al., 2000). In the years when the solar system was thought to have formed from a hot, monotonically cooling solar nebula, CAIs were seen as the first condensates from that system (Grossman, 1972; Grossman and Larimer, 1974), but as more was learned about the complexities of the nebula and also of CAIs, this simple picture was discarded. It was not replaced by another specific CAI-paradigm, however, and for a decade or more meteoriticists were content to understand CAIs simply as having been formed at high temperatures in the nebula by some process different from the one that formed the chondrules, whatever that might have been. This did not change until the x-wind model of Shu et al. (1996) (and later papers cited in § 6.3.1.) offered a detailed model for the formation of CAIs and other chondrite components. Since that time several other fairly specific models for CAI formation have also appeared.

The purpose of the present paper is to describe and critique these models (§ 6.) and use them as a basis for identifying the most likely setting for the origin of CAIs (§ 7.). The paper should be seen as an attempt at synthesis, not as a review; it does not include the systematic literature surveys that characterize a review paper, and it expresses the author's opinions and interpretations to a degree that a review should not.

2. RELATIONSHIP BETWEEN CAIS AND CHONDRULES

CAIs and chondrules both formed in the temperature range ~1900K–~1400K in the early solar system. They differ mainly because chondrules were in that temperature range for a shorter time than CAIs were, not long enough to lose most of their complement of Si and Mg by evaporation and be reduced to the assemblage of refractory minerals found in CAIs.

An important question is whether variants of the same astrophysical process formed both CAIs and chondrules, and a number of investigators have looked for a compositional continuum between the two categories of objects in support of this idea (e.g., McSween, 1977a; Bischoff and Keil, 1984; Beckett and Grossman, 1988; MacPherson and Huss, 2000). (However, the existence of a continuum would be, at best, feeble evidence of similar formative processes. If both CAIs and chondrules formed from precursors of solar composition in the solar nebula, at temperatures high enough to permit evaporation and condensation, they might be expected to lie on overlapping

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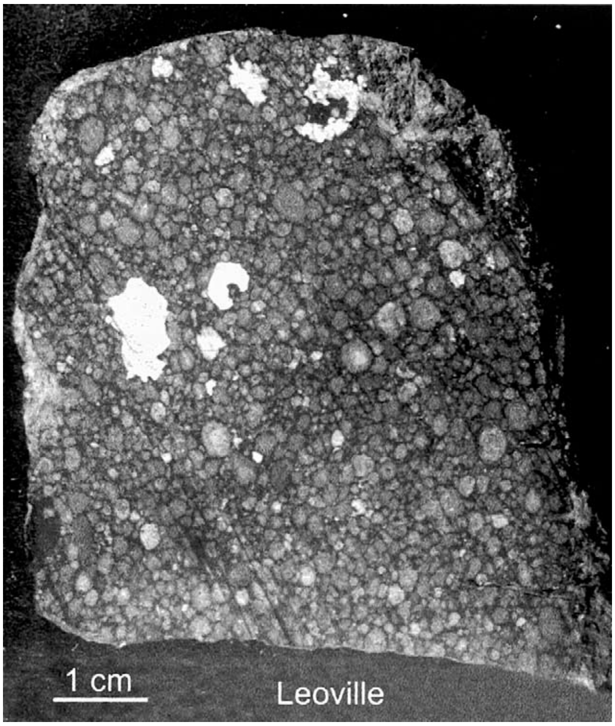

Fig. 1. A sawed slab of the Leoville, Kansas, CV3 chondrite (courtesy of Glenn I. Huss, American Meteorite Laboratory). The large irregular light-colored inclusion, as well as several small light objects, are CAIs. The numerous small, dark spheroids they are embedded in are chondrules.

compositional trends even if they formed in very different ways.)

In these studies, attention has focussed on an Al-rich subset of chondrules whose compositions place them near the junction between the condensation sequences of chondrules and CAIs in plots of chemical parameters. However, these Al-rich chondrules are younger than CAIs. Kita et al. (2000), Srinivasan et al. (2000), Huss et al. (2001), and Hsu et al. (2003) have found they consistently display values of $(^{26}Al/^{27}Al)_0$ that are about an order of magnitude smaller than the value of $\sim 5 \times 10^{-5}$ found for most CAIs. This difference is generally held to reflect decay of ^{26}Al between the times when the two sets of objects formed (§ 4.), and the difference in ratios corresponds to a ≥2 Myr difference in ages. (Studies based on a different isotopic system, U/Pb, also tend to show that chondrules are younger than CAIs (Amelin et al., 2002), but also that their periods of formation overlapped (Amelin et al., 2004)). If CAIs were formed during the brief class 0 and 1 accretion phases of protosolar evolution (§ 5.; Table 2) and chondrules continued to be formed in the very different T Tauri environment ≥2 Myr later, it seems unlikely that variants of the same process created them.

The Al content and other compositional properties of Al-rich chondrules has been ascribed by several authors (Krot and Keil, 2002; Krot et al., 2002; Ash et al., 2003) to the presence of a component of CAI material in the precursors that were melted to form the chondrules. Huss et al. (2003) describe a CAI with $(^{26}Al/^{27}Al)_0 = 3.7 \times 10^{-5}$ that is embedded in an olivine-pyroxene chondrule with no evidence of ^{26}Al.

3. SHORT-LIVED RADIONUCLIDES AND THEIR SOURCE

Perhaps the most interesting property of CAIs is the patterns of isotopic anomalies they contain that demonstrate they once contained radioactive nuclides with very short half-lives: notably ^{41}Ca, half-life 0.10 Myr; ^{26}Al, 0.74 Myr; ^{10}Be, 1.5 Myr; ^{53}Mn, 3.7 Myr; ^{182}Hf, 9.0 Myr; and ^{129}I, 15.7 Myr (see reviews by Wasserburg, 1985; Podosek and Swindle, 1988). Evidence of these nuclides, which decayed to extinction long ago, is most prominent in the CAIs, but it can also be found in chondrules. Survival of this isotopic evidence shows that little time elapsed between the nucleosynthetic event(s) that created the short-lived nuclides and incorporation of the latter in chondritic minerals, and also that some of these minerals have remained unaltered or little-altered since that time. (Two other short-lived nuclides that are also present in meteorites have not been found in CAIs: ^{60}Fe, 1.5 Myr (Shukolyukov and Lugmair, 1993a; Shukolyukov and Lugmair, 1993b; Tachibana and Huss, 2003; Mostefaoui et al., 2003) and ^{107}Pd, 6.5 Myr (Kelly and Wasserburg, 1979; Chen et al., 1999). The inherently low levels of Fe and Pd in CAIs make evidence for these nuclides difficult to detect in them.)

The short-lived radionuclides in CAIs and meteorites are understood by most authors to have been synthesized in presolar astrophysical settings. Sources that have been invoked are supernovae (Truran and Cameron, 1978; Meyer and Clayton, 2000; Cameron, 2001), novae (Clayton and Hoyle, 1976; Hillebrandt and Thielemann, 1982; Gehrz et al., 1993), asymptotic giant branch (AGB) stars (Wasserburg et al., 1994; Busso et al., 2003), and Wolf-Rayet stars (Cameron and Truran, 1977; Arnould et al., 1997). Of course for one of these sources to be useful requires that solar system formation occurred near to the star that generated short-lived radionuclides, so the latter could be incorporated in CAIs before they decayed to indetectability. This requirement was answered in the case of a supernova source by the *supernova trigger* concept of Cameron and Truran (1977) and Cameron (1991), which postulates that the supernova that supplied ^{26}Al and other nuclides to the solar system also initiated collapse of a nearby cloud core that became the solar system. This idea (now referred to as triggered star formation) has been generalized to include planetary nebula ejections, nova eruptions, and other astrophysical events in addition to supernova explosions, as sources of pressure that could initiate the collapse leading to star formation (Vanhala et al., 1998). Stars thought to be the products of recent triggered star formation are described by Thompson et al. (1998), Preibisch and Zinnecker (1999), Ortega et al. (2002), and Redman et al. (2003).

The most durable of the concepts named have been nucleosynthesis in massive stars before and when they supernova, and in AGB red giant stars which emit the nuclides produced in stellar winds. Novae eject too little material to account for the solar system's content of ^{26}Al (Cameron, 1993). While ^{26}Al, ^{41}Ca, and ^{107}Pd can be produced in Wolf-Rayet stars, ^{60}Fe and other short-lived radioactivities cannot be (Arnould et al., 1997). (Probabilistic objections to supernova and AGB origin also should be noted. Adams and Laughlin (2001) argue that the probability of formation of the solar system in a stellar cluster large enough to contain a massive star that supernovas and enriches the early solar system in radioactive species, and

Table 1. A simplified classification of CAIs in the Allende CV3 chondrite.[a]

	Amoeboid Olivine Aggregates	Fine-Grained Inclusions	Fluffy Type A Inclusions	Type B Inclusions[b] (+Compact Type A Inclusions)	Type C Inclusions (plagioclase-rich)
Abundance in Allende (approx. volume %)[c]	$\sim$2%	$\sim$2%	$\sim$0.25%	B + C $\sim$0.25%	B + C $\sim$0.25%
Size (diam.) in Allende	$<$10 mm	$<$10 mm	$<$1 mm–$>$20 mm	$\sim$5–$\sim$25 mm	$\sim$2–$\sim$10 mm
Shape	Contorted	Contorted	Contorted	Subrounded	Subrounded
Texture	Fine-grained ($\sim$10 μm), aggregational, often sintered	Aggregation of 5–100 μm layered bodies	Fine-grained ($\sim$200 μm), porous, highly altered	Coarse (0.5–2 mm) igneous texture. Some have melilite mantles	Igneous textures
Minerals, in approx. order of abundance	Olivine (Nepheline)[d] Spinel Pyroxenes Sulfides	Spinel Pyroxenes Melilite (Nepheline, Sodalite, Anorthite, Grossular)[d] Perovskite	Melilite Hibonite Spinel Perovskite	Melilite Ti-Pyroxene Spinel Anorthite	Anorthite Ti-Pyroxene Melilite Spinel

[a] Distilled from Kornacki (1983), Wark (1983), MacPherson et al. (1988), and Brearley and Jones (1998); also D. A. Wark (private communication). It is important to note that proportions and properties of CAI types are quite different in other (non-CV) chondrite classes.

[b] Unique to CV chondrites (incl. Allende).

[c] Kornacki (1983).

[d] Minerals in parentheses are alteration products of melilite.

Table 2. Recognized classes of low-mass young stellar objects.[a]

	Class 0 YSOs	Class I YSOs	Class II YSOs	Class III YSOs
Description	Protostars in the early main accretion phase. Hydrostatic core has formed but probably not yet accreted majority of final mass. Main FU Orionis epoch	Relatively evolved protostars in the late accretion phase	"Classical" T Tauri stars: pre-main-sequence stars with optically thick protoplanetary disks	"Weak-line" T Tauri stars: PMS stars with optically thin (debris?) disks
Duration of stage	1–3 × 10^4 years	1–2 × 10^5 yr	1–10 Myr	1–10 Myr
Observability	Embedded in optically thick dust clouds; reradiated emission peaks at submm wavelengths	Embedded in less dense clouds; reradiated emission in the IR is observed	Peak emission in near IR and visible	Peak emission in near IR and visible; strong x-ray signal
Bipolar outflows (mass loss rate $\approx$0.05–0.1 $\times$ mass accretion rate)[b]	Short-lived jetlike CO molecular outflows	Outflows much less powerful and collimated than in Class 0	Bipolar jets/winds	No outflow
Bolometric temp., T_{bol}[c]	$<$70K	70–650K	650–2880K	$>$2880K
Circumstellar material (disk and infalling envelope)	$M_{env} + M_{disk} \approx 1\ M_\odot$ $M_{env} \geq 10 \times M_{disk}$	$M_{env} + M_{disk} \approx 0.03 - 0.1\ M_\odot$	$M_{disk} \approx 0.03$, $M_\odot$ envelope mostly gone	$M_{disk} < 5 \times 10^{-3d}\ M_\odot$
Mass accretion rate[e]	$10^{-5} - 10^{-6}\ M_\odot\ yr^{-1}$	$10^{-6} - 10^{-8}\ M_\odot\ yr^{-1}$	$10^{-7} - 10^{-9}\ M_\odot\ yr^{-1}$	Accretion not detected

[a] From Shu et al. (1987), Berthout (1989), André and Montmerle (1994), André et al. (2000), and N. Calvet, private communication.

[b] Bacciotti et al. (2003).

[c] Myers and Ladd (1993). T_{bol} is the temperature of a blackbody having the same mean frequency as the observed continuum spectrum.

[d] Nürnberger et al. (1998).

[e] Calvet et al. (2000).

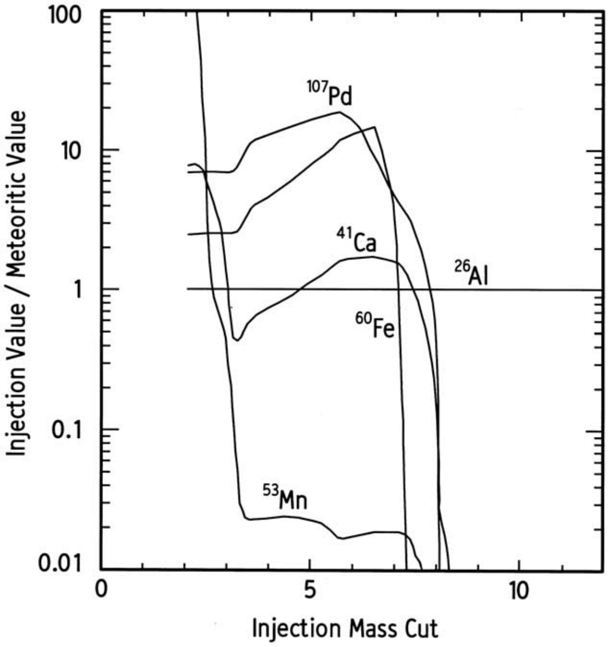

Fig. 2. Production of CAI radionuclides by a 25 $M_\odot$ supernova, modeled by Meyer and Clayton (2000) and Meyer et al. (2003). The amount of each nuclide, relative to its initial concentration in CAIs, is plotted as a function of the assumed amount of the 25 $M_\odot$ star that is available for injection into the protosolar cloud. (*Mass cut* refers to the amount of material from the core of the presupernova star that is excluded from inclusion in the protosolar cloud, in solar masses.) For the whole range of mass cuts, the authors assume that enough supernova ejecta (typically $\sim 10^{-4}$ of the amount available) is added to the solar system to account for the 5×10^{-5} initial value of ^{26}Al/^{27}Al. A decay interval of 0.9 Myr between the supernova explosion and incorporation of debris in CAIs is assumed. This figure, which is based on calculations of Meyer et al. after their 2003 paper, was kindly supplied by B. S. Meyer.

is also sufficiently diffuse to allow the planetary orbits to remain unperturbed, is very small [≈0.01]. Kastner and Myers (1994) estimate the probability that a molecular cloud in the present solar neighborhood will be seeded by an AGB star is ≈5%, and the probability that any particular star-forming region in the cloud is seeded is several orders of magnitude smaller.)

A perennial objection to supernova origin has been that it overproduces the nuclide ^{53}Mn, but this assumes the entire substance of the star that exploded was sampled by the solar system. Manganese-53 would form mostly in the core of the supernova, and if the explosion ejects only the outer layers of the star, leaving its core as a neutron star or black hole, the ejecta is depleted rather than enriched in ^{53}Mn. Meyer and Clayton (2000) and Meyer et al. (2003) have used this concept as the basis for supernova nucleosynthesis models that are remarkably successful in accounting for the abundances of short-lived radionuclides in CAIs. Figure 2 shows the relative amounts of five key radionuclides delivered to the protosolar cloud, as a function of the mass cut, for a model in which the initial stellar mass is 25 $M_\odot$ and 0.9 Myr elapses between the stellar explosion and the time when the radionuclides are incorporated in CAIs. For a mass cut of 7 $M_\odot$, the meteoritic concentrations of ^{26}Al and ^{60}Fe are produced, along with 1.5x and 4.2x the meteoritic levels of ^{41}Ca and ^{107}Pd.

An alternative to stellar nucleosynthesis is that the short-lived radionuclides in meteorites may have been created in the solar system, by nuclear reactions between energetic particles (protons, ^{3}He, ^{4}He, ions of other elements) from the young sun and target nuclei in the protosolar disk. The idea has been studied most recently in connection with the x-wind model of protostellar evolution (§ 6.3.2.). A degree of success has been achieved in modeling the abundances of some of the CAI radionuclides in this context by Lee et al. (1998), Gounelle et al. (2001), and Leya et al. (2003).

A recent development has been the discovery by McKeegan et al. (2000) (see also Chaussidon et al., 2002; Marhas et al., 2002b; Srinivasan, 2002; MacPherson et al., 2003) that CAIs contained ^{10}Be, with a half-life of 1.5 Myr, when they formed. The light elements Li, Be, and B are formed only by spallation reactions, which have not been associated with the stellar sources named; so this appears to require formation of CAIs near the sun, where spallation by solar energetic particles could create ^{10}Be and, potentially, other short-lived radionuclides. However Desch et al. (2004) have made the case that the ^{10}Be in CAIs can have been introduced into the solar system in the form of ^{10}Be galactic cosmic rays, instead of by spallation in the early solar system. This would be consistent with the observation of CAIs containing ^{10}Be but not ^{26}Al or ^{41}Ca (MacPherson and Huss, 2001; Marhas et al., 2002b).

There are severe problems with production of radionuclides in the solar system. The target material must be heavily irradiated, near the sun. Irradiation needs to be in free space (Ramaty et al. (1996) argues that irradiation of the nebular gas would overproduce ^{9}Be and ^{6}Li, which can be made by spallation of the CNO atoms abundant in the gas; Leya et al. (2003) do not appear to address this problem.) Irradiation by ^{3}He, which would be more efficient than proton irradiation, overproduces ^{41}Ca relative to ^{26}Al. The greatest difficulty comes in making ^{60}Fe by local energetic particle irradiation. The neutron-rich character of ^{60}Fe places it far from abundant potential target nuclei in the chart of the nuclides, which translates into small cross-sections for energetic particle reactions in the solar system. Srinivasan et al. (1996), Sahijpal et al. (1998), Marhas et al. (2002a), Marhas and Goswami (2003), MacPherson et al. (2003), and Busso et al. (2003), among others, have studied the production of short-lived radionuclides via irradiation by solar energetic particles in the solar system and have concluded that the concept is unworkable, except possibly for the production of ^{10}Be. The present paper concurs with this position, and proceeds from the premise that the radionuclides in CAIs had their source in a presolar stellar source.

4. THE BIMODAL DISTRIBUTION OF ^{26}Al

Discussion in this paper focusses on ^{26}Al, the first very-short-lived extinct radionuclide to be discovered (Lee et al., 1976), the most extensively studied, and the most interesting from the standpoint of early-solar-system chronology and the nuclide's role as a heat source in early small planetesimals. Many CAIs have initial contents of ^{26}Al expressed as (^{26}Al/^{27}Al)$_0$ $\sim 5 \times 10^{-5}$, but lesser values of the ratio are also found (see, e.g., MacPherson et al., 1995), and many CAIs have (^{26}Al/^{27}Al)$_0$ $= 0$ to within error. There is a roughly bimodal distribution of (^{26}Al/^{27}Al)$_0$ among CAIs (Fig. 3; see also Fig. 1

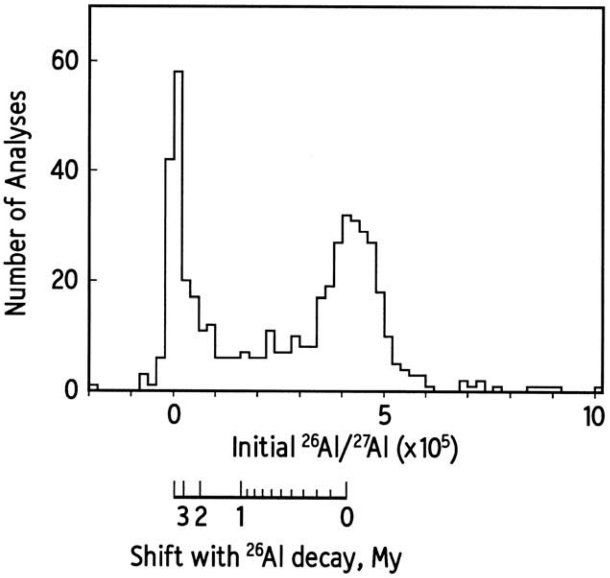

Fig. 3. Histogram of inferred initial $^{26}Al/^{27}Al$ found in 496 analyses of CAIs, from MacPherson et al. (1995). Only analyses of samples in which Al/Mg is high ($Al/Mg > 100$), where the presence of radiogenic ^{26}Mg is particularly unequivocal, are included. The lower abscissa shows how ^{26}Al decay before CAI formation would change $(^{26}Al/^{27}Al)_0$ with time.

of Sahijpal and Goswami, (1998)), but this does not correspond to a bimodal distribution of times; CAIs formed at any time greater than 2 or 3 Myr after the $(^{26}Al/^{27}Al)_0 \sim 5 \times 10^{-5}$ CAIs would all fall in the $(^{26}Al/^{27}Al)_0 \sim 0$ peak. Also, the data are not homogeneous enough to allow the distribution of $(^{26}Al/^{27}Al)_0$ ratios to be accurately drawn. An unknown fraction of the $(^{26}Al/^{27}Al)_0 \sim 0$ entries in Figure 3 are the product of metamorphic resetting. Yurimoto et al. (2000) found values of $(^{26}Al/^{27}Al)_0$ ranging between 3×10^{-5} and 5×10^{-5} within a single anorthite crystal in an Allende CAI, illustrating the potential for selective alteration. CAIs with and without evidence of ^{26}Al occur within millimeters of one another in chondrites.

Leaving aside metamorphic resetting, which is not generally held responsible for all of the variability of $(^{26}Al/^{27}Al)_0$ in Figure 3, two interpretations have been placed on the nonuniform distribution of ^{26}Al in CAIs when they formed (e.g., Podosek and Cassen, 1994). The *chronological interpretation* assumes the solar system received a single dose of ^{26}Al before it formed, presumably from a presolar stellar source, and this was well mixed into solar system material, producing an overall abundance ratio $^{26}Al/^{27}Al \sim 5 \times 10^{-5}$. Some CAIs formed promptly from this material, and they still display the $(^{26}Al/^{27}Al)_0 \sim 5 \times 10^{-5}$ signature; but other CAIs and also chondrules did not form until much later, in some cases after ^{26}Al in the solar system raw material had decayed to indetectability. Allowing for the sensitivity of the instruments that searched unsuccessfully for ^{26}Al in these CAIs, and the half-life of ^{26}Al, this would mean some of them (e.g., Hibonite-ALlende or HAL inclusion of Lee et al., 1979) formed as much as 7 Myr later than the CAIs with $(^{26}Al/^{27}Al)_0 \sim 5 \times 10^{-5}$.

The other interpretation, termed by Podosek and Cassen *radical heterogeneity*, holds that differences in $(^{26}Al/^{27}Al)_0$ among CAIs are not primarily manifestations of age (e.g., Lee et al., 1979; Fahey et al., 1987; Anders et al., 1991). They simply demonstrate that ^{26}Al was not evenly distributed throughout early solar system material, and some CAIs formed from material that did not contain ^{26}Al. The nebula would have been both temporally and spatially heterogeneous during the finite time when newly synthesized nuclides from a presolar stellar source were mixing into the protosolar cloud, but temporal heterogeneity offers a more plausible explanation for the bimodal distribution of ^{26}Al in CAIs than spatial heterogeneity, which turbulence would quickly eliminate in systems as small as the CAI-forming region is likely to have been.

A purely chronological interpretation of all the ^{26}Al data would require at first an intense flurry of CAI-forming activity, when the $(^{26}Al/^{27}Al)_0 \sim 5 \times 10^{-5}$ CAIs were created, and thereafter the continuation of CAI-formation activity at a much lower level for $\approx$7 Myr, with some CAIs of all ages being transported to ~3 AU and kept suspended by turbulence until they were joined by the $(^{26}Al/^{27}Al)_0 = \sim 0$ CAIs; whereupon chondrule formation occurred and the ensemble began to accrete. However, protostellar systems are thought to evolve substantially in their first millions of years (e.g., Gullbring et al., 1998; Calvet et al., 2000), and it is unlikely that the high-temperature environment needed to produce these objects could have persisted for so long.

More plausibly, the bimodal distribution of $(^{26}Al/^{27}Al)_0$ ratios in Figure 3 expresses a temporal heterogeneity of distribution of ^{26}Al in the protosolar cloud during the time when ^{26}Al-bearing supernova debris was mixing into the protosolar cloud (plus some metamorphic resetting). Vanhala and Boss (2000) conclude that such a temporal heterogeneity was possible. D. D. Clayton (private communication) increases the likelihood of temporal heterogeneity by noting that the shock wave which triggered protosolar cloud collapse would have been a precursor wave that propagated through the interstellar medium, and it did not contain freshly synthesized nuclides (as assumed by Vanhala and Boss (2000)); these nuclides arrived later. Sahijpal and Goswami (1998) have suggested that ^{26}Al-free CAIs formed before debris from the triggering supernova reached their site of formation. Early rather than late formation of the ^{26}Al-free hibonite grains described by Fahey et al. (1987) is dictated by those grains' anomalous contents of ^{50}Ti, since late formation would favor homogenization of isotopic compositions in the nebula.

In either case, there is a problem in understanding how early-formed CAIs with $(^{26}Al/^{27}Al)_0 \sim 5 \times 10^{-5}$ could have been stored for as long as 7 Myr before they became mixed with more recently formed ^{26}Al-poor CAIs and chondrules and incorporated in chondrites (solutions are suggested in § 7.3.).

5. BREVITY OF THE PERIOD OF CAI FORMATION

An important constraint on the process of formation of CAIs, the oldest known objects in the solar system, is the observation that most or all of them formed during a very short period of time. If the dispersion of values of $(^{26}Al/^{27}Al)_0$ in the canonical peak near $(^{26}Al/^{27}Al)_0 = 5 \times 10^{-5}$ in Figure 3 is ascribed entirely to differences in times when the CAIs in the peak formed, the range of times is only ~0.5 Myr. To the extent that analytical error, metamorphic disturbance, and less-than-perfect homogenization of protosolar cloud core material contributed to the dispersion of values, the CAIs may have formed in an even shorter period. Hsu et al. (2000) describe a single CAI containing three discrete lithic components whose values of $(^{26}Al/^{27}Al)_0$ span a time interval of ~0.4 Myr.

An astrophysical event or process of similarly brief duration should be sought to associate with the formation of CAIs.

6. ASTROPHYSICAL SETTINGS FOR CAI FORMATION

Four classes of young stellar objects (YSOs), representative of successive stages in the earliest evolution of premain-sequence solar-mass stars, have been identified and studied (Table 2). These stages provide the framework in which the chronology and processes of CAI formation must be understood.

The number of specific environments contemplated for the formation of CAIs and/or mechanisms for their transport has grown from zero 15 yr ago (§ 1.) to about five today. These are briefly reviewed below.

6.1. Formation Near the Radius of the Present Asteroid Belt

This setting was implicit in the early CAI literature, and is still widely assumed for chondrule formation. More recently attention has shifted to the innermost solar nebula for CAI formation, but production near the radius where chondrites accreted remains a possibility. Alexander (2003) studied the formation of CAIs at this radial distance during transient heatings caused by (e.g.) passage of the same type of nebular shock waves employed by Desch and Connolly (2002) to make chondrules, and he found models that approximately account for the range of compositions and degree of stable isotope fractionation of CAIs.

However, the substantial differences between CAIs and chondrules named in § 1., reflecting qualitatively different degrees of thermal processing, must be accounted for. If the chondrule-forming process, operating at 2 to 3 AU, also created CAIs, it is hard to understand why a chemically continuous spectrum of products was not created, and why the CAIs were not size-sorted as chondrules were. No explanation has been offered for these discrepancies.

6.2. Formation in the Triggering Supernova

In Cameron's (2003a, b) model for the nucleosynthetic and triggering supernova, CAIs or their precursors condense in the expanding envelope of the supernova rather than in the solar system, on a time scale short enough for the CAIs to incorporate putative ^{7}Be (half-life, 53 d) that might have been synthesized by the supernova. Cameron (private communication) minimizes differences this might produce between the stable isotope compositions of the CAIs and that of native solar nebula material, both of which derive ultimately from the same parent cloud.

Supernova condensates are generally held to consist of fine dust (e.g., Kozasa et al., 1991; Wooden et al., 1993), which would be inconsistent with the size of the CAI components thought most likely to be condensates (the layered bodies that comprise group II fine-grained inclusions, 5 to 100 μm in dimension; § 7.2.1.), but very little is actually known about the size distribution of supernova condensates. There are several problems with supernova condensation of CAIs. Such an origin cannot be reconciled with models of supernova synthesis like that of Meyer et al. (2003) (§ 3.), since an essential element of the latter is ~0.9 Myr of free decay between the cessation of nucleosynthesis and the time when radionuclides were incorporated in CAIs. The length of this free decay period cannot be much changed by trading it off against the mass cut assumed, because of the differences in half-lives of the radionuclides tracked.

Moreover, the equilibrium condensation of CAIs invoked by Cameron (2003a) in supernova ejecta is rendered problematic by the observation of Clayton (1998) and Clayton et al. (1999) that a supernova's radiation environment would dissociate gas molecules that should be stable, making equilibrium chemistry impossible. Ebel and Grossman (2001) explored the consequences of condensing minerals from a gas of free atoms, and found mineral assemblages dissimilar to those of CAIs. Carbon minerals should condense in expanding supernovae (Clayton et al., 1999), and such minerals (graphite, SiC, diamond) are a component of supernova dust that has been identified in chondrite matrices (see references in Clayton et al., 1999), but they have not been reported in CAIs. Busso et al. (2003) note that CAIs produced in supernova jets should contain correlated abundances of ^{26}Al, ^{41}Ca, and ^{10}Be which are not observed in CAIs.

6.3. Formation Near the Sun

Through the 1980s it was understood that disk material accretes to young stars at an equatorial boundary zone. Inconsistencies of this accretional paradigm were: (1) T Tauri stars have slow angular velocities, much less than the Keplerian velocities at their equators (Königl, 1991), and material feeding into their equators at the Keplerian velocity should spin them up to much higher angular velocities; (2) UV excesses in the spectra of T Tauri stars point to radial accretion velocities of hundreds of km/s, comparable to the free-fall velocity and too great for equatorial accretion (Edwards et al., 1994). Königl proposed a new model in which the accretional flow is controlled by stellar magnetic field lines of kilogauss strength that couple the T Tauri stars to their disks and regulate the angular velocity of the stars. When inward-flowing disk material reaches the radius where stellar and disk angular velocities are equal, it becomes attached to dipole magnetic field lines that channel it to high latitudes on the star, where it impacts at free-fall velocity (Fig. 4). The disk is truncated at the corotation radius because matter inside this radius, constrained to rotate with the magnetic field, would do so at less than the Keplerian velocity, so it would evacuate the region and fall onto the protostar. This concept has gained wide acceptance.

6.3.1. The x-wind model

The x-wind model of Shu et al. (1994, 1996, 1997, 2001) describes one form magnetic accretion might have taken. This body of literature will be referred to collectively as XWA, for x-wind authors. The model is thought to hold for stars of near-solar mass generally, and for the young sun and its accretion disk in particular.

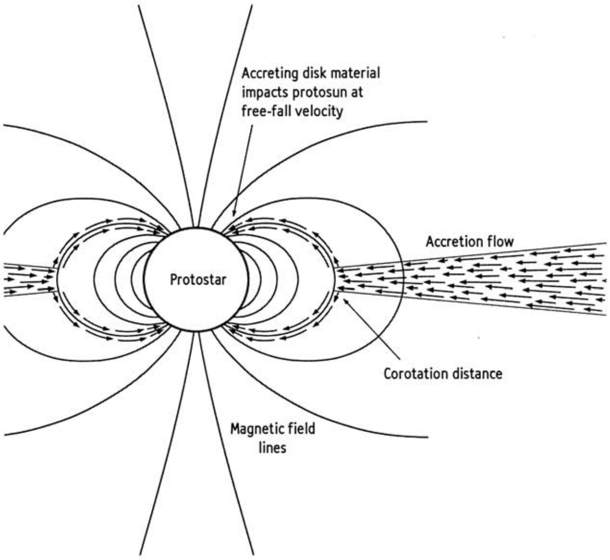

Fig. 4. Schematic diagram showing magnetic accretion of disk material onto a protostar. The concept assumes the corotation radius is coincidentally the same as the radius at which disk gas is heated and thermally ionized enough to become attached to magnetic field lines. At that distance the accretion flow leaves the disk midplane and follows dipole field lines onto the protostar.

In the x-wind model (Fig. 5) "x" refers to the corotation radius (R_x), inside which the disk is truncated. Magnetic field lines which would be regularly spaced in a simple solar dipole field tend to be crowded together in a narrow annular band near R_x, where they pass through the protostellar disk. XWA call this band the x-region, and ascribe a very small radial width to it, comparable to the thickness of the disk. The weaker field lines which otherwise would be threading through the disk outside of the x-region are swept in by disk gases as they accrete to the protostar, which bunches them in the x-region, where they build up strength until they can resist further compaction by the inflowing disk accretion.

In the vicinity of the x-region, inward-flowing disk gas becomes sufficiently thermally ionized for its motion to be constrained to follow magnetic field lines. Thereafter the gas flow follows two distinctly different paths, like the limbs of an "X," with angular momentum balance controlling the partitioning between these paths. XWA estimate that ≈2/3 of the matter flowing through the x-region climbs onto closed stellar field lines which direct it inward to high latitudes on the protostar (the *funnel flow* of Fig. 5), while the other ≈1/3 of the matter follows effectively open field lines that lead away from the star. This escaping partially ionized gas, the x-wind, being constrained to follow outwardly directed field lines that are rotating at the angular velocity of the protostar, is slung away *magnetocentrifugally* from the star.

In the case of the solar system, the gap between the inner edge of the disk and the surface of the protosun during the embedded phase of growth of the sun (when it was a class 0 or I protostar) was roughly 0.04 AU wide. In the outer ~25% of this gap (the *reconnection ring* of Fig. 5), the magnetic field had reversed poloidal components on either side of the midplane, which caused reconnection events and impulsive flares similar to those observed in the modern sun. These flares accelerated coronal ions and electrons to cosmic-ray energies.

The system described was not static, being affected by magnetic cycles analogous as those seen in the modern sun. The time scale of these cycles was much shorter than the time scale on which the rotation rate of the protosun could be changed, so during them the magnetic field geometry changed relative to the position of the accretion disk. It fluctuated about the mean configuration shown in Figure 5, at times bringing the footprint of the x-wind into the reconnection ring.

6.3.2. *CAI formation in the x-wind model*

XWA have attempted to account for the formation of CAIs, and for their content of short-lived radionuclides, in the context

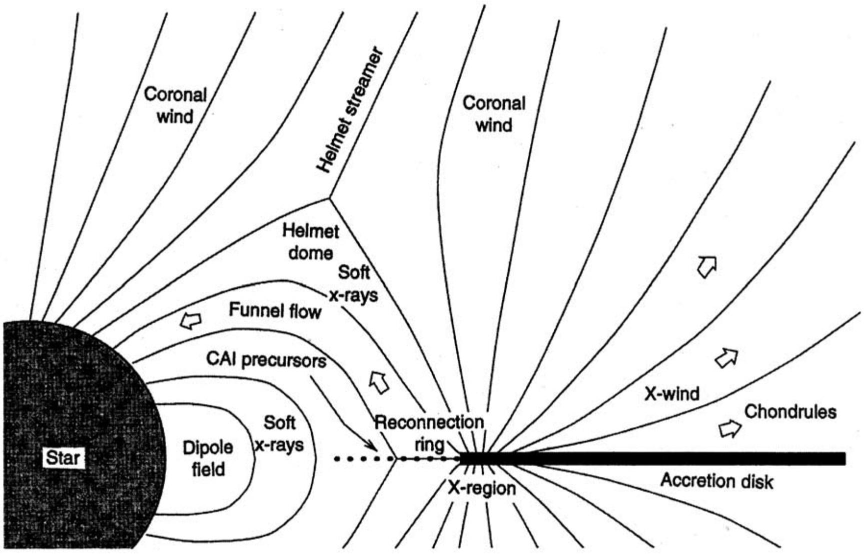

Fig. 5. Schematic diagram of the magnetic field configuration in the x-wind model. From Shu et al. (1997).

of the x-wind model. Though the present paper discounts the concept of radionuclide formation via energetic particle irradiation near the sun (§ 3.), the possibility remains that CAIs were formed in the x-wind environment.

In the x-wind model of Shu et al. (2001) and Gounelle et al. (2001), gas flowing from the x-region to the surface of the protosun (the funnel flow, Fig. 5) swept with it entrained solid condensations. These tended to drop out of the funnel flow and accumulate in Keplerian orbits within the reconnection ring (*CAI precursors* in Fig. 5). Some solids also leaked directly from the inner edge of the disk into the reconnection ring. The gap in the nebular disk that included the reconnection ring contained plasma with a temperature of $\sim 10^7$ K and a mean density of $\sim 3 \times 10^8$ ions cm^{-3}, corresponding to a pressure of $\sim 4 \times 10^{-7}$ bar. Orbital drag against the plasma caused the solid particles to spiral in toward the protosun on a time scale of ~20 yr. Since the plasma in the reconnection ring was optically thin, the local radiation environment was able to keep solid objects in the outer ~25% of the disk gap that were shaded from the sun survivably cool, in spite of their 10^7 K plasma environment.

ProtoCAIs in the reconnection ring were melted and vaporized to varying degrees by the energy periodically deposited in them by large and small solar flares. In addition, solids on the inner edge of the orbiting belt of particles, which were not shadowed from the full protosolar radiation, evaporated, to be replaced by other solid particles as they spiraled in. During lulls between large flares, the vapors produced recondensed onto residual protoCAIs or formed new ones. The protoCAIs were irradiated by high-energy charged particles accelerated by flare events, creating the short-lived radioactivities of § 3. by energetic particle reactions. In this model $(^{26}\text{Al}/^{27}\text{Al})_0 \sim 5 \times 10^{-5}$ describes the steady-state concentration of ^{26}Al that was maintained in the reconnection ring as continuing irradiation of solid matter was balanced by addition of new disk material to the zone; repeated evaporation and recondensation prevented individual protoCAIs from recording differences in history.

The energetic particle models of XWA require the protoCAIs to have layered structures during the period when they were irradiated, which in general they no longer have, consisting of Ca,Al-rich cores surrounded by Ca-poor ferromagnesian mantles ~1 mm thick. The layering is held to have been produced during melting of the protoCAIs, which yielded either immiscible melts of CAI and ferromagnesian composition, or ferromagnesian melt with coexisting solid CAI material. Surface tension effects favored a CAI core inside a ferromagnesian mantle.

Fluctuations in the magnetic state of the young sun caused the position of the x-region to migrate in and out, on a time scale of ~30 yr, relative to the truncated disk. When R_x and the base of the x-wind become relatively small the latter moved into the radial zone where protoCAIs had been processed, picking the latter up and flinging them over the nebular disk. After the protoCAIs left their shaded position on the reconnection ring midplane they were heated by protosolar radiation for a period of days, and during this time ^{26}Al that had been created in their mantles by spallation of Mg isotopes diffused into their refractory cores, after which the relatively volatile ferromagnesian mantles were lost to evaporation. Thereafter, depending upon the CAIs' dimensions and other factors, some of them decoupled from the x-wind and fell into the disk at the radial distances where chondrites were accreting.

6.3.3. *Problems with the x-wind model*

Six problems with the x-wind model are listed. The first concerns a detail of the model that specifically applies to the production of short-lived radionuclides in meteorites by nuclear reactions between solar energetic particles and target nuclei in the disk, a concept that § 3. discounts in any case. The other issues apply more generally to the idea that CAIs were formed near the x-region and transported by the x-wind to the site of chondrite formation.

(1) To understand how protoCAIs developed the structures needed to rationalize the CAIs' contents of ^{26}Al and ^{41}Ca, XWA postulate that melted protoCAIs separated into immiscible liquids which formed aluminous cores and magnesian mantles. However, experimental and theoretical petrologic studies show this would not happen, and if such an object is partly melted the refractory unmelted portion is Mg-rich, not Ca,Al-rich. The core/mantle structures required for protoCAIs by the x-wind spallation model cannot be justified (see Simon et al., 2002).

(2) In the x-wind model protoCAIs were made by vaporization and recondensation in the reconnection ring, but the recondensation was not chemically selective. All gas atoms impinging on a nucleus joined it. Subsequent thermal processing may have melted and partly vaporized the protoCAIs, but recondensation in accordance with the condensation sequence (Grossman, 1972) did not occur. Yet the evidence is compelling that condensation, under equilibrium or near-equilibrium conditions, played a key role in the formation of CAIs. The most unequivocal evidence comes from the set of CAIs classified as group II on the basis of their rare earth element patterns (Tanaka and Masuda, 1973; Mason and Taylor, 1982). These have been found to be depleted in the most refractory of the REE (Lu and Er) relative to other rare earth element (REE). Objects that owe their refractory character to having been partly vaporized—distillation residues—could not have this property. They would be depleted only in the less-refractory REE. Group II CAIs can only have been created by recondensation of the less-refractory REE after they became separated (as by distillation) from the more refractory REE in precursor material having the cosmic proportions of REE (Boynton, 1978).

(3) Condensation in the reconnection ring would have occurred from a gas of nonsolar composition after flares vaporized the rocky solids that had concentrated near the midplane in that region. In the model developed by Shu et al. (2001) O/H would have been $\sim 10^7$x greater than solar where protoCAIs were recondensing, because of concentration there of the O from vaporized silicates (Desch et al., 2004). The chemical and mineralogical properties of CAIs are inconsistent with formation at such a high oxygen fugacity (Krot et al., 2000).

(4) The mechanism by which the x-wind transports CAIs from the reconnection ring to where chondrites are accreting, briefly described by Shu et al. (1996) and Shang et al. (2000), is difficult to accept without reservations. The process is straightforward so far as gas is concerned. An element of partly ionized gas, though it starts with zero rotating-frame velocity at

the root of the field lines that guide the x-wind, is in a position of unstable equilibrium, and any perturbation outward will cause it to be spun away with increasing speed along a field line rotating with the same angular velocity as the protosun, attaining radial velocities >100 km sec^{-1}. However, XWA have not made it clear how solid particles get started in their flight. The particles are not constrained to follow field lines, and they must be lofted upward and blown outward by the moving gas. The problem is that at the root of a field line, where flight begins, the low-density wind available to move particles is still blowing very gently; indeed, the wind velocity is zero at the very root of the field line. How does a particle get started in its flight? In particular, an object as large as the 2.4-cm diameter CAI (~25 g) shown in Figure 33 of Clarke et al. (1970)? Once such an object is far enough along its path to feel a high-velocity wind, the idea becomes easier to accept. But how does it get to that position? Details of the computation of solid-particle motions have not been published by XWA.

(5) Though the concept of winds ejected magnetocentrifugally from disks of young stellar objects is broadly accepted, many, if not most authors hold that the wind emanates from a much wider annulus in the inner disk than the narrow x-region pictured by XWA, and they regard the x-wind model as an end member in a range of possible disk winds (Hartmann, 1998 § 8.10.; Königl and Pudritz, 2000). The wind flux emanating from a broad annular source instead of a narrow ring would be too thin to be able to propel solid particles as large as CAIs to greater radial distances in the disk.

(6) Finally, Muzerolle et al. (2003) have argued that the inner disks of many young stars, from which an x-wind would emanate, are too hot to permit the survival of solid particles.

These problems notwithstanding, the concept of CAI (and possibly chondrule) formation near the sun is a powerful one, and XWA deserve credit for focussing attention on that environment.

6.3.4. *Other models relying on transport of CAIs by bipolar jets*

Huss (1988) and Skinner (1990a, b) proposed that chondrules and CAIs formed in the energetic bipolar outflows associated with young stellar objects. In the x-wind model these outflows or jets are part of the x-wind. The highest-angle x-wind streamlines shown in Figure 5 bend to be perpendicular to the midplane, and the x-wind density is greatest along these vertical streamlines (Shu et al., 2000), making that portion of the wind visible as jets. However, XWA use only low-angle x-wind streamlines to deliver CAIs and chondrules to the site of chondrite formation. Liffman and Brown (1995, 1996), employing a different magnetic model of bipolar jet formation than that of XWA, have pursued the idea that chondrules, and by extension CAIs, were transported by the jets.

In the jet flow model the magnetic structure of the inner nebula is dominated by toroidal fields of opposite sign above and below the midplane. At the midplane, reconnection events create a current sheet of energetic particles, and the processing of chondrules and CAIs occurs in this environment, though Liffman and Brown give no details. If the toroidal fields are configured felicitously, they constitute astrophysical *de Laval nozzles* capable of accelerating a portion of the ionized disk gas from rest at the midplane to velocities of hundreds of km sec^{-1} in a direction perpendicular to the midplane. This is the source of bipolar jets from young stars. Some processed solid or molten objects from the disk are swept up with the jets, and those that are not accelerated to escape velocity fall back. As they lose drag support by the jet plasma, which thins with height, their orbital centrifugal accelerations, no longer balanced by the gravitational acceleration of a nearby sun, spin them outward onto the disk.

The jet flow model is interesting, but it must be considered speculative. It is not supported by observations (beyond the existence of bipolar jets), and only partly by theoretical studies. The efficacy of transport of solid objects from near the disk midplane to altitudes far enough from the sun for the latter's gravitational acceleration to be significantly diminished, so they can begin outward trajectories, has not been studied, and as in the x-wind model this may be a serious problem for the largest CAIs.

7. THE SETTING FOR CAI FORMATION

7.1. Time and Place

If the short-lived radionuclides in meteorites were formed by presolar stellar nucleosynthesis, the setting for CAI formation is strongly constrained by the distribution in them of ^{26}Al, which requires formation of most (or all) of the CAIs in less than 1 Myr (§ 5.). This almost certainly eliminates formation during the T Tauri stage of protostellar evolution, a context in which chondrite formation is often discussed, since that stage lasts for several Myr (Table 2). Formation of CAIs in the triggering supernova (Cameron, 2003a, b) predicts a narrow range of values of $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0$, but § 6.2. reviews the objections that can be raised to this model.

It seems clear that the only sufficiently hot, brief setting for CAI formation that is plausible was created by viscous dissipation near the midplane of the solar nebula, at radial distances less than ~2 AU, during the infall stage of protostellar evolution, while the mass accretion rate to the protosun was still greater than 10^{-6} M yr^{-1} (Bell et al., 2000). The protosun would have been a class 0/early Class I YSO at that time (Table 2).

Understanding how the CAIs were extracted from their hot site of formation is perhaps more challenging than identifying the site. Most of the CAIs created, with or without the gas they were embedded in, had to be moved to a cooler setting fairly abruptly. Abruptness is dictated because CAIs are products of an interrupted condensation sequence. The equilibrium condensation sequence (Grossman, 1972 and later papers on the subject) predicts that after formation of the familiar CAI minerals (Al compounds, melilite, spinel), continued reaction with the residual gas at lower temperatures (<~1400 K) should transform them to an entirely different set of lower-temperature minerals (olivine, pyroxenes, plagioclase), completely replacing the original CAI minerals, if equilibrium is maintained. The CAIs were cooled and/or removed from their reactive environment rapidly enough to prevent this from happening. Convection to the cooler surface layers of the nebula does not offer a satisfactory solution, since the dense CAIs should tend to sink back to the hot interior of the disk. Diffusion radially to cooler environments (§ 7.3.) would be slow, probably slow enough to allow reaction to a low-temperature mineralogy to proceed. The need for rapid extraction of CAIs from the hot inner nebula is a compelling argument for the operation of a powerful wind akin to those proposed by XWA (§ 6.3.1.) and other authors (§ 6.3.4.).

7.2. Processes

Calcium-aluminum-rich inclusions form an exceptionally diverse and complex family of rocks, which Table 1 only hints at. Their complexity is increased by the fact that the distribution of CAI types and sizes, and their abundance, is different in each of the chondrite classes; Table 1 reports only the CV chondrite class, and only one representative of that class (Allende). The discussion of CAI formation that follows cannot be exhaustive, and in fact is very brief.

7.2.1. Fine-grained and fluffy type A CAIs

These categories of CAIs, which comprise the bulk of the Ca,Al-rich inclusions in Allende (≈2% of the meteorite by volume), are the easiest to understand in the nebular context of this paper. They consist of aggregations of small zoned spheroids containing spinel at their cores and mantles of melilite or its replacement products (Wark and Lovering, 1977; MacPherson et al., 1981; Cohen et al., 1983; Holmberg and Hashimoto, 1992). Many of them have group II REE patterns, meaning their constituent spheroids condensed from a gas already depleted in the most refractory REE (Lu and Er) (§ 6.3.3.). (A nodule in which missing ultrarefractory elements are concentrated was found by Hiyagon et al. (2003)). A plausible framework of formative events would be: extreme heating of a volume of gas and dust in the innermost solar nebula; evaporation of all but the most refractory elements; separation and loss of the residual refractory solids; fairly rapid cooling of the gaseous system, so condensation occurred on many nuclei; aggregation of the condensed spheroids into CAIs; removal of the latter from the site of condensation before additional reaction with residual gases could occur; transport outward in the nebula; and later collection of the CAIs by accreting parent bodies followed by differing degrees of alteration of their minerals, especially melilite.

A problem of long standing with this picture is, the equilibrium condensation sequence (Grossman, 1972) predicts unequivocally that melilite should condense before spinel, so spinel should surround melilite cores in the condensed spheroids instead of the reverse, which is what is observed (e.g., Holmberg and Hashimoto, 1992; MacPherson et al., 2002). It is interesting that the Wark-Lovering rims which encase many CAIs (§ 7.2.4.) display the same inverted mineral sequence, which may mean that both structures resulted from the same type of thermal processing.

7.2.2. Amoeboid olivine aggregates

In Allende, amoeboid olivine aggregates (AOAs) are comparable in abundance to the CAIs discussed in § 7.2.1. It is misleading to describe AOAs as CAIs, since they are not greatly enriched in Ca and Al, but they are included in that category because they appear to be aggregates of fine-grained condensates (Grossman and Steele, 1976; Komatsu et al., 2001; Aléon et al., 2002) and are conspicuously different from the host of chondrules that surrounds them. Amoeboid olivine aggregates are strongly depleted in elements more volatile than Si, and in the siderophile elements Fe and Ni (Fig. 6; Komatsu et al., 2001). The refractory component of AOAs consists of included fine-grained CAIs composed of diopside, anorthite, and spinel (Komatsu et al., 2001). Here the required sequence of events was: evaporation of most or all of the dust in affected volumes of the nebula; condensation of small CAIs; continued rapid cooling and recondensation of everything except Fe metal, down to a nominal temperature of ~1300K, including the large volumes of Mg olivine dictated by the equilibrium condensation sequence; aggregation of the condensed matter into contorted (*amoeboid*) masses before further condensation or reaction could occur; outward transport of the AOAs; and their collection by accreting parent bodies followed by differing degrees of alteration of their minerals.

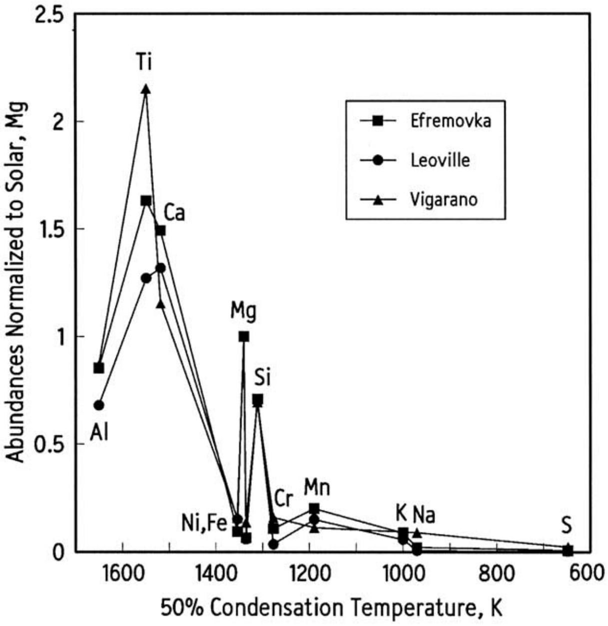

Fig. 6. Elemental abundances in amoeboid olivine aggregates, as a function of condensation temperature. Compositions are from unpublished defocussed-beam microprobe analyses by McSween (1977b); 50% condensation temperatures at 10^{-4} bar are from Wasson (1985). Shown are average compositions of 13 AOAs in Efremovka, 10 in Leoville, and 7 in Vigarano.

The most conspicuous property of AOAs is their abundance of olivine with almost no metal; this is what makes them lighter in color than surrounding chondrules. The equilibrium condensation sequence predicts that at system pressures of 10^{-4} - 10^{-5} bar, Fe metal should condense at very nearly the same temperature as Mg olivine, and at $>10^{-4}$ bar metal condensation should precede that of forsterite (Grossman, 1972). The absence of metal from AOAs probably means their minerals condensed at substantially less than 10^{-5} bar, and aggregation of the AOA minerals occurred soon after condensation of forsterite, before Fe metal had condensed. As in the case of Ca,Al-rich inclusions, rapid extraction from the site of condensation is indicated. The condensation of AOAs was not a process closely related to that of fine-grained CAIs, however, because AOAs are not depleted in the most refractory REE as many of the fine-grained CAIs are (Russell et al., 2003). Rare earth elements in AOAs are essentially unfractionated.

Neither fine-grained or fluffy Type A CAIs, nor AOAs, have been substantially remelted. This creates something of a conundrum: If CAIs generally are older than chondrules, they must already have been present in the nebula when chondrule precursors were melted; if so, why weren't the fine-grained and fluffy Type A CAIs and AOAs melted too?

7.2.3. Other types of CAIs

Other types of CAIs are much less abundant than those discussed in § 7.2.1. and 7.2.2., but are more prominent in the literature because some of them are larger and coarser-grained than the latter, hence more amenable to study. Most type A and B CAIs can be understood as the products of melting, partial evaporation, and isotopic fractionation of preexisting masses of condensed cosmic matter (e.g., Richter et al., 2002). However, detailed study of these CAIs often has revealed complexities that are difficult to understand, which the present paper will not attempt to rationalize.

7.2.4. Wark-lovering rims

Wark and Lovering (1977) noted that most Allende CAIs (not including AOAs) are rimmed by thin monomineralic layers of (from inside to out) spinel, melilite (or its reaction products), and pyroxene, aggregating $\sim$50 μm in thickness. Similar rims enclose the CAIs of other primitive chondrites. Wark and Lovering attributed the rims to late nebular condensation; but Wark and Boynton (2001), after finding REE and other refractory elements in the rims are concentrated by 2 to 7x over their abundances in underlying CAI material yet are present in the same abundance patterns as in the underlying material, argue compellingly that the rims are residues left after impulsive thermal events evaporated surface material from the CAIs. Wark and Boynton estimate a temperature $>$2500K for $<$2 s was required; a longer heat pulse would produce changes inside the CAIs that are not observed. Why this process would produce concentric monomineralic layers is not obvious. Wark and Boynton suggest a process of subsolidus diffusion subsequent to the flash heating, but have not elaborated on the concept.

The requirement to produce such rims in the early solar nebula is very difficult to satisfy, yet the evidence in the rims is too persuasive and too important to ignore. It is not hard to imagine sudden, powerful injections of energy in the early protosun/disk system; the difficulty comes in quenching a stellar radiation field or an enclosing hot gas medium abruptly. The energy source with the most promising time scale is magnetic reconnection flares, which have been invoked by Sonett (1979), Levy and Aracki (1989), Liffman and Brown (1996), Shu et al. (1997), and Feigelson et al. (2002) to explain the melting of early solar system solids. Most of the energy delivered by magnetic reconnection events is in the form of energetic particles, following magnetic field lines, which would be stopped in the outer skin (10–100 μm) of an intercepting CAI, heating the surface layer on a time scale of $<$0.1 s (Levy and Aracki, 1989). (Lee et al. (1998) rely on this surface localization of the irradiation to avoid production of ^{41}Ca in hypothetical layered protoCAIs; § 6.3.2.) Repeated exposure to the directed fluxes of flare particles would be required to account for WL rims that completely envelope CAIs. If this interpretation is correct, it constitutes strong evidence that the CAIs formed near the inner edge of the nebular disk, where magnetic reconnection flares would have occurred frequently.

7.2.5. FUN CAIs

A small subset of CAIs, the FUN CAIs, is characterized by large mass-dependent isotopic fractionations of O, Mg, and Si; nonlinear isotopic anomalies in other elements (Ca, Ti, Sr, Ba, Nd, Sm); absence of the decay products of short-lived radionuclides, other than ^{10}Be; essentially unfractionated REE patterns; and petrographic and chemical properties that are variable and unremarkable (Lee et al., 1979).

It has become increasingly clear that the FUN mass-dependent isotopic fractionations occurred when precursor materials were partially evaporated, and that the high degree of evaporation needed to produce CAI compositions and isotopic fractionations would not significantly fractionate REE patterns (Davis et al., 1991; Wang et al., 2001). The other properties of FUN inclusions appear to require that they are survivors of the earliest CAIs produced, having been formed from cloud core material before it became contaminated by nucleosynthetic products from a triggering supernova (Sahijpal and Goswami, 1998), and having experienced few enough cycles of CAI-forming activity (perhaps only one) that they preserve evidence of the isotopic heterogeneity of the interstellar dust in the protosolar cloud core.

7.3. Transport of CAIs

The chondrites containing CAIs derive from asteroids orbiting at mean distances of 2 to 5 AU. If the CAIs formed in the hot innermost zone of the solar nebula, as this paper argues, some mechanism of transport must have moved them out to 2 to 5 AU, and kept them at that distance for 1 Myr or more until chondrules were formed and the ensemble accreted into chondrite parent bodies, in spite of the fact that gas drag (Weidenschilling, 1977) and the inward accretion flow of the disk gas might be expected to cause them to spiral in to the sun in less than a million years (Wood, 1996).

One such process has been projected by Cuzzi and Davis (2003) and Cuzzi et al. (2003), who argue that turbulent diffusion of solid objects in the nebular gas might have counteracted these inward motions to a degree, moving a small fraction of the early formed CAIs outward and keeping them dispersed in the chondrite-forming zone for millions of years.

The other mechanism that can be pictured is wind transport from the inner disk, as proposed by XWA and Liffman and Brown (1995, 1996) (§ 6.3.). Winds could only move particles outward in the disk, of course, not protect them against gas drag and the accretion flow inward, but it is possible that CAIs thrown far enough out across the nebula would take a million years to be carried back inward as far as the asteroid belt.

A means of protecting CAIs against gas drag and the accretion flow that will not work is the model of Weidenschilling et al. (1998), in which the CAIs were stored in a first generation of planetesimals (>1 km dimension is required to decouple from the motion of embedding gas) which were broken up in time to make the CAIs available for reaccretion along with later-created materials into chondrite parent bodies. This notion is ruled out by the simple observation that the great majority of CAIs are not fragmental in morphology, many having instead fragile amoeboid shapes. Nor can the subrounded forms of many of the CAIs be attributed to melting upon collisional breakup of a planetesimal (because this would have erased the isotopic record of ^{26}Al in them), nor do they have adhesions on their surfaces representing remnants of planetesimal matrix material they might have been embedded in.

Whatever the transport mechanism was, it would have been extremely inefficient, and the CAIs in chondrites should be seen as a minuscule surviving fraction of the original population of inclusions that was created in the early solar system, which may have outweighed the legions of chondrules that would be formed later.

8. CLOSING REMARKS

Several years ago the author expressed the opinion that meteoriticists pay too much attention to the means and too little to the end, i.e., understanding the origin of meteorites; and that insufficient account is taken of the astrophysical context in which it must have occurred. The present study makes a conscious attempt to address this perceived need. After reviewing and critiquing proposed settings for CAI production, underlining the importance of the short time period in which most or all of the CAIs were formed ($<\sim 0.5$ Myr) and the need to promptly extract the CAIs (once formed) from their site of formation, and incorporating the observations and thoughts of many contributors to CAI research, the author assembled what seems to be a reasonably self-consistent framework of understanding. In this, short-lived radionuclides were synthesized in a supernova that triggered collapse of the presolar cloud core; during or immediately after the collapse most or all CAIs were formed in the nebula, near the sun, by the often-discussed processes of evaporation and condensation, during a brief ($<\sim 0.5$ Myr) period when the rate of disk accretion to the sun was still very rapid ($>10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1}$) and viscous dissipation kept the innermost nebular disk very hot; a small fraction of the CAIs created were transported a few AU outward in the disk by disk winds or turbulent diffusion; and there, as much as 2 Myr later, they mixed with chondrules that were being formed by a different process, and the *ensemble* became accreted into chondrite parent bodies.

While many of the constituent parts of this framework have been voiced before, there is value in viewing a comprehensive model all at once, the better to recognize its weak points.

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