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General Observations—Calcium-aluminum-rich inclusions (CAIs) in chondritic meteorites are <100 µm to >2 cm-sized objects consisting mostly of oxides and silicates of calcium, aluminum, titanium, and magnesium [1–4]. The dominant primary minerals are spinel (MgAl2O4), Al-Ti2+–rich calcic pyroxene (CaMgSi2O6−AlSiO3−CaTi2+AlSiO3−CaTi2+Al2O5), melilite solid solution (Ca2MgAl2Si2O8), hibonite (CaMg2Ti2Al2O8), perovskite (CaTiO3), and anorthite (CaAl2Si2O8) (see [5] for detailed mineral chemistry and a complete list of accessories). CAIs exhibit a great diversity of chemical, mineralogical, and textural properties, collectively indicating a wide range of evolutionary histories. Amoeboid Olivine Aggregates (AOAs) are irregularly-shaped objects consisting mostly of olivine but commonly containing within them small CAI nodules whose main constituents are spinel, pyroxene, and anorthite. High-precision U-Pb age measurements indicate that CAIs have ages of 4.57 Ga [7]; CAIs also have the lowest measured initial 87Sr/86Sr ratios of any solar system material [8, 9]. Most CAIs have remarkable isotopic properties: many contain the decay products of short-lived radionuclides, including 56Al, 41Ca, 10Be, and 53Mn [10], that existed at the time of solar system formation: most CAIs and also AOAs show non-mass dependent enrichment (up to several percent relative to terrestrial standards) in 16O over both 17O and 18O [e.g. 11]; and, many CAIs show small degrees of mass-dependent isotopic fractionation in elements such as silicon and magnesium. A peculiar but important subset of CAIs, called FUN inclusions, contain large nuclear (nonradiogenic) neptunium. A peculiar but important subset of CAIs, called many CAIs show small degrees of mass-dependent isotope anomalies (e.g. in 56Ti) of nucleosynthetic origin coupled with large degrees of mass-dependent isotopic fractionation and near absence of former 56Al. CAIs are sorted with respect to both size and type among the various chondrite types [4]. For example: CV3 chondrites contain by far the largest CAIs (1–2 cm), have a virtual monopoly on the prominent Type B [1] CAIs, and most CAIs show the effects of late-stage secondary mineralization that commonly included the introduction of alkalies and oxidized iron; CM chondrites contain small (<1 mm) CAIs that are hibonite-rich and nearly devoid of melilite, a phase common in CAIs in all other (except CI) chondrite types; CAIs in CR and CH chondrites commonly contain grossite (CaAl2O4), a phase that is extremely rare in all other chondrite types.

Reasonable Inferences—The U-Pb age distribution of CAIs is that existed at the time of solar system formation; the canonical model for oxygen isotopes in CAIs was that the 16O-rich signature derived from incompletely evaporated presolar grains, that were incorporated into CAIs, which later equilibrated to varying degrees with 16O-poor nebular gas. The discovery that bona fide presolar grains are
almost never $^{16}$O-rich, together with the finding that likely nebular condensate materials (AOAs, and CAIs having trace element fractionation patterns that can only be the result of condensation) are $^{16}$O-rich, suggest that it was the nebular gas and not the residual solids that were $^{16}$O-rich. The CAI precursors thus condensed from $^{16}$O-rich gas. The source of the $^{16}$O-rich signature is no longer thought to be presolar grains but, instead, the result of mass-independent chemical processes in the solar nebula [15, 16]; the observation that all CAIs and AOAs originally had virtually indistinguishable oxygen isotopic signatures led to the idea that all of these objects formed in a single and restricted nebular environment and were later distributed to the various chondrite-accreting regions. This idea was supported by the discovery [17] that CAIs contained the short-lived radionuclide $^{10}$Be at the time of their formation, because that isotope is generally thought not to be formed in stars but rather was likely formed locally in the solar nebula, near the protosun, as a result of particle bombardment [17] (although production in the interstellar medium is also a possibility [18]). Thus CAIs may all have formed near the sun.

**Unanswered Questions and Problems**—The data noted above have been used to support a model similar to that of [19] in which high temperature objects such as CAIs formed near the protosun and then were entrained in magnetically-driven bipolar outflow (“X-wind”) outwards from the sun. According to this model, much of the outflow was ejected into interstellar space, but some fell material back onto the nebular disk at large distances from the sun and there was available to be accreted into growing solid bodies. However, some observations cannot be obviously reconciled with such a model. (1) Nuclear anomalies in FUN inclusions suggest that they are highly primitive and have not experienced reprocessing sufficient to erase their isotopic signatures, yet their absence of $^{26}$Al would seem to indicate younger ages than “normal” CAIs. Do FUN CAIs really separate objects with separate histories from normal CAIs, or did they just form from isotopically-different material? If the former, multiple processes or multiple locations of formation gave rise to remarkably convergent evolution for these two groups of objects. A critical, needed measurement is establishment of an absolute high-precision radiometric age for one or more FUN CAIs, to establish unequivocally their ages relative to normal CAIs. (2) Sorting of CAIs by size into the various chondrite groups is consistent with the X-wind model, but sorting by CAI type is not. Why are Type B and grossite-rich CAIs so restricted in their occurrences, and why do CMs mostly lack melilitie-rich CAIs even though tiny melilitie-rich CAIs are common in many other chondrite types? For that matter, what are the relationships of the various CAI types to each other—spatial, temporal, and environmental? These are areas in which little work has been done, yet may be critical tests of the X-wind model. (3) It is now reasonably well-established that chondrules began forming 1–2 My after CAI formation yet, when they did so, few CAIs were present in the chondrule-forming region and those that were consisted mainly of pyroxene + spinel + plagioclase. Where were the melilitie-rich and hibonite-rich CAIs during the “chondrule-forming event”, if the X-wind spewed CAIs indiscriminately outward from the sun? How did the CAIs eventually become intimately mixed with chondrules just prior to chondrite accretion?

Finally, here are some miscellaneous thoughts, problems, and unanswered questions. (1) If $^{16}$O and $^{10}$Be both were the products of near-protoplanet processes, might there be some correlation in the magnitudes of the signatures when measured across CAI and chondrule populations as a result of formation at different heliocentric distances? (2) Virtually all CAIs possess thin multilayered rim sequences on their exteriors, known as Wark-Lovering rims. These rims commonly duplicate phases that are present in the CAI interiors, yet clearly formed in a very different and later event. After 30 years of studying CAIs, workers know a lot about the properties of rim sequences yet the nature of the fundamental and ubiquitous process that the rims represent remains poorly understood. Right now few workers are thinking about why or where the rims formed. (3) The major element compositions of CAIs are almost completely decoupled from their trace element fractionation patterns, but this has never been explained. For that matter, an unnoticed but potentially embarrassing feature of trace element fractionation models is that all of the elemental fractionation occurs within a tiny fraction of one degree in temperature; is this realistic in a nebula setting?

**References:**

ALUMINIUM-26 AND OXYGEN ISOTOPIC DISTRIBUTIONS OF CA-AL-RICH INCLUSIONS FROM ACFER 214 CH CHONDRITE.

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Introduction: Exists of a short-lived radionuclide, 26Al, and 16O-rich and 16O-poor reservoirs have been widely believed in the early solar nebula [1,2]. However, correlations between distributions of 26Al abundance and oxygen isotopic reservoirs in the nebula have not been well understood. Abundances of 26Al and oxygen isotopic compositions of fine grained Ca, Al-rich inclusions (FGIs) from Acfer 182 CH chondrite were varied from undetectable level to interference to 25Mg+ peak [7]. A hibonite crystal is sufficient to completely eliminate hydride contamination at a mass resolution power of ~4000 (at 10% valley), respectively. The FGIs were believed direct condensation from surrounding nebula gas [3,5,6], the correlation between 26Al abundance and oxygen isotopic composition may constrain the evolution of oxygen isotopic composition of nebular gas.

Here we report in situ ion microprobe study of Al-Mg system for four grossite-bearing FGIs and two grossite-free FGIs from Acfer 214 in order to investigate the correlation between the 26Al abundance and the oxygen isotopic heterogeneity.

Analytical Methods: The sample used in this study is a polished thin section of Acfer 214 CH chondrite. Back scattered electron images were collected using a JEOL JSM5310LV scanning electron microscope equipped with an Oxford LINK-ISIS energy dispersive X-ray detector. Quantitative elemental analyses of minerals were collected using JEOL JXA-8800 electron microprobe. Magnesium isotopic analyses were performed by the TiTech CAMECA IMS-1270. A 16O primary beam of 5µm in diameter of 10keV was used. Positive secondary ions of the 24Mg, 25Mg, 26Mg and 27Al were analyzed at a mass resolution power of ~4000 (at 10% valley), sufficient to completely eliminate hydride interference to 25Mg+ peak [7]. A hibonite crystal from Madagascar was used for standardization.

Sample Description and The Oxygen Isotopic Compositions: Six FGIs from Acfer 214 analyzed by [8] were selected in this study. Size distribution of these FGIs are 50-100µm in diameter. Grossite-free FGIs were a001 and a008. Grossite-bearing FGIs were a009, a011, a019 and a020. All inclusions have a melilite mantle with Al-diopside thin layer around the core. The core of a001 consists of hibonite and melilite surrounded by spinel grains. The core of a008 consists of small perovskite grains embedded in spinel. The core of a009 and a019 consist of grossite. Small perovskite grains were embedded in the core. The core of a011 consists of grossite, small perovskite and hibonite grains embedded in the melilite surrounded by spinel grains. The core of a020 consists of small grossite laths (typical width <3µm) embedded in melilite mantle.

Oxygen isotopic compositions of individual FGIs are homogeneously distributed among minerals within analytical uncertainty [8]. Oxygen isotopic compositions among FGIs distribute along CCAM line (-22.5‰<δ17O<–5.5‰). It was suggested that individual FGIs crystallized from isotopically distinct reservoirs of different 16O-enrichment.

Results and Discussion: We measured several spots from each FGIs for 25Al-26Mg systematics. The results are plotted in Fig.2. The 25Al-26Mg ratios correspond to mineral species analyzed; melilite (27Al/24Mg < 50), melilite + grossite (50 < 27Al/24Mg < 120), hibonite (27Al/24Mg = 119) and grossite (27Al/24Mg > 120), respectively. Melilite + grossite means that an analytical beam spot (~5µm in diameter) is overlapped for the both phases.

No detectable 26Mg-excesses have been observed for all six FGIs. Oxygen isotopic compositions change without 26Mg-excess, i.e., 16O-enrichment of FGI is not correlated with 26Al-abundance. This result suggests the following constrains for the evolution of protoplanetary disk:

(1) If the Al-Mg system is good chronometer, the formation time of FGIs had continued for three million years or more and heterogeneity of oxygen isotopic composition were existed in the protoplanetary disk through the duration.

(2) If the Al-Mg system is not chronometer, spatial heterogeneities of 26Al and oxygen isotopes existed independently in the protoplanetary disk and there are no correlation for their distribution.

(3) If the 26Al-absent FGIs formed before 26Al injection [9], oxygen isotopic heterogeneity already existed with protoplanetary disk before the injection.

Fig. 1 Oxygen isotopic compositions of Acfer 214. Each plot represents a typical value of individual FGI. TF and CCAM represent terrestrial fractionation line and carbonaceous chondrite anhydrous mineral line, respectively. The error bars are $\pm 2\sigma_{\text{mean}}$. Data were adopted from [8].

Fig. 2 $^{26}\text{Al}^{/}/^{24}\text{Mg}$ evolution diagram for melilite grains ($^{27}\text{Al}^{/}/^{24}\text{Mg}<50$), melilite + grossite ($50<^{27}\text{Al}^{/}/^{24}\text{Mg}<120$), hibonite ($^{27}\text{Al}^{/}/^{24}\text{Mg} = 119$) and grossite ($^{27}\text{Al}^{/}/^{24}\text{Mg} > 120$) from Acfer 214. Symbol represents individual FGIs as shown in Fig. 1. The error bars are $\pm 2\sigma_{\text{mean}}$. 
THE TRAPPING EFFICIENCY OF HELIUM IN FULLERENE AND ITS IMPLICATION TO THE PLANETARY SCIENCE. J. Matsuda and H. Omori, Department of Earth and Space Science, Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan. E-mail: matsuda@ess.sci.osaka-u.ac.jp

Introduction: Fullerene was believed to be widely distributed in the universe since its discovery [1], but have not been detected in meteorite for a long time [2]. Becker et al. [3, 4] reported the presence of fullerenes in Allende. The concentration of fullerene is as high as about 100ppb in some fraction of Allende. Heymann [5] insisted that fullerene could be one of host phases of trapped noble gases in carbonaceous chondrites. To think of the cage structure of fullerene, it is very reasonable to have an idea that fullerene would be one of noble gas carries in meteorites. In fact, Becker et al. [6] reported that both the Allende and Murchison fullerenes and the KTB fullerenes contained trapped noble gases.

In this study, we measured the He concentration in fullerene which was artificially produced in the He atmosphere, and have determined the trapping efficiency of He at the synthesis whether fullerene could be a noble carrier or not in the universe.

Sample and Experiment: The fullerene used in this study is a commercial one which was produced under the He atmosphere with the so-called “contact arc method”. The synthetic condition is well known. The pressure of the He atmosphere was 150±3 Torr. The applied voltage was 21±1V and the current was 70-100A. The He concentrations and He isotopic ratios of two samples (MTRC60-1 and MTRC60-2) of this fullerene were measured by the mass spectrometer VG5400 installed in Osaka University. The experimental details in noble gas measurements were in our previous studies [7, 8]. The obtained He concentrations in MTRC60-1 and MTRC60-2 were 8.9x10⁻⁶cm³STP/g and 8.4x10⁻⁶cm³STP/g, respectively.

Comparison of trapping efficiency of noble gases with that of CVD diamonds and its implication to the planetary science: The obtained trapping efficiencies of He for fullerene is very low, especially when we compared it with that for the Chemical Vapor Deposition (CVD) diamond. Matsuda et al. [7] synthesized CVD diamond using microwave (MWCVD) and hot filament (HFCVD) ionization of gases. It was remarkable that there was a strong difference between noble gas concentrations in two kinds of CVD diamonds: large amounts of noble gases were trapped in the MWCVD diamonds but not in the HFCVD diamonds. Furthermore, the heavy noble gases were highly fractionated compared with those in the ambient noble gases. Thus the trapping efficiency of He in the MWCVD diamonds is the smallest among those of all noble gases. The calculated trapping efficiency of He in MWCVD diamond is (3.6-4.8)x10⁻³cm³STP/g/Torr [7], which is about 5 orders of magnitude higher that that of fullerene. The trapping efficiency of He in HFCVD is only given as an upper limit (<3.5x10⁻⁴cm³STP/g/Torr), which makes it difficult to make a comparison with that of fullerene.

From this study, we can conclude that fullerene is not a noble gas carrier in the universe in spite of its cage structure.

**Constraints on the Origin of Chondritic Components from Oxygen Isotopic Compositions.**

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**Introduction:** At the time of Apollo, or more precisely, before Allende, cosmochemical evidence suggested that the inner solar system formed by condensation from a gaseous nebula that was at one time sufficiently hot to completely vaporize and homogenize essentially all elements. The discovery [1] of large magnitude isotopic anomalies in oxygen in the refractory (“anhydrous”) minerals of the Allende meteorite radically changed this view. Following this discovery, a large number of isotopic anomalies (e.g., in Ca, Ti, etc.) have been uncovered which demonstrate that high temperature processing was not able to erase all memory of initial conditions. Indeed, individual microscopic rocks that condensed in mass outflows from dying stars prior to the Sun’s birth have been recognized on the basis of exotic isotopic signatures; ironically, essentially none of these “presolar grains” are the carriers of the solar system’s premier isotope anomaly.

Oxygen is the third most abundant element in the solar system, and as such it plays a dominant role in the chemistry of both gaseous and condensed phases for extended periods of nebular evolution. We now know that the rocky bodies of our solar system are characterized by oxygen isotopic heterogeneities on all spatial scales, from microns to planets. These heterogeneities are predominantly due to the admixture of greater or lesser amounts of $^{16}$O compared to the minor isotopes, $^{17}$O and $^{18}$O, whose relative abundances remain nearly constant. Despite increasingly detailed investigation for 3 decades, understanding of the ultimate origins of the oxygen isotopic anomalies in solar system materials has been elusive and remains as arguably the most important outstanding problem in cosmochemistry.

Because the most extreme differences in oxygen isotope compositions are observed in refractory minerals, the CAIs and chondrules of primitive meteorites, the distribution of the oxygen anomaly is intimately associated with high temperature processing in the solar nebula. In this review, we explore what constraints oxygen isotope abundances can place on high temperature processing of solar nebula components, the relative roles of gas and dust fractionation and mixing, and the genetic relationships between different chondritic components. Finally, we offer some speculations regarding possible chemical origins for generating the oxygen anomaly.

**Oxygen Isotopic Compositions of Chondritic Components:** All meteorites and known planetary materials can be classified by their compositions in oxygen isotope space on the 3-isotope diagram [2]. These groupings are thought to be indicative of common origins from single asteroids or groups of related asteroids, ultimately reflecting similar source materials and degrees of thermal and chemical processing on their respective “parent bodies”. However, the components of undifferentiated meteorites (i.e., chondrites) have not been homogenized by such geologic activity and thus can serve as probes of nebular “reservoirs” of starting materials and thermochemical processes that may have altered initial isotopic abundances of oxygen. Interpretation of reservoir mixing (or unmixing) in terms of spatial heterogeneity and/or temporal evolution of the accretion disk is intimately related to understanding the genetic relationships and high temperature processing of distinct chondritic components. In this context it is important to emphasize that the average solar system oxygen isotope composition, as for example represented by the Sun, is essentially unconstrained by direct measurement.

**Calcium-Aluminum-rich Inclusions (CAIs).** The CAIs generally show the largest deviations from planetary compositions (represented by Earth, Moon, Mars and bulk asteroids) and the most prevalent isotope heterogeneities within individual objects. Thus, many CAIs – particularly the larger, more mineralogically complex varieties found preferentially in the CV chondrites – show up to ~5% excesses of $^{16}$O in some primary minerals (e.g., spinel and pyroxene) but also have major minerals (e.g., melilite, anorthite) that have apparently exchanged oxygen isotopes with a reservoir external to the CAI. This exchange occurred following original igneous formation of the CAI; in some cases, correlated petrographic and isotopic evidence suggests this exchange occurred at lower temperatures, probably mediated by aqueous fluids, whereas in other cases, high temperature processes, including partial melting and/or gas-solid diffusional exchange, are indicated. The former almost certainly occurred in an asteroidal regolith, but the latter can only be nebular. In any case, these heterogeneities indicate a partial approach to equilibrium between refractory dust and a larger reservoir consisting primarily of volatile species (e.g., H$_2$O) that is relatively $^{16}$O-poor. Whether that volatile reservoir represents solar composition is an open question.
Most of the smaller CAIs, found in carbonaceous chondrites (other than CV) and also in enstatite chondrites, are uniformly $^{16}\text{O}$-rich and do not show evidence of isotopic exchange. Many of these CAIs have distinctive, more refractory mineralogy (e.g., hibonite-rich) than the better-studied, larger CAIs from CV chondrites. They seem to have had simpler thermal histories than the CV CAIs and, specifically, have not interacted at high temperature with the isotopically heavy ($^{18}\text{O}$-poor) volatile reservoir that characterizes most chondritic materials (see below).

Evidence for a volatile reservoir that is $^{16}\text{O}$-rich is provided by analyses of phases that appear to be direct condensates from a nebular gas. This includes both fine-grained CAIs whose mineralogy, texture, and trace element abundance patterns indicate that they have not been substantially melted following gas-solid condensation, as well as rims of olivine-rich dust surrounding igneous CAIs. Other types of refractory objects, termed Amoeboid Olivine Aggregates (AOAs) are isotopically identical to these rims and are thought to have formed by condensation from a $^{16}\text{O}$-rich gas.

**Chondrules.** Like CAIs, chondrules also exhibit oxygen isotope variability, however it is typically much less extreme. Remarkably, and unlike CAIs, chondrules have a general isotopic affinity for the meteorite in which they are hosted. That is, chondrules from various chondrite groups generally have oxygen isotopic compositions that are related to that of the fine-grained matrix minerals in those meteorites. In some cases, parent body fluids have clearly controlled the extent of isotopic equilibrium between chondrules and matrix according to the isotopic contrast between the accreted dust and ices as well as reaction parameters such as fluid-flow, temperature, and time. Despite this overprinting, there is still a recognizable relationship between chondrules and matrix (or whole-rock), such that it seems probable that most chondrules acquired their pre-accretionary isotopic compositions by interaction (i.e., melting) within a gaseous reservoir that was characteristic of a particular time and place in the solar nebula, probably the same environment in which those chondrite groups accreted.

If this interpretation is correct, then oxygen isotope compositions can be diagnostic of provenance, at least for high-temperature processing of refractory materials. Following this logic, CAIs which have common isotopic compositions irrespective of whether they are hosted by carbonaceous, ordinary, or enstatite chondrites, have been interpreted as xenoliths. Stated another way, most CAIs have not been processed extensively at high temperature in the same environment as typical chondrules. That these objects accreted together into a common asteroidal parent body is therefore suggestive of large scale spatial heterogeneities and radial transport in the accretion disk, moreso than it is of temporal evolution of the oxygen isotope composition of the asteroid belt.

**Exceptions and caveats.** There are several important exceptions to the generalities outlined above which indicate complexity in oxygen isotope distributions. For example, some CAIs formed with uniformly $^{16}\text{O}$-poor compositions. Likewise, large $^{16}\text{O}$-enrichments have been found in a few chondrules, exceeding even the most extreme values observed in CAIs and AOAs. This is best understood as reflecting a common source for some of the dust component in the early solar system, but much more extensive processing (multiple melting) of the great majority of chondrules in the accretion regions of chondrites. The inferred absence of CAIs and AOAs from these sites during chondrule formation, and the mineralogic type-sorting of CAIs in different meteorite groups, are deep mysteries that must be addressed in the context of nebular chronology and dynamics. Finally, in comparing oxygen isotopes in different materials, it is important to appreciate that studies of matrix at the proper spatial scale are still in their infancy.

**Source of the Oxygen Anomaly:** Because the isotopic variations are (possibly exclusively) in the relative abundance of only $^{16}\text{O}$ (e.g, slope 1.0 line on the 3-isotope plot), and considering the primary nature of the $^{16}\text{O}$ isotope, it was originally expected that source of the oxygen anomaly was nucleosynthetically distinct dust grains that were incompletely mixed into the early solar system. That explanation, while not disproved, has fallen out of favor because of the distinct lack of correlation of oxygen isotope compositions with demonstrable nucleogenetic anomalies in refractory cations and the apparent absence of suitable presolar ‘carrier’ grains. Current hypotheses center on the overabundance of the $^{16}\text{O}$ isotope, relative to $^{17}\text{O}$ and $^{18}\text{O}$, and the possible role of either symmetry-dependent non-Boltzmann kinetics ($\eta$-effect) or isotopic self-shielding during UV-photochemistry either close to the nascent Sun (“X-point”) or at the surfaces of the protoplanetary disk, or even in the cold molecular cloud phase prior to nebula collapse to an accretion disk. Most of the chemical mechanisms invoke formation of isotopically heavy ($^{18}\text{O}$-depleted) water and its fractionation from other gaseous and/or rock-forming species; condensation of ices and reaction/transport on grain surfaces play crucial roles in achieving the fractionation. A current challenge is to incorporate production of non-mass dependent isotope effects and preservation in meteoritic materials into consistent models of disk evolution.

ROLE OF PLANETARY IMPACTS IN THERMAL PROCESSING OF CHONDRITE MATERIALS. H. J. Melosh1, P. Cassen2, D. Sears3 and G. Lugmair4, 1Lunar and Planetary Lab (University of Arizona, Tucson AZ 85721 jmelosh@lpl.arizona.edu), 2SETI Institute (46999 Dunlap Rd. Miramonte, CA 93641 pcassen@mail.arc.nasa.gov) 3Cosmochemistry Group (Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, AR 72701). 4Max Planck-Institute for Chemistry, Cosmochemistry, (P. O. 3060, 55020 Mainz, Germany).

Introduction: The origin of chondrules remains one of the central unsolved problems of meteorite science. Theories purporting to explain their origin abound, but consensus on any one theory is still elusive. A major complication is that chondrules are highly diverse and can be classified in several different groups. The most primitive “chondrites” apparently lack chondrules altogether. Everyone agrees that these ubiquitous structures record a history of sudden melting followed by rapid quenching, but the source of the heat, whether it is nebular electrical discharges, shock waves or something else, has not been established. One early suggestion for the origin of chondrules was impact melting [1]. Glassy, chondrule-like spherules are common in the lunar soil [2], where they are attributed to distal impact ejecta [3]. Microtektites, microkrystites [4] and highly altered spherules occur as distal impact ejecta in many parts of the Earth [5]. Thick beds of these objects in Archean rocks of Australia and South Africa closely resemble the texture of chondritic meteorites, although the terrestrial spherule beds are now highly altered from their original composition.

Can Impacts Make Chondrules? In terrestrial and lunar experience, impacts seem to be uniquely capable of producing small liquid droplets that cool to form glass or crystalline spherules [6]. However, impacts also produce a much larger volume of fragmented rock debris. Only the sorting provided by distance can separate the low volume, but fast-moving, melt and vapor fraction from the much larger volume of slow-moving rock debris in normal impacts. Impacts on asteroidal-size bodies cannot appeal to this separation mechanism because of their low escape velocity, so such impacts must inevitably eject far more fragmental material than molten droplets. Impacts on asteroidal-size bodies cannot appeal to this separation mechanism because of their low escape velocity, so such impacts must inevitably eject far more fragmental material than molten droplets. Some fragmental material does, indeed, occur in several classes of chondrules, but it is usually not the dominant component. Unless one makes the apparently extreme assumption of liquid target bodies (Sanders, this conference), it seems difficult to make a plausible case for an impact origin of chondrules, and so this mechanism has fallen out of mainstream consideration (but, in the light of recent data on 26Al [7], perhaps this possibility should not be dismissed).

Nevertheless, it seems worthwhile to examine once again this mechanism in the light of modern theories of planetary accumulation and recent spacecraft data. In particular, current accretion models [8] suggest that the present mass in the asteroid belt may be only about 0.01% of its original mass. Most of that mass may have been in the form of lunar to Mars-sized protoplanets whose mutual collisions could have ejected large masses of material (In contrast, the most numerous bodies were much smaller. The predominance of mass is due to the approximate 1/diameter 2 cumulative number distribution). In this case, the substantial escape velocities of such large bodies may have served as the filter that separated melt/vapor from fragmental material, just as distance sorts molten tektites from impact breccias on the present Earth.

Figure 1. Shock pressure versus impact velocity for Forsterite [9]. Fully dense Forsterite is quite refractory. However, if the target is porous, melting and vaporization may take place at considerably lower pressures [10] and escape velocity.

Giant Impacts: The basic physics of a planetary scale impact is the same as a small-scale asteroidal or even laboratory impact. The principal difference is the escape velocity of the target. Typical asteroidal escape velocities are a few m/sec, whereas the escape velocity of a moon-size body is about 2.5 km/sec. In such an impact only the fastest material can escape from the surface into space. Although the discovery of Martian meteorites has highlighted the process by which a small amount of solid material can escape a planetary-size body without serious shock damage
[11, 12], the bulk of the ejected material is subject to shock pressures large enough to melt or vaporize the rock (Figure 1). Slower-moving solid ejecta falls back onto the surface of the parent planet—which eventually either suffers a catastrophic collision that entirely disrupts it or, more likely, is ejected from the solar system by interactions with the newly-formed Jupiter. The ejected melt and vapor then condense and may accumulate on the surface of smaller bodies to form the progenitors of the chondritic meteorites.

The relative impact velocity during the early phases of accretion must be low enough that impacts do not eject more than the impactor’s own mass. However, during the later stages when relative velocities are increased by gravitational interactions with both Jupiter and other planetesimals, impact velocities increase and net accretion may give way to net erosion. For the present Moon, this transition occurs at about 10 km/sec [13], assuming vertical impacts. It is possible that oblique impacts may decrease this limit, but the necessary systematic computations have not yet been done. Oblique impacts also tend to enhance melting and vaporization by the process of jetting [14], a process implicated in current models of the moon’s origin by giant impact [15].

Impact melting and vaporization: When an impact of any size occurs the collision results in a shock wave that compresses, then releases material from high pressure. The compression process is irreversible and, if strong enough, may cause a change of state of originally solid material to liquid or vapor. Studies of the equation of state of olivine, a major constituent of most chondrules, indicate that the immediate effect of a shock is to transform olivine to a supercritical fluid at high pressure and temperature. At velocities high enough to initiate melting or vaporization the release path is generally on the melt side of the critical point, so the expanding hot fluid essentially boils and disperses into droplets (Figure 2).

Because of the relatively large impact velocities necessary to cause both planetary erosion and substantial melting, chondrules formation by this impact mechanism must involve large bodies whose escape velocity regulates the average impact velocity of the planetesimal swarm [17]: As stated by many previous authors, impacts on small bodies produced much more fragmented rock than melt. Besides separating melt and clastic fragments, large body impact also have the advantage that large impacts produce the bulk of the melt, just because large bodies dominate the mass distribution. However, if chondrules do originate in large body impacts, a number of consequences follow: 1) Chondrule production must have occurred late in the accretion process, since the large bodies on which they originated take time to grow. This prediction accords well with the generally low $^{26}$Al in chondrules [7]. 2) The accretion process must have allowed the formation of large, undifferentiated bodies. 3) Because impact melting and ejection requires rare, large collisions, the age distribution of chondrules should show several discrete spikes, each dating a single large collision. Future research must decide whether these predictions either support or rule out a chondrules origin by large impacts.

References:

FORMATION OF THE MELILITE MANTLE OF THE TYPE B1 CAIs: FLASH HEATING OR TRANSPORT? R. A. Mendybaev\(^1,2\), F. M. Richter\(^1,2\) and A. M. Davis\(^1,2,3\), \(^1\)Chicago Center for Cosmochemistry, \(^2\)Department of the Geophysical Sciences, \(^3\)Enrico Fermi Institute, University of Chicago, Chicago, IL, 60637; (ramendyb@uchicago.edu).

**Introduction:** Type B1 Ca-Al-rich inclusions are concentrically zoned objects and have relatively thick outer melilite mantle, while B2s are characterized by relatively uniform distribution of minerals. Despite intensive study, the origin of the diagnostic melilite mantle of the B1s remains unclear. It has been proposed that the melilite mantle could have been formed by fast inward fractional crystallization from completely molten droplets [1] or it was crystallized from a second liquid added to the preexisting core at the later stage of the evolution [2]. However, it is unclear why Type B2 CAIs which have similar size and bulk chemical composition to the B1s, have no melilite mantle. Recently we proposed [3] that formation of melilite mantles in B1s and their absence in B2s might be due to differences in the evaporation rates of Mg and Si from the surface of the partially molten droplets relative to their diffusion rates in the melt. It was expected that cooling of partially molten droplets of CAI-like compositions under relatively oxidizing conditions, when evaporation rates are comparable to or slower than the diffusion rates, would result in Type B2-like textures. On the other hand, cooling under extremely reducing conditions when evaporation rates are significantly faster then the diffusion rates would result in depletion of the outer parts of the droplets in Mg and Si and thus melilite would crystallize there first followed by its crystallization in the central parts as droplet cools. Such variations in melilite composition are in fact typical for Type B1 CAIs. For example, melilite from the outer mantle of TS23 is significantly more gehlenitic (Åk28±9) than melilite from the core of the inclusion (Åk51±13) [7]. Formation of TS23 by evaporation of a molten droplet with initial composition of δ [8] requires the loss of ~30% MgO and SiO\(_2\).

**Experimental results and discussion:** First we experimentally determined crystallization temperature of melilite as a function of melt composition. By combining the results of our experiments with those of earlier experiments [5-7], we find a simple systematic relationship for the crystallization temperature of melilite and its composition as a function of melt composition expressed as in term of the molar ratio \((\text{MgO}+\text{SiO}_2)/(\text{Al}_2\text{O}_3+\text{CaO})\). The relationship is shown in Fig. 1. The Fig. 1 clearly illustrates that within the range of \((\text{MgO}+\text{SiO}_2)/(\text{Al}_2\text{O}_3+\text{CaO})\) ratio from 0.4 to 1.2 typical for natural CAIs, the melilite crystallization temperature increases from 1230ºC to 1530ºC as melt becomes depleted in volatile components MgO and SiO\(_2\) with an associated change in melilite composition from Åk65 to Åk1. The fact that the crystallization temperature of melilite and its Åk content depend on bulk composition of the melt from which it crystallizes is well known, but plotted in the manner shown in Fig. 1 it provides a simple quantitative parameterization that can be used to estimate the crystallization temperature of melilite and its composition for a broad range of CAI-like melts. Also shown in Fig. 1 are the crystallization temperature and composition of melilite expected from the thermodynamic calculations [8]. The calculated results are in reasonably good agreement with the experimental data in relatively MgO- and SiO\(_2\)-poor compositions, but for MgO- and SiO\(_2\)-rich melts the differences between the measured and calculated melilite crystallization temperatures and its composition becomes as large as ~200ºC and ΔÅk~40. This suggests that the parameterization of the thermodynamic properties of the melilite used in [8] needs further adjustments.
which would result in enrichment of the residual liquid in heavy Mg and Si isotopes of about 5‰ and 3‰, correspondingly.

Fig. 2 illustrates three possible scenarios for evaporation of initial melt of δ composition in the solar nebular environment. First represents fast heating event, such as a flash heating by shock waves, to ~1500º followed by relatively slow cooling (<50ºC/hr) in H₂-rich environments (P H₂ > 10⁻⁴ bar). Second scenario includes fast heating to ~1450º followed by isothermal evaporation. Third possible pass illustrates slow heating to ~1450º followed by slow cooling in H₂-rich gas. The last scenario mimics radial transport of droplets toward the inner (hot) parts of the solar nebula followed by its return in the colder parts of the solar nebula. All three possible scenarios was modeled experimentally using synthetic samples 2.5 -3.5 mm in size with the composition close to δ. The experiments were conducted in flowing H₂ or H₂-CO₂ gas mixtures with oxygen fugacities varying from relatively oxidizing conditions with log fO₂~IW to extremely reducing with log fO₂~IW-10 (gas of solar composition is characterized by log fO₂~IW-6). The experimental technique and starting materials were the same as described in [4].

Relatively thick (0.2 -0.5 mm) melilite mantle, such as shown in Fig. 3, was observed in all runs conducted at log fO₂≤IW-6. Unlike natural CAIs, melilite formed in the isothermal experiments was reversely zoned with Mg-rich central parts of the grains and Mg-poor in the outside [4]. Normally zoned melilite was observed in all experiments in which the cooling was involved. Fig. 3 shows a continuous melilite mantle formed around the droplet heated in H₂ from 1200ºC to 1400ºC at 5ºC/hr followed by immediate cooling to 1250ºC at the same rate. Composition of the melilite in the mantle varies from Åk20-25 in the outermost parts of the mantle to Åk55-60 in the innermost parts. More gehlenitic melilite was observed when samples were exposed to higher temperatures. Melilite mantle was also observed when sample was heated from 1200ºC at 5ºC/hr in hydrogen and quenched when temperature reached 1400ºC, but the mantle was only ~5 µm thick. This melilite could have served as nucleation sites when temperature started to lower. So far we found no textural or compositional differences between run products which were simply cooled from high temperatures and the samples which were slowly brought to high temperatures and then cooled. This suggest that high temperature events such as flash heating by the shock waves and/or radial transport of the material in the solar nebula could result in formation melilite mantle of Type B1 CAIs.

Summary: 1) We find a simple systematic relationship between the crystallization temperatures of melilite and melt composition. 2) We experimentally showed that melilite might crystallize not only by cooling from above the liquidus temperatures, but it also can be formed during the melting process in hydrogen-rich environments. 3) Melilite mantle can be formed by isothermal evaporation of partially molten droplets, or by slow heating or cooling in hydrogen-rich environments. 4) We found no textural or chemical differences in run products with different pre-cooling history. This allows us to suggest that both rapid heating followed by slow cooling, as associated with shock waves, and slow heating followed by slow cooling which might associate with radial or latitudinal transport of matter in the solar nebula could be responsible for the formation of Type B1 CAIs.

THE IODINE-XENON SYSTEM IN OUTER AND INNER PORTIONS OF CHONDRULES FROM THE UNNAMED ANTARCTIC LL3 CHONDRITE.

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Introduction: Alteration processes may affect I-Xe system in unequilibrated ordinary chondrites. It was shown that at the edges, where a contribution is made by matrix material around the rim, $^{129}_{\alpha}$Xe/$^{128}$Xe values are generally lower (later apparent ages) than in the main chondrule mass [1]. In this work we attempted to investigate whether thermal metamorphism can affect the I-Xe system in LL3 chondrites which did not experienced aqueous alteration.

Samples: Six chondrules from the Unnamed Antarctic meteorite L3/LL3 [2] were used in this study. Typically chondrules from this meteorite have varying grain sizes and generally not mineralogically similar to each other [3]. For this reason it was not meaningful to directly compare radial Xe profiles, using laser microextraction, as was done in the case of finer grained chondrules from the Sahara 97096 EH3 chondrite [1]. Instead, we compare the average concentration of major Xe components in three original and three chondrules from which rim material (with matrix intergrowth) has been removed. All six chondrules were irradiated by thermal neutrons, with the Xe subsequently analyzed by ion-counting mass-spectrometry [4] (I-Xe chronology for these chondrules is reported elsewhere [5]).

Results and discussion: We consider three xenon components: trapped $^{132}$Xe (after correction for fission Xe), radiogenic $^{129}$Xe (a product of $^{129}$I decay) and neutron-induced $^{128}$Xe (a proxy for $^{127}$I). The first two components are shown in Fig. 1. Large error bars (2σ) reflect large variation of Xe concentrations among different chondrules, especially for the non-abraded chondrules. However, the average values of Xe concentration are different with both trapped $^{132}$Xe and radiogenic $^{129}$Xe systematically higher in the abraded chondrules, suggesting removal of a more Xe-poor matrix. The correlation between trapped $^{132}$Xe and radiogenic $^{129}$Xe (iodine) suggest a common incorporation mechanism for these two volatile elements.

Figure 2 shows the relationship between the correlated ant total radiogenic $^{128}$Xe, illustrating the degree of $^{129}$Xe retention.
Here, once again, despite the large error bars, the abraded chondrules appear to differ from the non-abraded chondrules. The abraded chondrules have smaller spread in n-capture $^{128}$Xe, indicating a more uniform iodine concentration, and a higher fraction of $^{128}$Xe correlated with radiogenic $^{129}$Xe, indicating better retention of iodine. The inner parts of the chondrule seem to preserve radiogenic $^{129}$Xe better than the outer parts which perhaps includes some intergrown matrix.

**Conclusion:** These results suggest that the I-Xe system in the inner parts of these chondrules seem to be more robust during thermal metamorphism in chondrules from LL3 chondrites than the outer parts, that the presence of chondrule rims may distort I-Xe chronology.

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NUCLEOSYNTHESIS OF SHORT-LIVED RADIOACTIVITIES IN MASSIVE STARS. B. S. Meyer\textsuperscript{1}, Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-0978, USA (mbradle@clemson.edu).

\textbf{Introduction:} A leading model for the source of many of the short-lived radioactivities in the early solar nebula is direct incorporation from a massive star \cite{1}. A recent and promising incarnation of this model includes an “injection mass cut”, which is a boundary between the stellar ejecta that become incorporated into the solar cloud and those ejecta that do not \cite{2-4}. This model also includes a delay time between ejection from the star and incorporation into early solar system solid bodies.

While largely successful, this model requires further validation and comparison against data. Such evaluation becomes easier if we have a better sense of the nature of the synthesis of the various radioactivities in the star. That is the goal of this brief abstract.

In what follows, I present the results of a calculations run at Clemson University. With collaborators Lih-Sin The and Mounib El Eid, I have calculated the presupernova evolution of a 25 solar mass star. We then exploded the star and post-processes the accompanying nucleosynthesis \cite{4}. The present abstract discusses briefly the synthesis of six isotopes (\textsuperscript{26}Al, \textsuperscript{36}Cl, \textsuperscript{41}Ca, \textsuperscript{60}Fe, \textsuperscript{107}Pd, and \textsuperscript{182}Hf).

\textbf{26Al:} Figure 1 shows the pre-supernova (just prior to explosion) and post-supernova mass fractions of \textsuperscript{26}Al as a function interior mass coordinate in the star. The entire envelope (reaching out to the surface of the star at about 18 solar masses due to mass loss) contains \textsuperscript{26}Al due to dredge up of the hydrogen burning shell. From Figure 1 it is clear that the supernova neutrinos and supernova shock passage are responsible for production of \textsuperscript{26}Al inside about 5.5 solar masses (the inner edge of the helium shell in the presupernova star). Outside about 5.5 solar masses, however, the explosion does not alter the presupernova \textsuperscript{26}Al abundance. Unless matter from deep inside the star is injected into the solar cloud, most injected \textsuperscript{26}Al was produced in the presupernova evolution.

\textbf{36Cl:} Figure 2 shows the pre- and post-supernova mass fractions of \textsuperscript{36}Cl. For this isotope, it is clear that the bulk of the \textsuperscript{36}Cl ejected from the star is made in the presupernova evolution. This production is due to s-process synthesis in core and shell helium burning and shell carbon burning. Such synthesis is robust. Moreover, the lack of light particles in the carbon shell (from about 2.3 to 5.5 solar masses) means there is little alteration of the presupernova abundances by shock passage. Only in the inner layers of the star near 2 solar masses do explosive burning upon shock passage significantly enhance the presupernova \textsuperscript{36}Cl.

\textbf{41Ca:} Figure 3 shows the mass fractions of \textsuperscript{41}Ca in the initially 25 solar mass star just before and one year after the explosion of the star.
\(^{41}\text{Ca}\): As Figure 3 shows, the \(^{41}\text{Ca}\) ejected from the star, like the \(^{36}\text{Cl}\), mostly derives from the presupernova evolution. Also like the \(^{36}\text{Cl}\), the \(^{41}\text{Ca}\) is mostly produced in s-process synthesis in core and shell helium burning and shell carbon burning.

\(^{60}\text{Fe}\): As seen in Figure 4, the \(^{60}\text{Fe}\) in the outer part of the ejecta (from \(~5\) to \(~6\) solar masses) is predominantly made in the explosion. This is due to the neutron burst that occurs during shock passage of the helium shell. This neutron burst releases enough neutrons to drive material past unstable \(^{59}\text{Fe}\) and enhance the \(^{60}\text{Fe}\) over its lower, presupernova helium shell abundance. Presupernova \(^{60}\text{Fe}\) in the carbon shell is little affected by the supernova shock. Explosive burning around 2 solar masses makes some \(^{60}\text{Fe}\) in the supernova.

\(^{107}\text{Pd}\): Figure 5 shows that most of the \(^{107}\text{Pd}\) ejected from the star is from presupernova s-processing. Some supernova processing occurs in the inner parts of the carbon and helium shells.

Fig. 4: Mass fractions of \(^{60}\text{Fe}\) in the initially 25 solar mass star just before and one year after the explosion of the star.

\(^{182}\text{Hf}\): Figure 6 shows that much of the \(^{182}\text{Hf}\) ejected from the star is produced during the explosion by the neutron burst in the helium shell. Some \(^{182}\text{Hf}\) (and \(^{107}\text{Pd}\)) may also be produced in the r-process, but if this happens, it does so deep in the star near the nascent neutron star surface at \(M_r\) approximately 1.5 solar masses.

Fig. 6: Mass fractions of \(^{182}\text{Hf}\) in the initially 25 solar mass star just before and one year after the explosion of the star.

Discussion: In the model in which the matter injected into the proto-solar nebula comes from the outer layers of the star, e.g., [4], we can see that the \(^{26}\text{Al}\), \(^{36}\text{Cl}\), \(^{41}\text{Ca}\), and \(^{107}\text{Pd}\) predominantly come from presupernova synthesis. The injected \(^{60}\text{Fe}\) and \(^{182}\text{Hf}\) are mostly made in the neutron burst during the explosion itself. This means that if indeed \(^{36}\text{Cl}\) and \(^{107}\text{Pd}\) are somewhat too abundant, as perhaps suggested by our previous work [4], we should look to the details of the presupernova model for the possible problems. The treatment of mixing or some key reaction during helium shell burning would be likely culprits. If the yields of \(^{60}\text{Fe}\) or \(^{182}\text{Hf}\) prove problematic for the injection model, then we must look to the details of the explosion for possible solutions.

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The two-fluid analysis of the Kelvin-Helmholtz instability in the dust layer of a protoplanetary disk: A possible path to the planetesimal formation through the gravitational instability

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Introduction: The discovery of extrasolar planets is indicating that the formation of Jupiter-mass planets is a robust process. According to the core accretion scenario, the formation of protoplanet involves first the condensation and coagulation of dust grains, their assemblage into planetesimals and later into solid protoplanetary cores, and finally accretion of the remaining gas onto these cores. In addition, the planetesimals are supposed to be the building blocks of comets and asteroids. The initial stage of coagulation of dust grains due to thermal motion continues up to about centimeter size. The growth of macroscopic bodies, from cm to km sizes, is not well understood.

One of the solutions to this problem is gravitational instability (GI). If particles settled into a layer having sufficiently high density and low velocity dispersion, density enhancement would spontaneously collapse under their self-gravity forming km-sized planetesimals.

There is a critical issue in this GI scenario. As dust grains settle toward the midplane, the rotational velocity increases around the midplane because of the relative ineffectiveness of the radial pressure gradient compared to the centrifugal force and the solar gravity. The rotational velocity is a function of the distance from the midplane, thus the shear may induce the turbulence. The slightest amount of turbulence in the nebular gas prevents dust grains from settling. Many authors have investigated this issue (Weidenschilling et al. 1984, Cuzzi et. al. 1993, Champney et. al. 1995, and Sekiya 1998). In the case of the minimum solar nebula, they concluded that the gravitational fragmentation of the dust layer is impossible if the turbulence is developed. Sekiya (1998) showed that for the large values of the total dust-to-gas mass ratio a density cusp can appear, which was interpreted by Youdin & Shu (2002) as the triggering of gravitational instability.

In order to understand the nature of instability, linear analyses were performed. Sekiya & Ishitsu (2000) have performed the linear analysis of the shear instability for the constant Richardson number dust density distribution. Their result confirms standard expectations by showing that the midplane shear layer becomes unstable when the minimum value of the Richardson number decreases below 0.226. Sekiya & Ishitsu (2001) investigated the instability using the hybrid dust density distribution in which the dust layer has a constant density and transition regions.

For this distribution, the growth rate of the shear instability is much larger than the Keplerian frequency when the dust density at the midplane is larger than the gas density.

Ishitsu & Sekiya (2002) investigated the shear instability of the hybrid dust density distribution including the Coriolis force but neglecting the tidal force. Their results show that the Coriolis force has little effect on the growth rate of the shear instability. Ishitsu & Sekiya (2003) investigated the shear instability of the hybrid dust density distribution including both the Coriolis force and the tidal force. They showed the tidal force stabilizes the shear instability. However the shear instability occur before the dust density reaches the critical density of the gravitational instability. They use a single-fluid approximation. Garaud & Lin (2004) performed the linear analysis including two-fluid formalism with strong coupling approximation (D<1cm) and destabilizing effect of radiative cooling. They confirm that the shear instability occurs prior to gravitational instability.

We remove the strong coupling approximation from the previous analyses, that is, we take into account the effect of the relative motion, neglecting the Coriolis force and the tidal force.

Result: We analyzed the linear stability in the flow whose shape is the Heaviside step function velocity profile. We found the stabilizing effect due to friction and the condition for stabilization (Figure 1).

![Figure 1 – The growth rate of KH instability for the Heaviside step function velocity profile.](image)
We analyzed the linear stability in a more realistic protoplanetary disk where its velocity profile is continuous. We determined the growth rate of KH instability in wide range of parameter space (Figure 2).

Figure 2 - The contour of the peak growth rate of the Kelvin-Helmholtz instability as function of the dust to gas density ratio on the midplane and the size of dust. The growth rate is normalized by the Keplerian frequency.

We compared the various timescales for dust grains in the disk as functions of the size of dust and the degree of the dust settling onto the midplane, and found a possible path to the planetesimal formation through GI.

SHOCK-WAVE HEATING MODEL FOR CHONDRULE FORMATION: HEATING RATE AND COOLING RATE CONSTRAINTS. H. Miura and T. Nakamoto, Pure and Applied Sciences, Univ. of Tsukuba (miurah@rccp.tsukuba.ac.jp), Research Fellow of the Japan Society for the Promotion of Science, Center for Computational Sciences, Univ. of Tsukuba (nakamoto@rccp.tsukuba.ac.jp).

Introduction: Some observational constraints for chondrule formation models have been reported: short heating time, low cooling rate, elevated gas pressure, size sorting, and so on (e.g., [1]). Shock-wave heating model is one of the most plausible models for chondrule formation because it can explain some observational constraints naturally.

Recently, a new constraint was proposed from observations of the lack of isotopic fractionation in troilites (FeS) [2]. The kinetic evaporation model suggests that a rapid heating rate of $10^4$-$10^6$ K/hr for a temperature range of 1273-1573 K is required to explain observed isotopic fractionations [2]. In the case of shock-wave heating model, the gas drag heating behind the shock front is so rapid ($10^6$ K/hr) that isotopic fractionation is suppressed [3].

However, in the shock-wave heating model, dust particles in pre-shock region are gradually heated by the radiation from post-shock region. According to the numerical simulations of [4], heating rate by radiation is too slow ($\sim 300$ K/hr) to suppress the isotopic fractionation.

Magnitude of the pre-shock heating due to radiation is sensitive to the optical depth in the region because the basic mechanism of this process is the blanket effect. The optical depth depends not only on the dust to gas mass ratio but also on the size distribution of the dust particles.

The purpose of our study is to investigate how the thermal history of dust particles in the shock waves is affected by the optical properties of the pre-shock region, which depend mainly on the dust size distribution and the dust to gas mass ratio. In order to investigate these effects, we have developed a new shock-wave heating code with the radiative transfer among the dust particles and calculated the thermal history of chondrules. We calculate the thermal histories with various shock wave conditions, and based on our calculation results, we discuss the appropriate conditions of solar nebula in which the isotopic fractionation is suppressed.

Shock-Wave Heating Model: We assume that shock waves are generated in the solar nebula and they are steady and plane-parallel. The shock velocity $v_s$ and the number density of nebular gas in the pre-shock region $n_0$ are principal parameters for shock-wave heating model. We calculate the post-shock structure taking into account nonequilibrium chemical reactions. Equations describing precursor grain evolution are eq. of motion, eq. of energy, and eq. of radius shrinkage by evaporation [e.g., 5].

Radiation transfer. The transfer of dust thermal radiation has been already treated in [4, 6]. However, they did not take into account the line emission of gas molecules. In a real situation, some amount of line emission emitted in the post-shock region can escape toward the pre-shock region. Since the line emission also heats the dust particles in the pre-shock region, we have to take into account the transfer of the line emission. Regarding absorption by gas molecules, we use the photon escape probability method ([7]). Regarding absorption by dust particles, we solve the radiation transfer equation precisely.

Precursor dust particle model. We assume two size distribution models for precursor dust particles in this study: simple power-law distribution and lognormal one. The dust to gas mass ratio in the pre-shock region, $C_b$, is changed. We assume that the size range of dust particles is from 0.01 m to 1 cm and divide it into 31 bins. We calculate time evolutions of all bins simultaneously with gas dynamics.

Results: We calculate the thermal histories of dust particles for various conditions.

Shock heating in high density regime. Figures 1 and 2 show the results for high density environment: the pre-shock gas number density $n_0$ is $10^{14.5}$ cm$^{-3}$ and the shock velocity is 8 km s$^{-1}$ (hereafter, HD shock). It is expected that such high density shock waves are generated due to the gravitational instability of the solar nebula ([4]).

Fig. 1 shows the dust temperature of 250 m particle in radius in an optically thick environment: dust size distribution is power-law and dust/gas mass ratio is $3 \times 10^{-2}$. Horizontal axis is the time after dust particles go through the shock front, $t$, and vertical axis is dust temperature, $T_d$. We assume that the dust particle passes the shock front when $t = 0$. Two horizontal dotted lines represent 1273 K and 1573 K, respectively. From Fig. 1, we find that the pre-shock dust temperature exceeds 1573 K. In this case, since the optical depth in the pre-shock region is very large (~15.7), the radiation field becomes strong by the blanket effect. The heating rate for a temperature range of 1273-1573 K is about 272 K/hr and it is too slow to suppress the isotopic fractionation. On the other hand, we calculate the cooling rate when dust...
particles resolidify because it is also an important parameter for chondrule formation. The cooling rate for a temperature range of 1573-1400 K is about 41 K/hr.

Fig. 2 shows the result for optically thin environment: dust size distribution is lognormal and dust/gas mass ratio is 1x10^{-2}. From Fig. 2, we find that the pre-shock dust temperature is lower than 1273 K. After passing the shock front, the dust temperature increases rapidly due to the gas drag heating. The heating rate is about 1.8x10^6 K/hr and it is rapid enough to suppress the isotopic fractionation. In this case, since the optical depth is low (~0.77), the blanket effect does not work well. This situation is consistent with the observations of isotopic fractionation. However, the cooling rate does not well-match with experiments. As well as in the pre-shock region, in the post-shock region the radiation field is weak. Therefore, the radiation heating is not effective in the post-shock region, so the dust temperature decreases rapidly. The cooling rate is about 4.9x10^4 K/hr. This value is much larger than experimentally inferred chondrule cooling rates.

Shock heating at low density regime. Figure 3 shows the result for low density environment: the pre-shock gas number density \( n_0 \) is 10^{11} cm^{-3} and the shock velocity is 56 km s^{-1} (hereafter, LD shock). It is expected that such low density and high velocity shock waves are generated in upper solar nebula by X-ray flares and associated winds ([8]). In Fig. 3, the pre-shock dust temperature is lower than 800 K because the optical depth is very small (~2.5x10^{-4}). The heating rate is rapid (~1.4x10^6 K/hr) enough to suppress the isotopic fractionation as well as Fig. 2. The cooling rate is about 2.9x10^3 K/hr and it is broadly consistent with experimentally inferred chondrule cooling rates.

Discussions and Summary: In this study, we calculate the thermal histories of chondrules and their heating/cooling rates for two shock wave models. Based on our results, it seems that LD shocks can reconcile heating and cooling rate constraints to each other. On the contrary, for optically thin HD shocks, although the heating rate is consistent with observations, the cooling rate is much larger than that inferred by experiments. And for optically thick HD shocks, the heating rate is too slow to suppress the isotopic fractionation, though the cooling rate is consistent with experimental value. These results suggest that the shock waves induced by X-ray flares in upper solar nebula is appropriate for chondrule formation.

The only indisputable evidence on the occurrence of amino acids outside our planet is their detection in carbonaceous chondrites. However only a small fraction was found in chemically free state, whereas hydrolyzable derivatives of unknown composition (possibly amides) is a major source of the detectable amino acids. The difference between carbonaceous chondrites and the icy bodies (interstellar ices and comets) is the basic component, which is water in the latter case. Thus it is reasonable to expect for a higher content of hydrolyzed derivatives (free amino acids as final products) in the icy bodies, as compared to the one in carbonaceous chondrites. As a preliminary test for energetic feasibility of this type of reactions, we studied theoretically the reaction of glycine amide hydrolysis, at the B3LYP/6-31++(d,p) level. We found that a very high activation barrier makes this reaction prohibited. Besides molecular water, a similar hydrolytic effect might be produced by hydroxyl radicals (OH) generated under ionizing action of cosmic rays. Therefore we tested the reaction of glycine amide with OH radical as well. Nevertheless, although the barrier height decreased significantly, by ca. 30 kcal/mol, it remained positive.
MICRON-SIZED SAMPLE PREPARATION FOR AFM AND SEM. P.F. Moretti¹, C. Fazzari², A. Maras³, A. Cricenti³, E. Palomba⁴,
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Introduction: Scanning electron microscopy (SEM), coupled with energy dispersive spectroscopy, is used for morphology and mineralogy analysis. Nevertheless, atomic resolution images can be obtained by the use of atomic force microscopy (AFM).
A comparison between the results obtained with the two imaging techniques is required, but the sample preparation is usually different.
In fact, the metal deposition required for SEM imaging can destroy the details of the rugosity properties of the sample imaged by AFM.
In the framework of the next sample return mission for extraterrestrial material analysis, we describe a cheap technique to prepare micron-sized samples of solid material to be analysed with AFM (contact mode) and SEM. The sample is not coated with conductive material but is deposited onto a conductive grid and fixed with a wax.
The AFM and SEM images are shown. Pros and cons of the technique are discussed.
AFM, FE-SEM AND OPTICAL IMAGING OF A SHOCKED L/LL CHONDRITE: IMPLICATIONS FOR MARTENSITE FORMATION AND WAVE PROPAGATION.

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Introduction: Martensite is a structure of metallic alloys due to a diffusionless transformation. In steels, the martensitic transformation is usually associated to fast cooling rates but it is indeed a shearing process involving very little atoms displacements.

Faster the process, finer are the layers of martensite, while the total amount only depends on the available energy. Martensite formation is very sensitive to metallic composition, impurities [1], and initial pressure [2].

In meteorites, the cooling rates are typically provided by the size of cloudy zones of the metallic phases [3] or by the nickel spatial distribution in the taenite-kamacite interface [4], while martensite is usually associated to shock metamorphism from S4 to S6 [5], [6].

We analysed a thin section of an ordinary chondrite (L/LL4 S3, determined by petrographic indicators [7]), showing a barred chondrule (figure 1) and many metallic zones with martensite (figure 2).

The rather pronounced heterogeneity of the shock pressure is clearly visible in the spatial distribution of the martensite over the whole section. We show images obtained by optical, field emission scanning electron microscopy (Fe-SEM) and atomic force microscopy (AFM) in order to understand the wave propagation and the martensite formation.

The AFM images, in particular, have been collected with a spatial resolution of 2 nm. Such an approach allow to identify martensite as surface topography and/or lateral friction changes.

Figure 1: Optical image (transmitted light) of a ~ 2 x 1.5 mm² thin section of a L/LL4 S3 ordinary chondrite. The marked region is shown in figure 2.

Figure 2: Optical image (reflected light) of the ~ 350 x 200 m² metallic zone marked in figure 1. A red marker indicates the region shown in figure 3 and 4.

Figure 3: 10 x 10 m² Fe-SEM image (at 14 kV) of the marked region in figure 2.

Figure 4: the same region in figure 3, imaged by AFM (contact mode). Color table indicates the corrugation from 0 (black) to 400 nm (white).
References:
INFRARED SPECTROSCOPY OF CHONDRITES AND THEIR COMPONENTS: A LINK BETWEEN METEORITICS AND ASTRONOMY?

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Introduction: Astronomical infrared spectra of a wide range of interstellar objects have become available in recent years, especially owing to space based telescopes like SPITZER. Among them are spectra of circumstellar discs of young stars, which represent the solar system in an early stage. To find out what these spectra can tell us about the mineralogical composition of these discs, infrared spectra of objects with known composition are needed. Studies in this area have been made by the analysis of synthetic analogs e.g.[1] and of IDP e.g[2]. In a further step, we try to find a connection between meteoritics and astronomy by systematically obtaining infrared (IR) spectra from minerals and other components (like calcium-aluminium rich inclusions (CAI) and chondrules) of primitive meteorites. We assume that these materials are very useful for this purpose, since they have formed in environments probably more similar to the origin of the astronomical spectra than terrestrial analogues.

Techniques: We applied a whole range of IR techniques on material from chondrules and CAI, using a Perkin Elmer Autolmage IR microscope and a SpectrumOne workbench. This was necessary owing to the often extremely fine grained nature of these materials, which made a separation of single, homogeneous mineral grains often impossible. In-situ measurements were conducted using the microscope in the specular reflectance mode, which allows to obtain spectra from areas down to 10-10 μm. From these reflectance spectra, the absorption component could be calculated using the Kramers-Kronig algorithm. When small amounts of material could be separated from the specimen, the sample was powdered and analysed in the transmission/absorption mode of the microscope. The wavelength range covered by these techniques was 2.5 to 16 μm. When larger amounts of substance can be provided (e.g. bulk chondrules), we will use workbench techniques like diffuse reflectance mode. This techniques allows a larger wavelengths range from 2.5 to 50 μm. The chondrule analysed was on a polished block of an Allende sample (Fig.1a). For preliminary characterization, the phases were characterized by their stochiometry using SEM-EDX.

Results: As an example, we present in Fig.1b the results of in-situ measurements of a chondrule in the CV3.2 chondrite Allende, compared with a infrared spectra [3] of the circumstellar discs from the T-Tauri star TW Hya and Pictoris [4] (Fig.1c).

MID-INFRARED SPECTROSCOPY OF CAI AND THEIR MINERAL COMPONENTS. A. Morlok1,4; M. Koehler2,4; O.N. Menzies3,4; M. M. Grady1,4 1Department of Mineralogy, The Natural History Museum, Cromwell Road, London SW7 5BD, e-mail A.Morlok@nhm.ac.uk 2Institut fuer Planetologie, Wilhelm-Klemm-Str.10, 48149 Muenster, Germany 3Imperial College London, South Kensington Campus, SW7 2AZ 4IARC

Introduction: Calcium-aluminium rich inclusions (CAI) represent highly refractory materials formed very early in the history of our solar system. As such, infrared spectra taken from their components and minerals are of interest for the search of mineral phases in astronomical spectra of circumstellar discs of young stars. Although not completely pristine, these mineral phases formed possibly in environments similar to those found where the astronomical spectra come from.

So far, for comparison purposes mainly terrestrial analogs like synthetic minerals e.g.[1] or whole dust particles like IDP [2] have been used.

Techniques: Owing to the fine grained nature of the minerals and components, which made a separation of single, homogeneous mineral grains mostly impossible, a whole range of different FT-IR techniques was applied. For in-situ measurements we used a Perkin Elmer SpectrumOne FT-IR microscope in the specular reflectance mode, which allows to obtain spectra from areas down to 10^-10 m. From these reflectance spectra, the absorption part was obtained using the Kramers-Kroning algorithm. When it is possible to separate material from a CAI, we plan to analyse powdered samples in the transmission/absorption mode of the microscope. The wavelength range covered by these techniques is 2.5 to 16 m.

The CAI analyzed was on a polished block of a Ornans CO3.3 sample. Phases were preliminary characterized based on their stochiometry using SEM-EDX.

Results: The compact CAI (Fig.1a) mainly consists of spinel and melilit, surrounded by Al-diopside. Fig.1b shows the reflectance (R) and calculated absorbance spectra (k) of areas in the CAI.

Discussion: Fig.1c compares the results with infrared spectra of the circumstellar discs from the T-Tauri star TW Hya [3] and Pictoris [4] (Fig.1c). While there is no perfect fit, the band positions in the absorbance spectra e.g. of the melilit/spinel mixture and the Al-diopside exhibits some similarity with the TW Hya spectra for two bands.


Fig.1a-c. (a) BSE image, (b) reflectance (R) and absorbance (k) IR in-situ spectra, (c) astronomical data.
THE ORIGIN OF IRON ISOTOPE FRACTIONATION IN CHONDRULES, CAIs AND MATRIX FROM ALLENDE (CV3) AND CHAINPUR (LL3) CHONDRITES. E. Mullane 1, S.S. Russell 2 and M. Gounelle 1, 2,

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Introduction: Here we report on the Fe-isotope composition ($\delta^{56}\text{Fe}$ and $\delta^{57}\text{Fe}$) of chondrules, Ca-Al-rich inclusions (CAIs) and matrix from the Allende and Chainpur chondrites. Both meteorites are classified as petrologic type 3 and thus were only subject to a minimum of aqueous or thermal processing, although the effects of secondary alteration have been described in Allende [1].

Samples: We analyzed 12 chondrules, two CAIs (from Allende) and eight matrix aliquots. The textural types [2] within the chondrule sample set are: radial pyroxene, barred olivine, porphyritic olivine and porphyritic olivine-pyroxene, and these are a mixture of Type I (FeO-poor), Type II (FeO-rich) and Type III (radial pyroxene) chondrules.

Methods: Chondrules were taken from lightly crushed Allende and Chainpur samples and were cleaned of any adhering matrix by ultrasonic treatment. CAIs were also separated and the central portions, uncontaminated by iron rich matrix, were used for acid dissolution. Each sample was characterized using both a Phillips XL-30 SEM and a Cameca SX-50 electron microprobe. The Fe-isotope ratios $^{56}\text{Fe}/^{54}\text{Fe}$ and $^{57}\text{Fe}/^{54}\text{Fe}$ were determined using a fixed resolution IsoProbe MC-ICP-MS. Further details of the analytical method can be found in [3].

Results: Iron isotope compositions are consistent with mass fractionation of a single isotopically homogeneous source and the chondrules are both isotopically heavy and light with respect to the standard (IRMM-014) (Figure 1).

Allende: The overall variation of chondrules is: $\delta^{56}\text{Fe} = 1.98\%_o$; $\delta^{57}\text{Fe} = 2.87\%_o$. Many of the chondrules are isotopically distinct from the matrix, which itself is similar in composition to the standard (Figure 1). Larger chondrules are more fractionated (both heavy and light) than smaller chondrules. CAI Fe-isotope compositions are similar to the matrix.

Chainpur: Chainpur chondrules are less fractionated than those of Allende and fall between -0.18$\%_o$ to +0.27$\%_o$ for $\delta^{56}\text{Fe}$. Chainpur interchondrule matrix is similar in composition to that of Allende.

Discussion 1. Fe-isotope Composition of Matrix: The matrix aliquots taken for analysis were very small (~10µg) so that any disproportionate isotopic heterogeneity of individual phases, if present, could be identified. All aliquots have the same Fe-isotope signature indicating that the homogeneous Fe-isotope composition of Allende and Chainpur matrix material is pervasive, or that the matrix is sufficiently fine grained to homogenize the signature from different matrix components. It was long thought that matrix in type 3 chondrites was pristine, but it is now recognized that it contains a strong imprint of aqueous alteration in many meteorites [e.g. 4]. This alteration may have homogenized the Fe-isotope signature of Allende and Chainpur matrix material.

Discussion 2. Fe-Isotope Composition of CAIs: As most pristine CAIs contain no iron, any iron within a CAI will be derived from secondary sources, e.g. metasomatic introduction of iron from matrix during low temperature parent body processing [5]. The Fe-isotope composition of CAIs analyzed here are within error of matrix compositions (Figure 1). It is not difficult to explain the origin of this isotopically normal iron, as almost all iron in these CAIs is probably derived from exchange with unfractionated matrix [6].

Discussion 3. Fe-Isotope Composition of Chondrules: Chondrules are mainly isotopically different to the matrix. Fe-isotope fractionation may pre-date, post-date or be synchronous with chondrule formation, or may derive from repeated processing in a number of different environments.

1. Inherited from unequilibrated presolar precursor material?: No variations in presolar material between meteorites have been found that could not be accounted for by the history of the host meteorite or nebular processing and therefore meteorites sampled the average molecular-cloud material that was the raw material for the solar system [e.g. 7]. Consequently,
the differences in chondrule Fe-isotope composition cannot be accounted for by incorporation of different populations of presolar grains.

2. Inherited from heterogeneous nebular condensates?: Chondrule compositional diversity has been explained by formation from heterogeneous nebular condensate precursors [e.g. 8], but if these precursors were products of equilibrium condensation then large isotopic fractionation would be unexpected [9]. If compositions are inherited then chondrules must have remained as closed systems with respect to FeO, since their formation and given the amount of thermal and or aqueous processing that has occurred, this is unlikely to be the only process that constrains Fe-isotopes.

3. Produced by kinetic effects during one or more chondrule melting events?: FeO is the most volatile major component of chondrules [e.g. 10] and during the high temperature conditions (up to 1,900°C) predicted by flash heating experiments [e.g. 11,12] some mass dependent fractionation would be expected. The Fe-isotope fractionation exhibited by chondrules falls short of that predicted under Rayleigh evaporation [13]. The Fe-isotope compositions of the chondrules analyzed here are not consistent with Rayleigh evaporation, nor is the degree of fractionation related to bulk FeO content.

Our chondrule samples include both fully melted and partially melted examples. Fe-isotope fractionation does not vary systematically with texture. Those chondrules which experienced almost complete melting are both isotopically light and heavy with respect to the standard. Reworking successive generations of chondrules has probably modified Fe-isotope compositions, e.g. the most isotopically heavy chondrules may derive from a melt which attained liquidus temperatures more than once. The precursor to the isotopically lightest chondrule in our sample set, may not have been subject to as many aggressive heating events.

4. Effect of opaques?: Iron-isotopes show the greatest fractionation (both heavy and light) in opaque-free inclusions. In chondrules with minor or accessory opaques the Fe-isotopes are moderately fractionated (both heavy and light), but not to a similar extent as the opaque-free chondrules. Opaque rich chondrules show minor to no isotopic fractionation. It seems that the addition of opaques reduces the fractionation, but some opaque-free chondrules are also unfractiated with respect to the standard, indicating that an unfractiated signature does not derive solely from the presence of opaque phases. However, it seems that metal inclusions play a role (however small) in governing the bulk isotopic signature of the chondrules.

5. Due to isotope redistribution during parent body alteration?: The discovery that chondrule size and extent of fractionation are related for Allende chondrules has important implications for parent body equilibration effects as it is possible that smaller chondrules are more susceptible to equilibration than larger ones. The chondrules taken from Allende and Chainpur are of a similar size, but Chainpur chondrules are less fractionated. Thus, Chainpur chondrule Fe-isotopes may be more modified than Allende chondrules. This may reflect different degrees of equilibration within each chondrite. Chainpur chondrules may have been shifted towards more homogenous values by later addition of Fe, either from a nebular reservoir or parent body alteration.

Conclusions: We observe a greater range of Fe-isotope fractionation than has previously been documented in ordinary or carbonaceous chondrites and the fractionation systematics are consistent with mass fractionation of a single isotopically homogeneous source. Parent body processing appears to play a significant role in determining the Fe-isotope composition of Chainpur and Allende CAIs and chondrules. This is responsible for essentially all of the incorporation of iron into Allende CAIs (which yield and Fe-isotope composition identical to that of the matrix). The Fe-isotope composition of Chainpur chondrules have been homogenized to a greater extent than Allende. Measurable heterogeneities among chondrules indicates that events prior to parent body accretion also affected the Fe-isotope composition. The effects observed are much less than expected from Rayleigh fractionation. The isotopic array falls on a mass fractionation line, implying that heterogeneous precursors were not responsible for the differences. Instead, the final isotopic composition is probably the result of a complex history of several heating events under different conditions. Exsolution of metal may also play a role.

Protoplanetary Disk Evolution: Early Results from Spitzer. J. Muzerolle\textsuperscript{1}, E. T. Young\textsuperscript{1}, S. T. Megeath\textsuperscript{2}, C. Lada\textsuperscript{2}, and the MIPS and IRAC teams
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The Spitzer Space Telescope, with its two imagers, the Infrared Array Camera (IRAC) and the Multiband Imaging Photometer for Spitzer (MIPS), provides a new and unprecedented capability for mid-infrared studies of disk evolution from the earliest formation stages through the planet formation epoch and beyond. I present first results from a survey of young stars and stellar clusters spanning an age range of 1-100 Myr. These observations have the ultimate goal of constraining circumstellar disk properties and lifetimes, for both primordial and regenerative debris disks, as a function of stellar mass and environment.

Combining observations with ground-based optical and near-infrared data, we have compiled spectral energy distributions with which to broadly characterize protoplanetary disks. We have preliminary results for a representative sample of \textasciitilde 7 young clusters, including both regions with active star formation and older open clusters with little or no primordial material left over.

\textit{Star-forming regions.} The youngest clusters (~1 Myr-old) show protostellar populations similar to what have been observed in nearby well-studied regions such as Taurus, including both objects with circumstellar accretion disks and protostellar sources with envelopes. We are finding a small fraction of objects as young as 1 Myr with signs of inner disk clearing within the central ~1 AU. These may be primordial disks caught in the act of dissipating, perhaps induced by the presence of growing planetary bodies. We also see a small but nonzero fraction of objects which show no signs of accretion activity (weak T Tauri stars) yet exhibit infrared excess at wavelengths up to 24 microns, indicative of remnant primordial disks.

\textit{Planetary debris disks.} Our early observations of open clusters with ages >20 Myr indicate a surprising variation in disk properties. Roughly 10-20\% of the massive cluster members (spectral types B-A) show excess emission at 24 microns indicative of planetary debris disks, analogous to the Vega phenomenon. There are hints of a correlation of disk fraction with age; however, we find a significant fraction of objects without excesses even in the youngest clusters in this age range. This reflects either a wide range of initial disk lifetimes, or possibly that the debris disk phenomenon is dominated by a more stochastic process, produced by recent collisions of planetesimals within the disk. Furthermore, we have found several surprisingly strong 24-micron excess sources, primarily in solar-type or low-mass stars that may be analogs of the era of maximum bombardment in our own solar system.
**Introduction:** Chondrules show wide range of compositional diversities, which is thought to be due to heterogeneity in precursor materials and modification of precursor compositions during chondrule formation, that is, selective loss by evaporation or gain by condensation of specific components.

The diversity of chondrule compositions includes Mg/Si fractionation, total Fe and FeO content variations, alkali-depletion, and rare refractory enrichment. Silica is enriched in the outer regions of chondrules compared to the interior; more abundant occurrence of pyroxene in the rim than in the core of various chondrules in carbonaceous and ordinary chondrites, outward SiO2-enrichment in the mesostasis glass of Semarkona [1], and silica-rich rim in CR chondrites [2]. The observation indicates condensation of Si during cooling. Alkaline elements are also often enriched in the outer portion of chondrules. On the other hand, FeO is almost homogeneously distributed in chondrules, suggesting that evaporation and/or condensation would not be directly responsible for their diversity.

Quantitative modeling to explain the diversity of chondrule composition has recently been developed: chemical equilibrium calculation [3], kinetic evaporation in the presence of back reaction at isothermal conditions [4], and kinetic condensation during cooling [5] models. Although these models have partly succeeded in explaining the compositional diversity of chondrules, they assume homogeneity of droplet with or without crystals. Heterogeneous distribution of minerals and melt in a chondrule, however, will affect the evolution of cooling silicate melt droplets. In the present study, we investigate the kinetics of condensation for a system consisting of melt-crystals, and the role of crystal distribution on the chemical evolution of chondrules is examined.

**Chondrule compositions:** Tomomura et al. [6] obtained accurate bulk chemical composition of all the chondrules in Krymka and Bishunpur thin sections by averaging about 500 point analyses with EPMA for individual chondrules, and they showed that most of chondrules in Semarkona have very constant Al2O3+CaO contents and that the Mg/Si/Fe factionation is the fundamental diversity for chondrules in ordinary chondrites. If we ignore the abundance of FeO, MgO/SiO2 ratios of those chondrules distribute at both Mg- and Si-rich sides of the averaging solar system MgO/SiO2 ratio, that is, about half of chondrules are MgO>SiO2, and the latter half are MgO<SiO2.

**Kinetic condensation model for bulk composition of silicate melt:** A quantitative model for kinetic condensation consists of Hertz-Knudsen equation that describes condensation or evaporation rate as a function of ambient pressure and temperature, mass balance equation that describes condensation or evaporation rate of a species as a function of the change of size and composition of a melt sphere, and pressure equation that relates pressure and temperature of the system. The model has three parameters: degree of supersaturation \((P/Peq)\), dust enrichment factor that is normalized by the canonical solar system elemental abundance, and cooling rate that is linear and normalized by free evaporation rate. The system consists of 10 elements, Na-K-Fe-Ca-Mg-Al-Si-Ti-H-O. The condensed phase treated is melt alone without crystals. The initial bulk composition is CI, CA-depleted CI, and Fe-depleted CI. The starting condition is total gas.

The model calculates trajectory of composition of melt and coexisting gas with cooling from totally evaporated gas with CI composition. By changing the parameters (cooling rate, degree of supersaturation, and dust enrichment of the system), the reproducibility of Semarkona chondrule compositions are examined.

**Kinetic condensation model for melt-crystal system:** Once crystallization takes place in a melt sphere, distribution of crystals affects the condensation and evaporation rates and therefore chemical evolution of chondrules. The model describes condensation or evaporation rate of elements as a function of melt/crystal ration at a sphere surface. Condensation or evaporation coefficient (extent of kinetic barrier) of an element differs between melt and crystal, and the difference in the crystal/melt ratios at the melt surface changes the total condensation or evaporation of an element.

The model has a parameter for the melt/crystal ratio at the surface. Although the system is multi-component, there are limited experimental data for condensation coefficient and only the case for MgO-SiO2 binary system was examined. Total melt fraction is defined assuming chemical equilibrium.
Crystallization is assumed to start at the surface of a melt surface, because of higher energy compared to the interior. We do not consider the energy change. Diffusion within a sphere is not considered, though it would be important with decreasing temperature.

**Evaporation and condensation coefficients:**
There is no experimental work to obtain condensation coefficient of not only silicate melt but also crystalline phases. Only evaporation coefficients are obtained for forsterite [7-9] and silicate melt [10,11] for limited conditions. More comprehensive data as a function of temperature and gas compositions including oxygen and hydrogen will be needed. Due to limitation of available data, only the evaporation process for the system consists only of MgO-SiO2 is examined here.

**Results and discussions:**
A part of calculation has been reported in [12]. Although the diversity of FeO-poor chondrule compositions is roughly reproduced as directly condensed melt from the gas of CI composition, a precursor previously depleted in the refractory components (Al and Ca) by a quarter and Fe by half gives better results. It is fitted best if the gas cooled fairly rapidly (dimensionless supersaturation degree=0.02-0.05). The actual cooling rate varies with gas/dust ratio (Fig. 1). FeO-rich chondrules are hardly reproduced as direct melt condensates regardless of the fractionation of the precursors and cooling conditions. Gas coexisting with melt can have Si-rich composition (Si/Mg>CI), and if melt-gas separation took place, the separated gas could quenched into Si-rich melt spheres. It, however, requires an Fe-depleted precursor. The crystallization temperature is dependent on O/H/dust ratio and the degree of fractionation of the precursors, but the dependence becomes small with increasing dust/gas ratio (Fig. 2).

If crystallization in a melt sphere starts from the surface, it suppresses condensation, because the condensation coefficients for crystals should be smaller than melt. If we assume that the condensation coefficient for silicate melt is unity (no kinetic barrier) as often assumed and that for forsterite is 0.1 by extrapolating the evaporation coefficient to condensation conditions, the condensation time for the melt-crystal sphere is prolonged by an order of magnitude depending on the fraction of surface area occupied by melt.

In summary, quantitative modeling enables us to estimate the formation conditions and growth rate of chondrules, which is strongly affected by the melt/crystal distribution in a chondrule sphere.

**References:**

![Fig. 1 Cooling rate for FeO-poor chondrules as a function of gas/dust ratio. The dimensionless supersaturation should be between 0.02 and 0.05.](image1.png)

![Fig. 2 Temperature for the start of crystallization for FeO-poor chondrules as a function of gas/dust ratio.](image2.png)
OXYGEN ISOTOPE EXCHANGE RECORDED WITHIN ANORTHITE SINGLE CRYSTAL IN VIGARANO CAI: EVIDENCE FOR REMELTING BY HIGH TEMPERATURE PROCESS IN THE SOLAR NEBULA. K. Nagashima, M. Yoshitake, and H. Yurimoto, Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Ookayama 2-12-1, Meguro, Tokyo 152-8551, Japan. (ku@geo.titech.ac.jp)

Introduction: It is believed that Ca-Al-rich inclusions (CAIs) have been formed initially in a $^{16}$O-rich solar nebula followed by processing in a $^{16}$O-poor solar nebula based on the O isotopic distribution among the CAI minerals [1]. The clear evidence for O isotope exchange from $^{16}$O-poor to $^{16}$O-rich composition in the CAI was reported [2]. They proposed remelting and recrystallization during short-term heating events in $^{16}$O-poor nebula as the O isotope exchange mechanism. Recently, anorthite grains with an intracrystalline O isotopic zoning in the CAI of Vigarano chondrite were found [3-5], while the determination of isotope exchange mechanism was not conclusive because the spatial resolution was not enough. In this study, high precision isotope imaging analyses with micro-scale resolution (isotopography [6-8]) are applied to obtain O isotope distribution in the Vigarano CAI. This would allow depicting the isotopic exchange mechanism in the CAI.

Experimental: The sample used in this study is a coarse-grained type B2 CAI (TTV1-01 [3]) found in a thick section from Vigarano CV3 chondrite. Petrologic and mineralogical studies by scanning electron microscope (JEOL JSM-5310LV) equipped with energy dispersive X-ray spectroscopy (Oxford LINK ISIS) were made before and after the isotopography.

Isotopographs were obtained by the TiTech isotope microscope (Cameca ims 1270 + SCAPS [6]). The analytical techniques for isotopographs generally followed those described in [7, 8]. The size of an ion image corresponds to 70 x 70 µm on the sample. The typical mass sequence for acquiring secondary ion images was $^{27}$Al-, $^{28}$Si-, $^{16}$O-, $^{18}$O-, and $^{16}$O- for one cycle.

The digital image processing using the blind deconvolution algorithm and a moving-average with 3 x 3 pixels were applied to simple secondary ion ratio image in order to reduce defocusing of the images and to reduce the statistical error, respectively. The $^{16}$O-$^{18}$O isotopographs were normalized to SMOW scale using $\delta^{18}$O$_{SMOW}$ values for minerals obtained by spot analyses.

Results: Two $\delta^{18}$O isotopographs of each area containing anorthite #B and #C grain [5] were obtained. BSE image of the area containing anorthite #B grain is shown in Fig. 1. Anorthite #B is a blocky-shaped grain with the size of ~50 µm. The chemical composition is nearly pure CaAl$_2$Si$_2$O$_8$ for both anorthite grains. The #B grain contains spinel grains and is adjacent to åkermanite-rich melilite (Åk69) and fassaite containing 16.9 wt% Al$_2$O$_3$ and 2.2 wt% TiO$_2$.

The isotopograph of $\delta^{18}$O of the area containing #B are shown in Fig. 1 with the backscattered electron image of the same area. Yellow curves in the isotopographs are outline of anorthite #B grain. The arrow at grain boundary between melilite and anorthite in upper-left region of the images shows location of traverse shown in Fig. 2. Craters of SIMS analyses are observed in the backscattered electron image. Abbreviations: sp = spinel, mel = melilite, an = anorthite, fas = fassaite, and alt = alteration products.

Fig. 1. Corresponding images of backscattered electrons and oxygen isotope ratio ($\delta^{18}$O) of an area containing anorthite #B. Yellow curves indicate outline of anorthite #B grain. The arrow at grain boundary between melilite and anorthite in upper-left region of the images shows location of traverse shown in Fig. 2. Craters of SIMS analyses are observed in the backscattered electron image. Abbreviations: sp = spinel, mel = melilite, an = anorthite, fas = fassaite, and alt = alteration products.
Figure 2 shows compositional (\(^{27}\text{Al}/^{16}\text{O}\)) and \(\delta^{18}\text{O}\) profiles perpendicular to the grain boundary between \#B and melilite indicated by the arrow in Fig. 1. From \(\delta^{18}\text{O}\) profile, O isotopic composition of \#B near the edge (<4 \(\mu\text{m}\) from the grain boundary) is constant (\(\delta^{18}\text{O} \sim 5 \text{‰}\)) against the distance, and same as that of melilite within analytical error. At ~4 \(\mu\text{m}\) from the grain boundary, O isotopic composition abruptly changes toward to \(^{16}\text{O}\)-rich composition. Then, O isotopic composition becomes constant value with \(^{16}\text{O}\)-rich composition (\(\delta^{18}\text{O} \sim -40 \text{‰}\)) in the center of \#B (>~8 \(\mu\text{m}\) from the grain boundary).

**Discussion:** The CAI, TTV1-01, have crystallized from a liquid droplet because of an intergrown texture of coarse-grained crystals and rounded outer-shape [5]. The \(^{16}\text{O}\)-rich spinel, which is the first major liquidus mineral [9], indicates the liquid droplet was initially enriched in \(^{16}\text{O}\). On the other hand, melilite and part of anorthite \#B are \(^{16}\text{O}\)-poor. Two kinds of mechanisms of O isotope exchange can be considered to form such \(^{16}\text{O}\)-poor minerals: solid-state diffusion or melting and recrystallization in \(^{16}\text{O}\)-poor environment. If O isotope exchange is due to solid-state diffusion, O isotopic compositions should change gradually inside the grain from the grain boundary. The \(\delta^{18}\text{O}\) profile rules out solid-state diffusion as a mechanism to generate O isotopic zoning in \#B. On the other hand, the melting and recrystallization in \(^{16}\text{O}\)-poor environment adapt to the profile showing abrupt change with a sharp boundary of O isotopic distribution in a single crystal [2, 10]. Therefore, the \(^{16}\text{O}\)-poor anorthite results from O isotope exchange during melting and recrystallization caused by a reheating event in \(^{16}\text{O}\)-poor environment. The slope across \(^{16}\text{O}\)-poor/\(^{16}\text{O}\)-rich boundary in Fig. 2 results from defocusing effect of ion optics plus O diffusion of heating event. If we assume this slope is due to the diffusion contribution, we estimate maximum reheating duration using the diffusion coefficient for O in anorthite [11]. Applying the crystallization temperature of anorthite of 1260°C [9], maximum reheating duration of the slope is calculated to be ~5 days. Such short reheating duration is consistent with the case of [10]. These results indicate that the heterogeneous O isotopic distribution of the CAI resulted from short-term heating events in the solar nebula. A possible candidate for the astrophysical setting to form the CAI might be the inner edge of the solar nebula around the protosun [12].


![Fig. 2. Compositional (\(^{27}\text{Al}/^{16}\text{O}\)) and \(\delta^{18}\text{O}\) profiles indicated by the arrow in the isotopographs in Fig. 1. Distance is measured from grain boundary between melilite and anorthite \#B grains determined by \(^{27}\text{Al}/^{16}\text{O}\) profile. Each plots is averaged over ~±0.5 \(\mu\text{m}\) width from the arrow along a direction parallel to the grain boundary (i.e. the direction perpendicular to the arrow) in order to reduce statistical errors. Red curve indicates a diffusion curve fitting the plot assuming the one-dimensional diffusive pair. The parameters of the curve are fitted to 2(Dt)\(^{1/2}\) = 1.5 \(\mu\text{m}\), \(\delta^{18}\text{O}\) of overgrown anorthite = 5%, and initial anorthite (not melted) = -40 %, where D and t are oxygen self diffusion coefficient and annealing time, respectively.](9072.pdf)
CHONDRULE FORMING SHOCK WAVES IN SOLAR NEBULA BY X-RAY FLARES.
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Chondrules and X-Ray Flares: Chondrules are considered to have formed through some heating events in the early solar nebula. Though the specific heating mechanism has not yet been understood clearly, the shock wave heating is considered to be one of the most plausible models to explain the various properties of chondrules [1,2]. However, the source and the place of shock waves are still under debate. Proposed models include bow shocks in front of fast moving planetesimals [3], accretion shocks at the surface of nebula [4], and spiral density waves induced by the disk self-gravity [5], though every model has some drawbacks.

Here, we propose a new model: shock waves in the upper region of the solar nebula induced by X-ray flares associated with the young Sun. X-ray flares, common among T Tauri stars [6], emit plasma gas, which cools to be a strong neutral gas wind. The energy, the dimension, and the frequency of X-ray flares associated with T Tauri stars are much larger than those of the current Sun. Typical luminosity in the X-ray wavelength region is about two orders of magnitude higher than the current solar flare [6]. Such energetic flares emerge about once a day [6], almost three orders of magnitude more frequently than the current Sun. Because of the enormous amount of energy released by the X-ray flares, the flares should have some effects on the dynamics and energetics of a protoplanetary disk around the star. Observations of X-ray flares around young T Tauri stars indicate that their activity decreases with a time scale of the order of $10^6$ yr [6], which is similar to the range of chondrule formation ages, i.e., from about 1 Myr to 3 Myr after formation of CAIs, the oldest solid objects in the solar system [e.g., 7-9].

In this work, we numerically simulate the X-ray flares and expanding magnetic bubbles with the disk, and examine whether or not shock waves which can form chondrules are induced in the nebula.

MHD Simulations: We have carried out 2-D MHD numerical simulations of X-ray flares around a central star and expanding magnetic bubbles/winds with a disk [10]. Figure 1 shows the initial density distribution in a 1 AU region. Outer boundary of the computation domain is 3 AU from the central star. Details of numerical procedure are described in [10].

The density distribution at $t = 5.37 \times 10^5$ sec is displayed in figure 2. The upper region of the solar nebula is disturbed by the magnetic bubble/wind propagating above the disk. The gas pressure and the ram pressure distributions along the solid line in figure 2 are shown in figure 3. We can see that the shock front is present and the ram pressure is almost the same with the gas pressure at the shock front. The propagation velocity of the front along the solid line is about 90 km/s.

In analyses of chondrule formation by shock-wave heating [2], conditions of shock waves that can heat and form chondrules were investigated for a wide range of shock properties. Comparing results of this study with [2], it seems possible to form chondrules by shock waves induced by X-ray flares.

Discussions:

Presence of Chondrule Precursors in Upper Solar Nebula: In the absence of turbulence, the chondrule precursor particles of 0.1 mm radii may not be present in the upper region of the solar nebula, because the sedimentation time scale of dust particles is of the order of $10^3$ yr [11] (shorter than the age of chondrules). However, turbulence in the nebula may lift precursor particles in the upper region for longer time. For example, using a turbulent nebula model, it was shown that 0.1-mm sized dust particles could be present at $Z = 3 h$ ($h$ is the scale height of the disk), though the concentration is very small [12]. Thus, it seems possible that chondrules are heated and formed in the upper region of the solar nebula by shock waves which are induced by X-ray flares.

A Variety of Chondrule Ages: In primitive chondrites, chondrules with a variety of ages are randomly mixed in less than mm scale. The difference of ages among chondrules in the same meteorites is at least 1 Myr [e.g., 7, 8]. This implies that each heating event influences only a limited portion of chondrules at a time, otherwise, older chondrules should be reheated and their age difference should be much smaller. Our model here may meet this requirement. The heating events take place only in the upper part of the nebula, while most of the dust particles stay in the lower part of the nebula.
**Frequency of Heating Events:** Can this model explain abundant chondrules seen in meteorites? It is estimated that the total number of heating events to produce such an abundant chondrules is about several times over all the dust particles in a period of 2 Myr [9]. This means that each dust particle was heated several times in the 2 Myr period averagely. For a dust particle, heating once every a few $10^5$ yr is enough. This frequency is rather low. If the frequency is higher than this, it seems difficult to reconcile the chondrule age distribution: age distribution would shift to younger side. In our model, it is not easy for a dust particle to be in the upper solar nebula. Thus, the inferred low frequency of the heating event seems consistent with the model.

**Dust to Gas Mass Ratio before Shock Waves:** According to an analysis for the collisional destruction among dust particles in shock waves [13], the dust/gas mass ratio before entering the shock wave is inferred to be of the order of or less than 0.01, otherwise, the chondrule size distribution in ordinary chondrites cannot be reproduced. This inferred dust/gas mass ratio may be consistent with the current model, because the dust concentration in the upper solar nebula is expected to be small.

**Chemical and Isotopic Properties of Chondrules:** Chondrules may have experienced chemical fractionations due to evaporation of volatiles at chondrule-forming temperatures. On the other hand, the evidence of a large degree of isotopic fractionations has not been found in chondrules [e.g., 14]. It should be investigated whether the proposed heating mechanism can explain such properties of natural chondrules in future work.

ORGANIC GLOBULES WITH ANOMALOUS NITROGEN ISOTOPIC COMPOSITIONS IN THE TAGISH LAKE METEORITE: PRODUCTS OF PRIMITIVE ORGANIC REACTIONS. K. Nakamura1, S. Messenger1, L.P. Keller2, G.J. Flynn2 and S. Wirick3. 1Office of Astromaterials Research & Exploration Science, NASA Johnson Space Center, Houston TX 77058, keiko.nakamura1@jsc.nasa.gov 2Dept. of Physics, SUNY-Plattsburgh, NY12901, 3Dept. of Physics, SUNY-Stony Brook, NY11794.

Introduction:
Interstellar grains in molecular clouds consist primarily of silicate minerals, organic material, and ices [1]. These interstellar materials are heated and partially evaporated during the birth of the protosolar nebula, and the remaining core-mantle grains grow into large aggregates by collision and subsequent sticking to become planetesimals [2,3]. The chemical diversity of meteoritic material such as chondrules, Ca-Al rich inclusions and amoebo-olivine aggregates reflects the material distribution in the late stage of the disk evolution before planetesimal formation began. Organic matter in carbonaceous chondrites should also be considered as a sensitive probe for the extent and timing of high temperature processes in the solar nebula. Current models suggest that many of the organic molecules found in the hydrated carbonaceous chondrite meteorites were synthesized by aqueous processing of a suite of precursor molecules, some of which were interstellar with significant isotopic anomalies, such as excesses of deuterium (D), and 15N [4].

Tagish Lake is a unique carbonaceous chondrite which bears mineralogical and chemical similarities to the CI and CM chondrite group [5,6]. Reflectance spectroscopy suggests that this meteorite is a rare sample from outerbelt (D-type) asteroids [7], which are believed to be very water-ice rich and mineralogically primitive [8]. Tagish Lake possesses abundant presolar SiC and nanodiamonds [9] together with bulk H and N isotopic anomalies that fall within the range observed among other primitive chondrites [9,10,11].

Organic globules (100-500nm) are found distributed throughout the Tagish Lake matrix [12]. Infrared spectroscopy measurements show that matrix regions with abundant organic globules are also enriched in aliphatic hydrocarbons and esters [12,13]. These globules are remarkably similar to those artificially produced by UV photolysis of organic ices that are believed to be analogues for interstellar grain mantles [14]. While H isotopic measurements would provide a strong diagnostic test of this hypothesis, their small size (mostly 100-500nm) and the naturally low abundance of D currently precludes D/H isotopic measurements on individual globules. Here we report N isotopic imaging and X-ray absorption near-edge spectroscopy (XANES) study of individual hollow organic globules.

Methods: Fragments of the carbonate-poor lithology from a pristine sample of Tagish Lake (TL3B6) were studied. The samples were embedded in elemental S and sliced with a diamond ultramicrotome, thus avoiding any possibility of contamination with organic epoxy. TEM observations of thin sections (~70nm thick) were performed at the Johnson Space Center in order to identify organic globules for subsequent C and N isotopic analysis. Fourteen of these globules were measured for C and N isotopes, 3 of which were also studied by C-XANES.

A scanning transmission X-ray microscope (STXM) was used to determine C distribution in the sections and to obtain C-XANES spectra for C functional groups in the globules at the National Synchrotron Light Source (NSLS) on a beamline X1A at Brookhaven National Laboratory.

The C and N isotopic imaging studies were performed with the Washington University Cameca NanoSIMS ion probe. We measured C and N isotopes: 12C, 13C, 12C14N, 12C15N and 28Si simultaneously while operating in multicollection mode. A 16 keV, 2 pA Cs+ primary ion beam was used, which had a nominal beam diameter of 100nm.

Results and discussion: STXM C-mapping shows that amorphous carbon is ubiquitous throughout the saponite-rich matrix. C-XANES spectra of the hollow globules also exhibit typical amorphous carbon features. Compared to the Tagish Lake fragments previously studied by C-XANES [15], the matrix of the fragment studied here is significantly and uniformly richer in C as determined by C-XANES imaging. This result is consistent with our previous C isotopic imaging study [16] and the EELS study done by [17] who suggested that the C in the clay matrix is the source of the globules.

Isotopic images show that 12 out of 14 organic globules measured are significantly 15N-rich enriched, ranging from ~ +200 ‰ to a maximum +700 ‰. These globules appear to be the most 15N-rich phase in the field of view, as exemplified in (Fig.1a), where a globule pair identified by TEM (Fig.1b) is clearly associated with a 15N-rich hotspot.
The $^{15}$N enrichments observed in organic matter from primitive meteorites and IDPs are often ascribed to extremely low temperature chemical fractionation in a presolar cold molecular cloud [18]. The fact that these globules almost uniformly exhibit N isotopic anomalies far in excess of the bulk meteorite and surrounding matrix suggests that they were a population of submicrometer organic grains that predate the formation of the Tagish Lake parent body. The spread in $^{15}$N/$^{14}$N ratios of globules probably reflects varying extent of alteration or isotopic exchange during aqueous alteration, which has been invoked to explain their morphology and chemical signatures [12]. The most $^{15}$N-rich globules should most closely reflect the original chemical composition of the globules, perhaps marking discreet presolar organic grains.

Although organic globules have been reported in other meteorites, their origins have been uncertain because of the potential for contamination. The globules in Tagish Lake are shown to be indigenous based on their anomalous N isotopic composition, and they are found to be far more abundant than in other meteorites. The high abundance of these globules in Tagish Lake is interesting given that this meteorite is thought to have originated from the outer regions of the asteroid belt where thermal processing may have been less severe. However, this view is not easily reconciled with the fact that Tagish Lake contains abundant chondrules, which must have formed at temperatures far in excess of the thermal stability of the globules. The coexistence of high temperature phases and thermally labile materials within Tagish Lake and other meteorites either reflects extensive radial mixing of material or late accretion of thermally labile materials after the disk had cooled.


Figure 1: (a:top) N isotopic image acquired by NanoSIMS of a Tagish Lake thin section previously found to contain a pair of hollow globules (b: below). The globules are $^{15}$N-rich (+600 ‰) compared with the bulk meteorite (< +100 ‰)
YET ANOTHER CHONDRULE FORMATION SCENARIO

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Abstract We propose that the nebular shocks currently favored as a model to form chondrules and other annealed silicates in the solar nebula originate in the dynamical activity in the envelope of forming Jovian planets. In contrast to the classic ‘core accretion model’, our 3D hydrodynamic simulations show that this envelope is not a 1D hydrostatic structure but is instead vigorously active and contains densities and temperatures that appear similar in magnitude and spatial extent to those thought by Desch & Connolly [1] to be responsible for the production of chondrules in the solar nebula.

Introduction According to the most likely theory for Jovian planet formation, Jupiter formed through the accretion of gas into an envelope surrounding a solids onto a rock and ice core, which then cools and compresses through a very nearly hydrostatic process over \( \sim 6 \) Myr (the ‘core accretion’ model). In the classic model [2], a 5-15\( M_\oplus \) rock/ice core forms at a distance of \( \sim 5 \) AU or more from the central star [3] over a period of about 1/2 million years. It then begins to grow a hydrostatic, gaseous envelope which slowly contracts and becomes more massive over a time period of as long as 6 Myr, reaching a total of about 30 \( M_\oplus \). In the final stage, the envelope begins to collapse and a relatively rapid accretion period follows, ending with the planet in its final morphology.

A critical assumption in the core accretion model is that gaseous envelope in the second stage is hydrostatic. We present a study designed to investigate whether this assumption is in fact valid, and to investigate the existence and character of the activity in the flow if it is not.

Our models: We model the flow of gas in a 3D cutout box centered on 10\( M_\oplus \) core, embedded in a circumstellar disk and orbiting a 1\( M_\odot \) star at \( a_{pl} = 5.2 \) AU. We use a 3D PPM based hydrocode [4] with a grid nested 6 deep to evolve the flow. The simulation volume extends 4 Hill radii \(( R_H = a_{pl}(M_{pl}/3M_\odot)^{1/3}, \) corresponding to about 1.1 disk scale heights) in each direction, defining a volume of \((0.897 \text{ AU})^3 \). Linear resolution on the finest grid (covering \( \pm 1/8 R_H \) in each direction) is about 1.3 times the diameter of Neptune \((6.5 \times 10^9 \text{ cm}) \). The grid is fixed to the planet, so that the simulations are performed in a rotating coordinate system. We use a ‘shearing sheet’ approximation, modified to include some non-linear terms neglected in the standard method.

We use an ideal gas equation of state with \( \gamma = 1.42 \) and include heating due to compression and shocks, but no radiative heating or cooling. The core is embedded in an initially near Keplerian background flow, balancing gravitational forces and a radial pressure gradient due to the initial condition of the underlying disk. The disk is assumed to extend from 0.5 to 20 AU, and have surface density and temperature profiles set to power laws proportional to \( r^{-1} \). The scales are set with \( 2 \Sigma_{pl} = 500 \text{ gm/cm}^2 \) and \( T_{pl} = 200 \text{ K} \). Volume densities required for the initial condition are obtained from the surface density and the disk scale height.

Results of our simulations: In figure 1, we show 2D cutouts of the gas density and temperature, taken through the disk midplane. The density structures are highly inhomogeneous and become progressively more so closer to the core. Densities both above and below that of the background flow develop due to shocks that produce hot ‘bubbles’, which then expand into the background flow. One such bubble is visible in the plots shown emerging to the lower right on the plot. Such structures are common over the entire the duration of the simulation and emerge in all directions, depending on details of the flow at each time. Material contained in these bubbles returns to the background disk.

Among a veritable zoo of models for the formation of chondrules and/or other annealed solids in the solar nebula [5,6], nebular shocks are currently favored as among the most likely to be the actual mechanism. Its drawbacks are that shocks that have the right density, temperature and velocity characteristics are hard to form and secondly, that it is difficult for these shocks to exist for a long enough time during the solar nebula’s evolution to produce enough bodies to match the current observations.

We propose that dynamical activity in the Jovian
Figure 1: 2D cutouts of the volume density (top) and temperature (bottom) taken through the disk midplane of the full 3D simulation and blown up to show the flow in the region $\pm \frac{1}{2} R_H$ around the core. Velocity vectors are shown projected onto the plane for the fourth and fifth grids, for the density plot. The white circle defines the radius of the accretion sphere $R_A = \frac{G M_{pl}}{c_s^2}$. The Hill volume is twice the size of the sub-box shown and is therefore not visible. The color scales are logarithmic and extend from $\sim 10^{-10}$ to $\sim 10^{-8}$ gm/cm$^3$ for density and from 180 to 6500 K for temperature.

The density and temperature parameter space for which significant annealing occurs [1–Table 5] are bounded by densities within a factor of a few of $10^{-9}$ gm/cm$^3$, quite similar to those found in the active regions of our simulations, in which temperatures appropriate for formation (1-2000 K) also are present. If present at all (see below for some caveats), the activity will endure for a long time, allowing both processing and reprocessing events to occur. Also, because there were a number of similar proto-Jovian objects in the solar system, processing will occur in many locations.

Skeptical remarks As with many other scenarios, there are a number of still unanswered questions contained in this scenario. Before any detailed analysis of the conditions in these simulations will be of real use for the theory of chondrule formation, we must perform models that included both radiative transport and a non-ideal equation of state for the gas. Without them, the densities and temperatures obtained in our simulations will contain significant errors compared to the real systems they are intended to model. Moreover, including them means the dynamical properties of the system will change, perhaps eliminating the shocks altogether. Although hopeful, we also note that the shock velocities ($M \sim 2$) are uncomfortably low compared to those quoted by [1]. Finally, after ejection from the envelope, this model does not address how the annealed bodies get to their final locations, in meteorites in the inner solar system.

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CAIS ARE NOT SUPERNOVA CONDENSATES. Larry R. Nittler¹. ¹Dept. of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Rd NW, Washington DC, 20015, (lrn@dtm.ciw.edu).

Introduction: In two recent abstracts, Lodders and Cameron [1, 2, hereafter LC04] reported a relationship between the abundances of extinct radioactivities in early solar system objects and their mean lifetimes. From this relationship, they suggested that calcium-aluminum-rich inclusions (CAIs) in primitive meteorites might have condensed within presolar supernova (SN) ejecta. Their argument was based on three lines of evidence: (1) CAIs have higher radioactivity abundances than the mean trend inferred for other meteoritic materials, (2) CAIs have slight $^{16}$O enrichments and other stable isotope anomalies, relative to assumed bulk solar system composition, and (3) extensive mixing in supernova ejecta will lead to a homogeneous ~solar elemental composition, allowing for high-temperature condensation of the mineral assemblages found in CAIs. Here, I consider these arguments and show that a supernova origin for CAIs is untenable.

Mean Life Relationship for Extinct Radioactivities: LC04 plotted the ratios of extinct radioactive isotopes to stable ones for a range of meteoritic materials (CAIs, chondrules, sulfides, bulk chondrites, achondrites and irons) against their mean lifetimes ($\tau$) and inferred a relationship $R \propto \tau^2$ for many of the non-CAI data. The CAI data for $\tau<10^7$ yr lie above the main trend for the other materials. LC04 interpreted this trend to mean that the bulk meteorites (both primitive and differentiated) have the initial solar system abundances of the radioisotopes and the CAIs have higher abundances, perhaps indicating that they formed within SN ejecta. An unstated consequence of this analysis is that the chondrites, achondrites and irons must have all formed very soon ($<\tau$ for the shortest lifetime considered, that of $^{26}$Al) after separation of the solar nebula from the galactic process that formed the mean life- abundance trend. If parent body formation and differentiation took place over longer time scales, the abundances of the extinct nuclides would be lower than the starting values set by the trend. However, there is significant evidence from long-lived radioactivities (e.g., the Rb-Sr and Pb-Pb systems) that the formation of the various meteorites and their parent bodies took place over several million years [e.g., 3]. Thus, one should consider the low-$\tau$ portion of the LC04 plot with caution and in fact there is considerable scatter in the data below $\tau<10^7$ yr (especially when the plotted $^{60}$Fe data and other data not considered by LC04 [e.g., 4, 5] are taken into account). Moreover, there is recent convergence of several isotope systems, both short-lived and long-lived, indicating a consistent chronology for CAIs, chondrules and other meteoritic objects [6]. These data are consistent with the usual interpretation that the abundance of short-lived nuclides in CAIs are those that the solar system formed with and lower values found in other objects are due to their having formed later.

Isotopic Evidence: LC04 suggest that the ~5% excess of $^{16}$O observed in CAIs is consistent with a supernova origin. However, more than fifteen years of studies on bona fide stellar condensates in meteorites (presolar grains, [7]) have indicated that individual stars produce highly non-solar isotopic compositions. In contrast to presolar grains, the isotopic compositions of CAIs are remarkably close to that of the Sun, whose composition is the result of mixing of the ejecta of an enormous number of stars over the age of the Galaxy.

Figure 1: O-isotopic and $^{26}$Al/$^{27}$Al ratios for interior mass zones of a 15M$_{\odot}$ Type II supernova [8].

Shown in Figure 1 are the solar-normalized O-isotopic ratios predicted for different zones within an initially 15M$_{\odot}$ Type II (core-collapse) supernova [8]. Although this star was originally of solar composition, nucleosynthesis and mixing during stellar evolution has led to highly non-solar O isotopic ratios throughout the envelope and interior. The O isotope ratios for the four distinct isotopic zones within this SN model are plotted in Fig. 2, together with the measured surface ratios for two well-known ~15 M$_{\odot}$ red supergiants. The supergiant data agree well with the model.
prediction for the SN envelope and confirm that single massive stars have highly non-solar O isotopic ratios. From these data, it appears prohibitively difficult to account for the ~solar O isotopic ratios of CAIs if they indeed condensed within single supernovae. Although in principle one could arbitrarily mix the zones in such a way as to reproduce the ~solar O isotopic composition of CAIs, such a mixture is highly unlikely. Moreover, based on the range of isotopic compositions observed in presolar grains from supernovae (e.g., a three order of magnitude range of $^{12}$C/$^{13}$C ratios in SiC and graphite SN grains [9, 10]), isotopic diversity appears to be a rule for supernova condensates, in conflict with the isotopic uniformity of CAIs.

![Figure 2: O isotopic ratios predicted for mass zones of a Type II supernova [8] and those observed in two red supergiant stars [11].](image)

This argument also applies to other isotopic systems, of course. For example, Fig. 1 also shows the predicted $^{26}$Al/$^{27}$Al ratio in the 15M$_{\odot}$ SN model. This ratio is much higher than the canonical CAI value of $5\times10^{-3}$ throughout the star. This is consistent with presolar grain data [9] and again argues against CAI condensation within fresh SN ejecta. In addition, the solar isotopic composition of Mg and Si in CAIs would be hard or impossible to account for if the objects formed as SN condensates.

**Supernova mixing:** It has been well established for some time that extensive mixing occurs in SN ejecta. This is based on astronomical observations of SN and their remnants [12, 13], isotopic compositions of SN-derived presolar grains [9, 14] and hydrodynamical models [15]. However, contrary to the assertion of LC04 [2], these results do not indicate that “the interior becomes quite thoroughly mixed.” Rather, the available data indicate that the ejecta becomes quite clumpy, where clumps of newly-synthesized material from the deepest layers of the ejecta propagate outward through overlying zones [15]. This in fact results in very chemically heterogeneous ejecta, as confirmed both by X-ray observations of SN remnants by the Chandra observatory [e.g., 13] and by the wide range of isotopic ratios measured in SN presolar grains. Prior to any mixing, the SN envelope itself has ~solar elemental composition, but admixture of deeper material to provide radioactivities would most likely lead to heterogeneous and non-solar chemical compositions. Whether such compositions could result in the condensation sequence inferred for CAI minerals remains to be seen, but the isotopic evidence outlined above probably makes such an exercise unnecessary.

**Conclusions:**
CAIs did not form as supernova condensates. Most likely, they formed very early in solar system history when the solar nebula contained live radioactivities with short lifetimes, recently synthesized in one or more nearby supernovae.

**References:**
Introduction: Comets, fine-grained matrices of chondrites, and chondritic interstellar dust particles (IDPs) are each composed of both crystalline and amorphous silicates. The primitive solar nebula, in which comets and asteroids accreted, was formed from the collapsed core of a Giant Molecular Cloud, that, in turn, condensed from materials present in the interstellar medium (ISM). Despite observations that reveal the presence of crystalline magnesium silicate minerals in the shells of very high mass-loss-rate stars [1,2], typical silicate grains in the ISM are most likely to be amorphous, given their relatively long residence time in such a high radiation environment. An upper limit of ~3% crystalline grains can be derived from their non-detection in spectra of ISM solids [3].

If the vast majority of grains that enter the primitive solar nebula are amorphous, then the observation of crystalline dust in comets and primitive chondrite matrices indicates the action of specific processes required to transform the amorphous starting materials into the crystals that are observed. Below we discuss several examples of such processes.

Crystalline Silicates in Comets: One of the remarkable sets of observations made by the Infrared Space Observatory were studies of Comets Hale-Bopp and Hyakutake in the far infrared. Although Campins and Ryan [4] had postulated that crystalline olivine dust was present in the coma of Comet Halley, based on observations of fine-structure within the 10-micron silicate stretch, it was not until the observations of the phonon resonances of magnesium-rich silicate minerals in the far infrared that the idea of crystalline grains in comets was taken seriously. This idea contradicted models of comet formation that assumed that cometary materials had always been cold (<30K) or models of the ISM dust population that considered silicate grains to be amorphous (based on observational evidence).

This contradiction led to two hypotheses for the conversion of initially amorphous grains into the minerals observed in cometary comae. Nuth [5] and colleagues [6,7,8] suggested that evaporation and condensation processes produce large quantities of amorphous materials in the nebula and that these and the initially amorphous interstellar dust were annealed in the inner nebula, then transported outwards to the area of comet formation by an as yet undiscovered wind. Because comets begin aggregating at ~100 to 200 A.U. [9] such winds may be observable with newer generation telescopes and instruments.

Shock waves, caused by matter falling into the giant planets, were also suggested as a means to convert amorphous dust to crystalline minerals [10]. This suggestion avoided the problems of an undiscovered outflow, but these events are extremely sporadic, and occur only once every 100,000 years. These two scenarios predict vastly different models for nebular chemistry. In the second scenario, the chemistry of the nebula is occasionally punctuated by a very brief period of high temperature reactions, but is otherwise a relatively quiescent gas, becoming progressively hotter and denser as it spirals to the sun. Only materials that are incorporated into a planetesimal-scale or larger body survive, and these bodies are formed from ice and dust grains that are modified from their interstellar starting compositions by reactions in the outer nebula.

The first scenario has vastly different implications for nebular chemistry. Although materials must still be preserved in planetesimal-scale bodies to survive, their chemistry is no longer limited to modifications that can be made to interstellar materials as the parcel of gas and dust falls to its 'final' orbital radius. Because a small fraction of the infalling material is transported back out into the far reaches of the nebula, the chemistry of the outer nebula can reflect processes that occur at much higher temperatures and pressures than previously assumed. As one example, higher pressures and temperatures can greatly increase the efficiency of surface-mediated reactions that convert CO, N2 and H2 into complex hydrocarbons such as those observed in comets [11]. Organic residues remaining on the surfaces of nebular grains could easily account for the highly refractory mixture of aliphatic and aromatic hydrocarbons found in carbonaceous meteorites [12].

Crystalline and amorphous silicates in chondrite matrices: Observations of matrices in primitive chondritic meteorites show that amorphous ferrous silicates and magnesium silicates were important components of the fine-grained dust in the solar nebula [13]. Rare, primitive, unaltered carbonaceous, CM2 and ordinary chondrites have matrices that contain a significant modal abundance of amorphous materials. This amorphous material occurs as compacted nanometer to micron sized domains that act as a groundmass in which crystalline phases are embedded. The crystalline silicate component consists largely of magnesian olivines and
pyroxenes, including Mn-rich varieties [14]. Submicron olivines with varying FeO contents are also present in some [15,16] but not all [17] matrices. Distinct aggregates of crystalline grains with textures consistent with high temperature annealing also occur. Nanophase sulfide and metal particles are important components in these primitive chondrites in addition to trace amounts of presolar grains. Magnesian pyroxenes have intergrowths of monoclinic and orthorhombic structures (like those in chondrules) indicative of cooling from >1000°C at ~1000°C/hr [15,17]. Fine-grained FeO-rich olivines dominate the matrices of even mildly metamorphosed chondrites but are not nebular condensates, [e.g.18]. They formed by thermal and hydrothermal processing of amorphous nebular precursors within asteroids.

Primitive chondrite matrices share a number of characteristics with chondritic IDPs which are thought to come from comets [19]. These include the high abundance of amorphous materials, pyroxene structures indicative of rapid cooling and the presence of Mn-rich magnesium silicates. However, chondritic IDPs differ from the matrices of primitive chondrites in that grain sizes are smaller in IDPs, and presolar grains are more abundant (percent levels) [20-22].

In matrices of very weakly altered CM2 chondrites, most notably Y791198 [23], fine-grained rims consist largely of amorphous silicate material that has locally undergone partial hydration to form nanocrystalline phyllosilicates. Coarser-grained phyllosilicate phases, characteristic of more heavily altered CM chondrites are absent. Further, crystalline silicate phases of high temperature origin are extremely rare and consist of Mg-rich olivines, some of which are also Mn-rich. Distinct domains of sulfide-rich and sulfide-poor amorphous material are present on the submicron scale. These materials have many of the characteristics of the so-called granular units in IDPs [19].

**Implications for nebular processes:** Chondrite matrices and chondritic IDPs contain a mixture of materials with different formation mechanisms and thermal histories. The crystalline magnesium silicates, particularly micron to submicron defect-free, Mn-rich olivines, resemble forsterites in AOA's and may also be condensates, though inferred O-isotope differences suggest formation in different environments. Some magnesium silicates may also have formed from annealed amorphous material [24, 25]. The amorphous component of matrices could have a variety of origins. As discussed earlier, the bulk of silicate material entering the nebula was amorphous in character. Some component of this interstellar silicate material could have escaped thermal processing (evaporation or annealing) and been incorporated into chondrite matrices.

However, it seems improbable that this component is particularly voluminous [21, 22]. Very limited oxygen isotopic data for matrices and bulk chondrite data suggest that chondrite matrices are 18O-poor, like chondrules, and formed in a similar environment to the chondrules themselves, i.e. represent materials that have been processed within the solar nebula. However, further oxygen isotopic data are needed to confirm this suggestion for more chondrite groups. If amorphous matrix materials did indeed form in the solar nebula, then they may represent material formed by disequilibrium condensation during short-lived high temperature events or by radiation-induced amorphization during, e.g. FU Orionis events or the T-Tauri phase of the protosun. Formation of amorphous silicates may occur during the short-lived high temperature events which formed chondrules. In such events, evaporation of some component of nebular dust must have occurred and this material must recondense under disequilibrium conditions, favoring formation of highly disordered silicate materials. As well as inducing evaporation, less energetic thermal events or the higher temperature regions of the inner nebula may have annealed amorphous materials to form the crystalline aggregates of Mg-Fe-silicates that occur in chondrite matrices. It may be that the smallest single crystals of this material remained coupled to the gas for transport to the outermost nebula.

**References:**
A NEARBY SUPERNOVA INJECTED SHORT-LIVED RADIONUCLIDES INTO OUR PROTOPLANETARY DISK. N. Ouellette, Steven J. Desch and J. Jeff Hester, Dept. Physics and Astronomy, Arizona State University, PO Box 871504, Tempe AZ 85287-1504 (steve.desch@asu.edu).

The recent discovery [1] that the early Solar System held live $^{60}$Fe ($t_{1/2} = 1.5$ Myr) in substantial quantities ($^{60}$Fe/$^{56}$Fe $\sim 3 \times 10^{-7}$) has made it clear that our Solar System formed in proximity to a supernova. This neutron-rich short-lived radionuclide cannot be produced by spallation reactions within the Solar System [2,3]. An asymptotic-giant-branch (AGB) star could produce $^{60}$Fe [4], but the probability of a solar system being contaminated by an AGB star is $< 3 \times 10^{-6}$ [5]. A supernova origin is demanded by the $^{60}$Fe data. The only question is, in what evolutionary stage was the Solar System and how far away was the Solar System when the supernova occurred.

Most current models of injection of short-lived radionuclides (SLRs) by a supernova focus on the ability of a supernova shock to trigger the collapse of a molecular cloud core [6,7]. We advocate a very different model, one in which a supernova injects SLRs into the Solar System, after it has already formed a protoplanetary disk and has started forming meteoritic solids. Such a model was suggested by T. Gold in 1977, and was termed the “flypaper” model [8]. Chevalier [9] developed the idea more fully, and showed analytically that protoplanetary disks would probably survive a nearby ($> 0.1$ pc distant) supernova shock. If the disks do survive, it is almost inevitable that the SLRs from the supernova ejecta will be implanted in the disk. Supernova ejecta forms dust grains within a year after the explosion (e.g., as observed following SN1987A [10]), and SLRs can be expected to condense into these dust grains. When these dust grains encounter a nearby protoplanetary disk, they are very likely to embed themselves in the disk, as depicted in Figure 1. By analogy to the method by which interplanetary dust particles are collected, we prefer the term “aerogel” to describe this model. In this abstract we describe the physical circumstances pertaining to the aerogel model, and examine its consistency with known astrophysical and meteoritic constraints.

The aerogel model is consistent with astronomical and astrophysical constraints. First, it is very likely for a protoplanetary disk to reside in an H II region, next to a massive O star that will soon go supernova. Approximately 75% of all Sun-like stars form in such environments [11]. The Orion Nebula, for example, contains roughly 2000 young stars [12], and 55-90% of these stars possess disks [13], many of them directly imaged [14]. When $^1$Ori C (the 40 $M_\odot$ O6 star that is ionizing the Orion Nebula gas) goes supernova in $\sim 1$ Myr, all of these disks will be contaminated with SLRs. The typical distances of these disks from $^1$Ori C are $\sim 0.2$ pc [12], and the typical masses and radii of the disks are $\sim 0.03 M_\odot$ and $\approx 30$ AU (due to photoevaporation) [15]. The typical supernova will ejecta $\sim 10 M_\odot$ at $\sim 3000$ km/s [16], and deposit $\sim 10^{51}$ erg of energy in the H II region gas. Disks 0.1 pc away will see a ram pressure in the ejecta $\sim 10^{-2}$ erg cm$^{-3}$, which is sufficient to drive the supernova shock into the protoplanetary disk only to the point where densities $\approx 10^{-11}$ g cm$^{-3}$. The midplane densities of the Orion disks likely exceed this value inside 30 AU, and so the shock cannot destroy the disks beyond 0.1 pc [9,16]. A similar conclusion is reached by considering the momentum in the shock [9,16]. On the other hand, the shock can penetrate to within $\sim 1 AU$ of the disk midplane [16]. Dust grains in the supernova ejecta containing SLRs will pass through the shock, enter the disk, and be slowed (and probably vaporize) [16]. We have conducted simple 1-D calculations to confirm where the supernova shock stalls [16], and we are currently initiating 2-D and 3-D numerical simulations as well. Protoplanetary disks in H II regions are not destroyed by supernovae, but they can receive SLRs from them.

The aerogel model is also consistent with meteoritic constraints. It is already known that supernovae can supply all the known SLRs (except $^{10}$Be) in roughly the meteoritic proportions [7,17]. We attribute $^{10}$Be to Galactic cosmic rays previously trapped in the Sun’s molecular cloud core [18]. Therefore, the relative proportions of the SLRs are explained and the only question is whether the absolute abundances can be explained as well. In the case of the Orion Nebula, the forthcoming supernova will inject $\sim 10^{-4}$ $M_\odot$ of $^{26}$Al into the nebula [19]. A 30 AU-radius disk 0.1 pc away will intercept $2.5 \times 10^{15}$ $^{26}$Al atoms. The number of $^{27}$Al atoms in a 0.03 $M_\odot$, solar-composition [20] disk is $7.5 \times 10^{59}$. We therefore predict an initial ratio $^{26}$Al/$^{27}$Al $\approx 3 \times 10^{-5}$, in very reasonable agreement with the meteoritic value [7], and within the uncertainties introduced by unknown variations in
SLR-bearing grains depositing SLRs in the Sun's protoplanetary disk.

Grains Disk Molecular Cloud Interior H II Region YSOs & Disks Freely Expanding Supernova Ejecta

For example, the disks in Orion follow a King spatial distribution with scale $\sim 0.2$ pc [12], allowing us to predict the probabilities disk form with various initial $^{26}\text{Al}/^{27}\text{Al}$ ratios, as illustrated in Figure 2. The abundances of the SLRs are therefore explained, except possibly $^{41}\text{Ca}$, which is overproduced. However, if formation of calcium-rich, aluminum-rich inclusions (CAIs) took 0.4 Myr, as inferred from Al-Mg systematics by Galy et al. [21], the $^{41}\text{Ca}$ discrepancy is resolved as well. The aerogel model is consistent with the “late injection” constraint. A subset of CAIs is inferred to have formed before the injection of $^{26}\text{Al}$ and $^{41}\text{Ca}$ [22], a constraint that might be explained in supernova trigger models [6,7], but which is a natural prediction of the aerogel model.

The aerogel model makes some important predictions. If the SLRs must be injected as dust grains, volatile SLRs may not enter the disk. Also, the travel time of ejecta from the supernova to the disk is only $\sim 30$ years [9,16], so even very short-lived radionuclides may be injected. We note the recent evidence for live $^{63}\text{Ni}$ in the early Solar System [23]. The half-life of $^{63}\text{Ni}$, which decays to $^{63}\text{Cu}$, is only 101 years. If this evidence for live $^{63}\text{Ni}$ is confirmed, only the aerogel model could explain it.


Figure 1: Probability that Orion disks are born with various $^{26}\text{Al}/^{27}\text{Al}$ ratios. The Solar System is labeled with a star. If the Sun were born in the Orion Nebula, its initial $^{26}\text{Al}/^{27}\text{Al}$ would be high but not implausibly so.
Introduction: Some Ca,Al-rich inclusions (CAIs) or their precursors formed by condensation after removal of an early condensed highly refractory component. The evidence is based on their uniquely fractionated rare earth element (REE) patterns. These Group-II REE patterns are the best evidence for condensation processes [1]. They cannot be produced by evaporation of chondritic material. Chondrules are richer in SiO$_2$ and MgO and less refractory as CAIs and have sampled material that formed at lower temperatures at which all REEs were fully condensed. Misawa and Nakamura [2] were the first to report gas/solid fractionated REEs in chondrules from carbonaceous chondrites (CCs). They attributed the unusual REE patterns to incorporation of CAI-like components into chondrule precursor material [3,4,5]. Chondrules from un-equilibrated ordinary chondrites (UOCs) have, in most cases, largely unfractionated REEs [6]. The lack of non-igneous fractionation in REEs of UOC chondrules may indicate that chondrule recycling was more effective in UOCs than in CCs.

Results: Amongst 12 chondrules studied, we have identified five chondrules with positive and negative anomalies in Sm, Eu, Tm and Yb (Fig. 1a–e). The chondrules come from CV3 chondrite Vigarano, UOCs (Dar al Gani 369: L/H3; Dar al Gani 378: H/L3, Chainpur LL3.4). REEs are highly incompatible with respect to the major chondrule phases (olivine, pyroxene). Hence, mesostasis is the major REE carrier and mesostasis analyses will give informations about REE fractionation of bulk chondrules [6].

Discussion: We present two types of REE patterns. The first type (Fig. 1d,e) includes large negative anomalies in Sm, Eu and Yb accompanied by a slight LREE < HREE fractionation. This pattern is suggestive of incorporation of an ultra refractory condensate that formed under highly reducing conditions at high C/O ratios [8]. Thermodynamic calculations indicate that Sm becomes considerably more volatile with decreasing C/O ratio [9]. It was suggested by [8] that ultra refractory oldhamite (CaS) was the high-REE carrier phase in the precursor material of the two chondrules DaG369-RF02 and DaG378-RF03. Oldhamite occurs in the highly reduced enstatite chondrites (ECs). The presence of oldhamite in UOC chondrule precursor material would indicate mixing of UOC and EC material [8].

The second new REE pattern is characterized by positive Sm, Eu, Tm and Yb anomalies and a slight LREE < HREE fractionation (Fig. 1a–c). A very similar pattern has been observed in perovskite from ALH85085 (CH2) [10] and hibonite from the CM2 chondrite Murchison [11] (Fig. 1f). These patterns can be explained in terms of removal of the “reduced” ultra refractory component followed by condensation of the remaining gas with enrichments of the more volatile REEs.

The presence of Sm anomalies in chondrules indicates that a certain fraction of both, CC and UOC chondrule precursor materials formed by fractional condensation at non-canonical high C/O ratios [8]. An elevated C/O ratio can be the result of evaporation of C-rich material from the ISM. The data from [10,11] indicate that anomalous Sm may not be restricted to highly reduced material as CaS. None of the chondrules from CCs and UOCs contained CaS or any other exotic reduced phase. Either the reduced phases in the precursor had been oxidized during the chondrule forming event or oxides and silicates such as shown in Fig. 1f were the high-REE carriers with anomalous Sm.

The presence of gas/solid fractionated REEs in chondrules excludes extensive recycling of chondrules which would ultimately lead to largely unfractionated REEs. We suggest that chondrule recycling in the CC
and OC formation region was not effective enough to erase all nebular REE signatures in chondrules.

The number of chondrules with unusual REE patterns in a given meteorite is not well known. This would require REE analyses of hundreds of chondrules. A better knowledge of the fraction of unusual chondrules would allow to develop a stochastic model that predicts the maximum number of chondrule recycling steps.

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Fig. 1: C1-normalized REE concentrations in mesostases from (a,b) Vigarano, (c,d) DaG378 and (e) DaG369. (f) shows data from CAI hibonite and perovskite with distinct positive Sm anomalies (data from [10,11]).
METEORITIC CONSTRAINTS ON TEMPERATURES, PRESSURES, COOLING RATES, CHEMICAL COMPOSITIONS, AND MODES OF CONDENSATION IN THE SOLAR NEBULA.  
Michail I. Petaev$^{1,2}$, Denton S. Ebel$^1$, and John A. Wood$^2$. $^1$Dept. Earth and Planetary Sciences, Harvard University (mepetav@cfa.harvard.edu); $^2$Harvard-Smithsonian Center for Astrophysics (jwood@cfa.harvard.edu); $^3$Dept. Earth and Planetary Sciences, American Museum of Natural History (debel@amnh.org).

Introduction: Since about 1963, when Cameron [1] introduced the concept of the solar nebula to meteoritists, primitive chondrites have been studied to learn about nebular properties and evolution. The idea of a completely vaporized nebula led to the development of competing equilibrium [e.g.,2-5] and disequilibrium [6-8] models describing condensation of solid materials, which served as building blocks of chondritic meteorites. Despite the obvious need for some degree of fractionation disequilibrium during condensation in order to preserve high-temperature condensates, the equilibrium condensation sequence described by Grossman and Larimer [9] served, for more than a decade, as the major tool in interpretation of the mineralogy and chemistry of primitive meteorites.

With time, a detailed comparison of the equilibrium condensation sequence with mineralogy of meteorites revealed some significant discrepancies, which led to the development of new or refined condensation models. In addition, the incorporation of new, more precise data on mineral solid solutions into these condensation models allowed a direct comparison of calculated and measured mineral chemistry to be made. Altogether, these improvements enable us to place better constraints on the nebular processes that are the subject of the current review.

Methods: Models for condensation that are based on equilibrium thermodynamics, whether they account for fractionation of condensates or not, depend upon algorithms and data. We will review current efforts, and examine how calculation techniques, and the selection of particular data, bear on specific problems such as the relative appearance temperatures of feldspar and olivine in the cooling of a gas of solar composition at different total pressure.

Condensation in fractionated systems: From one hand, condensation of a gas of solar composition at total pressures at or below $10^{-3}$ bar produces essentially pure forsterite with negligible FeO contents, implying that more ferrous olivines as well as other FeO-bearing components found in essentially all primitive meteorites should have equilibrated with gas at more oxidizing conditions. From the other, the predicted lithophile behavior of Ca, Ti, Mg, Mn, Na, and K in the nebula of solar composition is inconsistent with the presence of sulfides and/or nitrides of these elements in enstatite chondrites, implying that the latter probably formed at more reducing conditions. Several models [10-12] were put forward to account for these deviations, with the paper by Wood and Hashimoto [13] having presented the first systematic study of mineral equilibria in systems enriched in varying proportions of different primordial components (such as gas, dust, ice, and tar) in the nebular source regions. They found they could account for some properties of primitive meteorites that were inconsistent with the equilibrium condensation sequence of the nebula of solar composition.

We will review the results of this study and extend this type of modeling to the systems, which include 19 most abundant elements.

Stability of melts: Using a simplistic, ideal solution model of silicate melts, Wood and Hashimoto [13] found that at certain enrichments of nebular source regions in dust relative to gas, silicate melts could appear among stable condensates. Yoneda and Grossman [14] and Ebel and Grossman [15] systematically explored melt formation using a more realistic, non-ideal models of CaO-MgO-Al$_2$O$_3$-SiO$_2$ liquid [14], and FeO-MnO-Cr$_2$O$_3$-TiO$_2$-Na$_2$O-K$_2$O-bearing silicate melt [15]. They found that the stability of melts depends upon both the nebular pressure and the initial enrichments of the nebular source regions in chondritic dust. It was also found that in dust-enriched systems silicate melts and coexisting solids could contain substantial concentrations of FeO at high temperature, comparable with those observed in some chondrules. Although a preponderance of evidence supports the theory that chondrules formed by remelting of solid precursors in transient heating events rather than by direct condensation of silicate melts from nebular gas, it is still important to estimate nebular parameters at which silicate melts can be stable. We will review the results of current models [14, 15] in some detail and compare them with meteoritic data as well as with physical models of solar nebula in order to place tighter constraints on the stability of silicate melts in the solar nebula.

Effects of condensate isolation: Despite the apparent failure of earlier disequilibrium condensation models [16-18] in accounting for the observed mineralogy of primitive meteorites, the very presence of high-temperature condensates in them requires an isolation of, at least, a portion of such condensates from further reactions with the residual nebular gas. This could, for example, occur by limited diffusion into grains in a fast-cooling nebula [4]. Depending upon the fraction of condensates isolated in the course of con-
densation, the condensation sequence of the residual gas may or may not be affected. To explore this issue Petaev and Wood [19] developed the CWPI condensation model, which assumes that as equilibrium condensation proceeds, a specified fraction of condensed phases is steadily withdrawn from reactive contact with the residual nebular gas at each step, presumably as a result of growth and aggregation of condensed mineral grains. They found that the isolation of condensates could drastically change the condensation sequence of the gas of solar composition and result in the appearance of new phases, some of which were found in primitive meteorites. It was also found that the segregation of coarse condensates from the fine dust and residual gas could result in volatility-based fractionation patterns similar to those observed in primitive meteorites. We will present new results of CWPI-type modeling in the system containing 19 most abundant elements. The results obtained so far show that the expansion of the system from 10 to 19 elements did not change main conclusions of [19]. Details of new calculations will be discussed at the conference.

**Effect of pressure:** Total nebular pressure still remains poorly constrained. Since the work of [5] it is customary for a meteoricist to think that an increase (or decrease) in total nebular pressure results in a corresponding change in condensation temperatures of all the minerals, so the equilibrium condensation sequence remains virtually unchanged. The only exception is the well-known olivine-metal reversal at ~7×10⁻⁵ bar [5]. Later it was found [14, 15] that the stability of silicates melts is also pressure-dependent. A systematic study of condensation at different pressures [20] found other important effects, in addition to the olivine-metal reversal. Meteoritic evidence for pressure-dependent condensation was published only recently [e.g., 21-24]. We will present new data on condensation sequences at different nebular pressures and use them and meteoritic data to estimate pressures in the nebular source regions of primitive meteorites.

**Nebular cooling rates:** Cooling rates derived from chondrules and CAIs are quite imprecise; they refer to some sort of transient events rather than to episodes of primary nebular condensation. Recently discovered zoned metal grains thought to be nebular condensates [24-28] provide an opportunity to estimate cooling rates during nebular condensation in the region where they formed. Calculated estimates of cooling histories of such grains [28] point to time scales of 5–10 weeks which include periods of active growth of a grain and its annealing in the nebular source region, followed by a prompt ejection and rapid burial in a cold environment (parent body?). A new round of calculations, which include new experimental data on diffusion of Ni, Co, and Cr [29], is underway.

**Concluding remarks:** At the conference we will attempt to integrate all these ideas into a more or less consistent model, to the extent possible. General outlines of such a model are as follows: (1) Monotonous, equilibrium condensation of nebular materials from a chemically homogeneous solar nebula is unlikely. (2) It appears that few, if any, primitive components condensed from a gas of the solar composition. Local chemical variations were a common place in the solar nebula. (3) Condensation of nebular gas was quite rapid, resulting in significant deviations from chemical equilibrium between condensed phases and the residual gas. Nevertheless, the equilibrium condensation sequence [e.g., 30] is still useful in a sense that it outlines a general trend of evolution of a parcel of cooling nebular gas. (4) Mineralogy and chemistry of primitive nebular components points to repeated episodes of condensation and/or nebular metasomatism, which often took place in nebular reservoirs with differing chemical compositions and total pressures.

THE I-Xe RECORD OF LONG EQUILIBRATION IN CHONDRULES FROM THE UNNAMED ANTARCTIC METEORITE L3/LL3. O. V. Pravdivtseva, A. P. Meshik and C. M. Hohenberg, McDonnell Center for the Space Sciences and Department of Physics, CB 1105, One Brookings Drive, Washington University, St. Louis MO 63130 (olga@wustl.edu).

Introduction: The unnamed Antarctic meteorite studied here is of primitive chondritic type L3 or LL3, probably of grade 3.5 – 3.6 [1, 2]. Detailed mineralogical and SEM analyses [2, 3] have revealed the existence of three distinct chondrule types in this meteorite. Both iron-rich and some iron-poor chondrules are present with variably recrystallized matrices or mesostases reflecting variable equilibration. Patchy equilibration of chondrule mesostases suggests thermal metamorphism after accretion.

Results: The fragments of twelve chondrules were received from the Geological Survey of Canada, six (ranging in weight from 2.1 to 12.0 mgm) were irradiated for I-Xe studies along with a sample of Shallowater, the internal standard. Other fragments of these twelve chondrules were saved for Pb-Pb analyses.

Chondrules are complex objects and potentially contain multiple iodine host phases. It was shown in the previous studies of Richardton and Elenovka chondrules [4, 5], that step-wise heating can provide the closure ages of two phases if the extraction temperatures do not overlap too much. Xe from these chondrules was extracted in step-wise heatings with 50 °C increments to provide optimum resolution between possible low and high temperature iodine host phases. Smaller temperature steps are not practical since these small chondrule fragments would not have enough radiogenic xenon for reliable measurement.

After correction for minor uranium fission contributions, $^{128}\text{Xe}$ and $^{129}\text{Xe}$ were plotted versus $^{132}\text{Xe}$, in which the relative slopes of apparent isochrons provide the closure ages relative to the Shallowater monitor (4,566 ± 2 Ma). All, except chondrule #2 demonstrate two fairly well resolved isochrons, showing Xe closure in distinct low- and high-temperature phases (Figure), but with higher uncertainties for the low-temperature phases, defined by a smaller number of temperature steps. However, when considered together, the four of the five low temperature isochrons define a consistent age interval, 24.2 ± 0.5 to 34.5 ± 0.8 Ma after (younger) than Shallowater 4,566 ± 2 Ma. Chondrule #3 yielded that same age, 32.6 ± 0.3, but for the higher temperature isochron, and the low temperature isochron indicated an even younger age, 83.5 ± 1.4 Ma after Shallowater.

The higher extraction steps all provide isochrons with much older apparent ages (Table), the oldest chondrules (#1 and #2) tend to have broader release peaks for their radiogenic $^{129}\text{Xe}$. The younger chondrules (#5 and #6) have very sharp release of radiogenic Xe in the 1300 °C – 1450 °C temperature interval and virtually no radiogenic signal above 1450 °C, suggesting post-formational metamorphism.

Although the apparent I-Xe ages spread from 4.5 ± 0.8 to 83.5 ± 1.4 Ma, they can be grouped according the temperatures of the release peak of the radiogenic $^{129}\text{Xe}$ and $^{128}\text{Xe}$ responsible for the isochrons. This probably indicates the presence of multiple iodine host phases. Detailed textural and mineralogical studies of this unnamed Antarctic meteorite [2, 3] have shown the presence of clinoenstatite, low-Ca orthopyroxene, Ca-pyroxene and a mesostasis or matrix partially or completely recrystallized to feldspar in chondrules.

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<td>1300 – 1900 °C</td>
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<tr>
<td>#1</td>
<td>4.5 ± 0.8</td>
</tr>
<tr>
<td>#2</td>
<td>5.5 ± 0.3</td>
</tr>
<tr>
<td>#3</td>
<td>32.6 ± 0.3</td>
</tr>
<tr>
<td>#4</td>
<td>15.0 ± 0.5</td>
</tr>
<tr>
<td>#5</td>
<td>11.1 ± 0.4</td>
</tr>
<tr>
<td>#6</td>
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</tbody>
</table>
The wide range of I-Xe ages provided by these 10 isochrons from 6 chondrules suggests a long period of equilibration. Same conclusion was drawn by Herd et al. [2], based on six U-Pb and Rb-Sr analyses of fragments from 5 chondrules. The young isochron ages for Pb-Pb and Rb-Sr, 4489 ± 43 and 4385 ± 40 Ma respectively, support the conclusion that this meteorite has a more complex heating history than indicated by the textures and mineral analyses.

An attempt is now under way to determine the carriers of the radiogenic xenon by laser extraction from different mineral phases on polish sections of these chondrules.

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EARLY STELLAR EVOLUTION. Bo Reipurth. Institute for Astronomy, University of Hawai‘i, 940 N. Aohoku Place, Hilo, HI 96720, USA (reipurth@ifA.hawaii.edu)

This talk will give a broad overview of our current understanding of key aspects of the formation and early evolution of low-mass stars based on the latest observational results.

Types of Young Low Mass Stars: In the present context, stars are considered to be of low mass when they have masses between the brown dwarf limit of 0.08 solar masses and about twice the mass of the Sun. Newborn and young low mass stars are classified according to their broad energy distributions into four categories [1]: Class 0 objects are true protostars, which are still in the process of assembling the bulk of their mass from an infalling envelope. Such objects are very cold and are detectable only at sub-millimeter wavelengths. Class I objects are still embedded in their placental clouds, but they have accreted most of their mass, although accretion for many of these objects still plays an important role. These objects can be detected at infrared wavelengths. Class II objects are generally associated with the classical T Tauri stars, objects that are mostly visible stars, but which have numerous spectral characteristics of residual accretion. Class III objects are still pre-main sequence objects, i.e. they have not yet started nuclear burning in their cores, but they show very few characteristics of stellar youth. It is generally assumed that the planet forming phase takes place during the Class III stage.

The Formation of Single and Multiple Stars: Our Sun is single, and this has given us a particular bias towards the study of single stars. However, 2/3 of all stars are in binary or multiple systems, so our understanding of star formation would be seriously incomplete if we cannot explain the formation of such systems. Binary stars are believed to be the result of fragmentation processes in dense star forming cloud cores [2]. If more than two stars are formed, important dynamical interactions will take place that can significantly affect the ability of the individual stellar embryos to feed on the infalling gas, and thus will have an impact on the masses that the individual stars eventually can attain [3].

Clustered Star Formation: Isolated star formation is rare. Almost all stars are formed in groups or clusters numbering from a few dozen to a hundred thousand or so [4]. The Sun almost certainly was formed in a clustered environment [5]. This poses a number of hazards to the circumstellar disks of newborn low-mass stars, including dynamical effects and irradiation by ultraviolet radiation from massive newborn stars [6].

High-velocity Jets: As low angular momentum material falls onto a nascent star, gas with higher angular momentum will be fed onto its circumstellar disk. Processes exist that will transfer angular momentum outwards in the disk while gas spirals inwards. At the inner disk edge, funnel flows along magnetic field lines will guide most of the gas onto the star, while a fraction is locked onto open magnetic field lines anchored in the innermost disk. Rotation of the disk forces the ionized gas that is locked onto the magnetic field lines to be flung away at high velocity [7]. High resolution observations of highly collimated jets at optical, infrared, and radio wavelengths have given us insights into the episodic nature of the mass accretion and mass ejection of newborn stars [8].

Disk Accretion Events: All young stars are irregularly variable at some level. The variability is mostly dominated by the infall of matter onto the stellar surface from the circumstellar disk. As stars move towards the main sequence this variability generally decreases. Two categories of variable young stars have attracted major interest, these are the FUors and the EXors [9]. The FUors, named after the prototype object FU Orionis, have major outburst amplitudes of 5-6 magnitudes, reaching luminosities of many hundred Suns, followed by slow decays lasting for several to many decades. The optical spectra of FUors are those of F and G supergiants. This phenomenon has been interpreted in terms of a major increase in accretion through a circumstellar disk, leading to a major release of energy that heats up the disk and makes it much more luminous than the central star [10]. EXors appear to be similar to FUors except that their outbursts last only about a year. These outbursts may be triggered by either instabilities in the disk [11], or by disturbances caused by the close passage of a companion star [12].

References: