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## Implications of isotopic anomalies and presolar grains for the formation of the solar system

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**Abstract:** Isotopic anomalies are widespread in primitive chondritic meteorites and most of them can be tied to specific presolar materials from the Sun's parent molecular cloud. The known types of presolar materials come from many stellar and interstellar sources and exhibit a wide range of thermal and chemical stability. Bulk compositions and the abundances and characteristics of presolar grains indicate that CI chondrites and CM2 matrices originated from unfractionated samples of the Sun's parent molecular cloud. In the least metamorphosed members of other chondrite classes, correlations between the abundances and characteristics of presolar grains and the bulk compositional properties of the host meteorites indicate that the chondrite classes arose through different degrees of partial evaporation of the dust inherited from the Sun's parent molecular cloud. Condensation from a gas of solar composition is effectively ruled out as the primary mechanism for the volatility-controlled fractionations among the chondrite classes.

**key words:** isotopic anomalies, presolar grains, chemical fractionations, chondritic meteorites

### 1. Introduction

Studies of the isotopic compositions of meteoritic materials have been going on since the 1950's (e.g., Wasserburg and Hayden, 1955; Patterson, 1955; Gerling, 1956; Fireman and Schwarzer, 1957). Some of the early meteorite work appeared to reveal significant isotopic anomalies that could not be explained by mass dependent fractionations during physical and chemical processes, by spallation reactions, or by decay of radioactive nuclides (e.g., Murthy, 1960, 1962a, b; Umemoto, 1962). However, these early anomalies turned out to be instrumental effects (e.g., Murthy, 1963; Chakraborty *et al.*, 1964; Dews and Newbury, 1966). The failure to find isotopic anomalies in natural materials led to the widespread belief that the solar system was a homogeneous isotopic reservoir. This belief was expressed clearly by Suess (1965) in the following paragraph:

“Among the very few assumptions which, in the opinion of the writer can be considered well justified and firmly established, is the notion that the planetary objects, *i.e.*, planets, satellites, asteroids, meteorites and other objects of our solar

system, were formed from a well-mixed primordial nebula of chemically and isotopically uniform composition. At some time between the time of formation of the elements and the beginning of condensation of the less volatile material, this nebula must have been in the state of a homogeneous gas mass of a temperature so high that no solids were present.”

This basic idea was a key component of most models for the early solar system well into the 1980's, and is a common theme in discussion of the early solar system even today. As an example, consider models for the chemical fractionations among meteorite classes. These chemical fractionations were first convincingly modeled using the concept of equilibrium condensation from a gas of solar composition (*e.g.*, Larimer, 1967; Larimer and Anders, 1967, 1970; Grossman, 1972). However, since about 1970, a growing list of isotopic anomalies in meteoritic materials (*e.g.*, Clayton, 1988) and the discovery of presolar grains in meteorites (*e.g.*, Lewis *et al.*, 1987; Tang and Anders, 1988) have demonstrated that the simple view of the solar system described by Suess (1965) cannot be correct. Yet, equilibrium condensation still plays a major role in the thinking about chemical fractionation (*e.g.*, Meibom *et al.*, 1999; Palme, 2001; Lin and Kimura, 2003).

In this paper, I will summarize the major features of the voluminous data on isotopic anomalies in meteorites and the types and distribution of known types of presolar materials. I will argue that these data can best be understood as reflecting the survival of components from the Sun's parent molecular cloud. I will identify the meteorites that appear to best reflect the bulk material of the molecular cloud, and then compare the fractionations recorded in the presolar components from unmetamorphosed meteorites in each of several chondrite classes to the chemical fractionations recorded in the bulk compositions of the same meteorites. These fractionations are correlated, which suggests that the same process is responsible for both types of fractionation. If so, then differential condensation from a gas of solar system composition, cannot be responsible for the chemical fractionations observed in chondrites because the evaporation required to produce the gas of solar composition would destroy the presolar grains and would eliminate any causal relationships between the two types of fractionation. Finally, I will present a model based on differential partial evaporation of molecular cloud dust that seems to explain the observations.

## 2. Isotopic anomalies in meteorites

The first evidence that the solar nebula described by Suess (1965) and widely accepted as the initial state of the solar system had, in fact, never existed was already being discovered in the early 1960's, although it was not immediately recognized. Reynolds (1960a, b, c) discovered two classes of isotopic anomalies in xenon. A “special anomaly” in  $^{129}\text{Xe}$  was interpreted to result from decay of  $^{129}\text{I}$  and was proposed as a potential chronometer for the early solar system (Reynolds, 1960c; Reynolds and Turner, 1964). In addition, “general anomalies” were found in many isotopes of xenon from several carbonaceous chondrites, and because of their similarity across meteorites, the composition was given the name “average carbonaceous chondrite” (AVCC) xenon. AVCC xenon showed anomalies in essentially all isotopes relative to terrestrial xenon. These anomalies were interpreted to reflect severe mass fractionation plus the addition

of a fission component. The fission component was given the name “carbonaceous chondrite fission xenon” (CCF-Xe) (e.g., Krummenacher *et al.*, 1962; Reynolds and Turner, 1964). CCFXe and correlated excesses in light isotopes later turned out to be Xe-HL from presolar diamonds (Lewis *et al.*, 1987). Huge variations in isotopic composition were also found in neon (e.g., Black and Pepin, 1969). Black (1972) actually proposed that one component (Ne-E) was presolar, but his suggestion was not taken seriously.

The first isotopic anomalies in elements other than noble gases were found in oxygen (Clayton *et al.*, 1973). The early, preferred interpretation for oxygen anomalies was that an  $^{16}\text{O}$ -rich carrier, probably from a supernova, had been scattered through the solar system (e.g., Clayton *et al.*, 1977). This idea gained support when isotopic anomalies in many elements that were broadly consistent with supernova synthesis began to be found in calcium-aluminum-rich inclusions (CAIs), primarily from Allende (e.g., Wasserburg *et al.*, 1977; McCulloch and Wasserburg, 1978a, b; Lee *et al.*, 1978). Cameron and Truran (1977) proposed that a supernova actually triggered the formation of the solar system. However, because the CAIs are highly refractory and contain many of the minerals predicted to be the first condensates of the hot solar nebula, there was no serious attempt to overturn the hot-nebula model, only to modify the model by allowing late injections of anomalous material (e.g., Cameron and Truran, 1977).

Another class of isotopic anomalies was discovered around 1980. Organic material from some primitive chondrites was found to be highly enriched in deuterium (Robert *et al.*, 1979; Kolodny *et al.*, 1980; Robert and Epstein, 1982; Yang and Epstein, 1983, 1984). The anomalies were so large that they could only have originated through ion-molecule reactions at very low temperatures such as those found in the Sun’s parent molecular cloud (e.g., Geiss and Reeves, 1981). At about the same time, large carbon isotope anomalies were being found in primitive chondrites (Swart *et al.*, 1983). These anomalies could not be understood in terms of late addition of supernova material to the early solar system. By the mid 1980’s, about one-third of the elements with more than one isotope and roughly half of the elements accessible to measurement had shown isotopic anomalies in meteorites (*cf.*, Clayton, 1988). These anomalies could not be explained by a single source and thus represented a direct and powerful challenge to the concept of a hot, homogeneous solar nebula. Yet most discussions of solar system origin were still based on the hot-solar-nebula paradigm.

### 3. Presolar grains in meteorites

With the discovery that Xe-HL and associated noble gases are carried in tiny nanodiamonds (Lewis *et al.*, 1987), the challenge to the hot solar nebula became too great to ignore any longer. Within a year, presolar SiC was identified as the carrier of Ne-E(H) (Tang and Anders, 1988), and the SiC was soon shown to have come directly from carbon-rich AGB stars (Zinner *et al.*, 1989; Gallino *et al.*, 1990; Lewis *et al.*, 1990). Shortly thereafter, presolar graphite was identified as the carrier of Ne-E(L) (Amari *et al.*, 1990). These three presolar components were quickly shown to be present in all classes of chondrites, in meteorites that have not been metamorphosed

enough to destroy their primary constituents (Huss, 1990). Since that time, several different presolar oxides, silicon nitride, and most recently, presolar silicates have been identified in meteorites and interplanetary dust (Table 1). These and other potential presolar components are widely distributed in primitive chondrites and indicate that meteorites sampled the average material from the Sun's parent molecular cloud (Huss and Lewis, 1995; Huss *et al.*, 2003).

The widespread presence of presolar grains in all classes of chondrites is very hard to reconcile with a hot solar nebula in which all solids were vaporized, no matter how well condensation from a gas of solar composition seems to explain the bulk compositions and chemical fractionations among chondrites. The reluctance to abandon condensation models is due in part to the fact that an equally detailed alternative has not been developed. In the rest of this paper, I will attempt to show that partial evaporation of the bulk dust inherited from the Sun's parent molecular cloud to different levels for different meteorite classes provides a viable way to understand not only the presence of presolar grains in meteorites, but also their relative abundances and the chemical

Table 1. Inventory of known types of presolar grains.

| Material  | Abundance in Prim. Material | Source                 | Thermal Resistance | Chemical Resistance | Ref.  |
|---|-----------------------------|------------------------|--------------------|---------------------|-------|
| <b>Reduced Types</b>  |                             |                        |                    |                     |       |
| Diamond   | ~1400 ppm                   | Supernovae ?           | Variable           | High                | 1     |
| Silicon Carbide   | ~14 ppm                     | AGB stars, supernovae  | High               | High                | 1     |
| Graphite  | ~10 ppm                     | AGB, supernovae, novae | Low                | Moderate            | 1,2   |
| Silicon Nitride   | >4 ppb                      | supernovae             | High?              | High                | 3     |
| D-rich organics   | ?                           | Molecular cloud        | Low                | Low                 | 4     |
| TiC, ZrC, MoC, RuC, FeC, & Fe <sup>o</sup> as subgrains in graphite | ?                           | AGB, supernovae, novae |                    |                     | 5     |
| <b>Oxidized Types</b>   |                             |                        |                    |                     |       |
| Al <sub>2</sub> O <sub>3</sub>                                      | 50 ppb                      | AGB stars              | High               | High                | 6     |
| Spinel  | 1 ppm                       | AGB stars, supernovae  | High               | High                | 7     |
| Hibonite  | ?                           | AGB stars              | High               | High                | 8     |
| TiO <sub>2</sub>  | ?                           | AGB?                   | High?              | Moderate            | 9     |
| <b>Silicates</b>  |                             |                        |                    |                     |       |
| Forsterite  | High, variable              | AGB stars              | High               | Low                 | 10-12 |
| Pyroxene  | High, variable              | AGB stars              | High               | Low                 | 11    |
| GEMS  | High, variable              | AGB stars, supernovae  | Low                | Low                 | 11,13 |
| <b>Others with unknown carrier indicated by isotope anomalies</b>   |                             |                        |                    |                     |       |
| Ne-E(H)*  | Similar to SiC?             | AGB?                   | Low                | Low                 | 14    |
| Chromium  | ?                           | ?                      | ?                  | Low                 | 15    |
| Molybdenum  | Similar to SiC?             | AGB?                   | Unknown            | Low                 | 16    |

Data from: 1) Huss and Lewis, 1995; 2) Amari *et al.*, 1990, 1993; 3) Nittler *et al.*, 1995; 4) Yang and Epstein, 1983; 5) Bernatowicz *et al.*, 1996; 6) Nittler *et al.*, 1997; 7) Zinner *et al.*, 2003; 8) Choi *et al.*, 1999; 9) Nittler and Alexander, 1999; 10) Messenger *et al.*, 2003; 11) Nguyen and Zinner, 2004; 12) Nagashima *et al.*, 2004; 13) Mostefaoui *et al.*, 2004; 14) Huss *et al.*, 2003; 15) Podosek *et al.*, 1997; 16) Dauphas *et al.*, 2002.

fractionations observed in meteorites. This approach is not as easy to model quantitatively as equilibrium condensation, but I believe it provides a more useful framework within which to understand the early solar system.

Key data to be used in this discussion are the abundances of several presolar components. It is currently very difficult to determine abundances accurately, because presolar grains are very small and low in abundance. The most reliable way found to date is to use distinctive noble gas components as tracers of their carriers (*e.g.*, Huss and Lewis, 1995; Huss *et al.*, 2003), although carbon isotopes also can provide good information about silicon carbide abundance (*e.g.*, Russell, 1992). However, these tracers do not give information about the abundances of presolar oxides and silicates. All data used in this paper were generated by measuring noble gases in acid residues produced in my laboratory following high-yield chemical procedures (Huss and Lewis, 1995; Huss *et al.*, 2003). They thus comprise a self-consistent data set. In previous papers, the measured abundances of the noble-gas components were converted to abundances of their carriers (Huss and Lewis, 1995; Huss *et al.*, 2003). For graphite and silicon carbide, this is the same as multiplying by a constant. But presolar diamonds contain three noble-gas components whose relative and absolute abundances in the diamond separate vary from meteorite to meteorite, reflecting the thermal history of the diamonds (Huss and Lewis, 1994a, b). In previous work, the abundances of diamonds in the chondrites today were calculated from the measured content of Xe-HL in the etched residue and the Xe-HL content of the diamond separate from the same meteorite (Huss and Lewis, 1995; Huss *et al.*, 2003). In this paper, we are concerned with the fractionations produced in the solar nebula, so I will use the abundances of the diamond noble-gas components in the bulk meteorite. This eliminates confusion caused by the change in Xe-HL content of diamonds as a function of thermal processing (*cf.*, Huss and Lewis, 1994b). Abundances of all presolar components in the figures were thus calculated in an equivalent way.

#### 4. The best samples of raw material for the solar system

In order to discuss partial evaporation of bulk molecular cloud dust, it is necessary to identify the material most representative of molecular cloud dust. The chondrites with bulk compositions closest to that of the solar chromosphere are the CI chondrites (*e.g.*, Anders and Grevesse, 1989). This compositional similarity suggests that CI chondrites accreted an approximately representative sample of the solid elements in the Sun's parent molecular cloud. The Orgueil CI chondrite has high abundances of presolar diamond, SiC, and graphite, and its diamonds have the highest concentrations of low-temperature P3 noble gases (Huss and Lewis, 1994a, 1995). Orgueil also contains presolar oxides (Hutcheon *et al.*, 1994), anomalous chromium (*e.g.*, Podosek *et al.*, 1997), *s*-process molybdenum (Dauphas *et al.*, 2002), and an unknown additional carrier of Ne-E(H) (Huss *et al.*, 2003). In addition, Orgueil contains deuterium-enriched organic material (bulk  $\delta D \approx +1360\text{‰}$ ; *e.g.*, Robert and Epstein, 1982; Halbout *et al.*, 1990) that is thought to reflect low-temperature ion-molecule reactions in the Sun's parent molecular cloud (*e.g.*, Kerridge, 1983). The known presolar materials in Orgueil span the range of thermal resistance and include both oxidized and reduced

types.

CM2 chondrites consist of 50–60% fine-grained hydrated matrix and 40–50% chondrules and CAIs (McSween, 1979). The bulk composition of the matrix is very similar to that of CI chondrites, and the bulk chemical-abundance patterns for CM chondrites have been interpreted in terms of roughly equal mixtures of CI-like matrix and material that was processed to high temperatures in the nebula, such as chondrules, CAIs, etc (*e.g.*, Wolf *et al.*, 1980). CM2 chondrites also contain high abundances of diamond, SiC, and graphite, P3-rich diamonds, presolar oxides, and deuterium-rich organics (Huss and Lewis, 1995; Huss *et al.*, 2003; Zinner *et al.*, 2003; Yang and Epstein, 1983; Kerridge, 1983). In fact, all of the presolar components found in CI chondrites are also found in CM2 matrix, and the abundances of known types of presolar materials, both labile and thermally resistant, are similar in Orgueil and CM2 matrices (*e.g.*, Fig. 1).

The above data suggest that CI chondrites and CM2 matrices formed from representative samples of the Sun's parent molecular cloud. Both CI chondrites and CM2 matrices have essentially unfractionated bulk chemical compositions. The presence of presolar components with a wide range of thermal and chemical stability suggests that the mixture of presolar materials in CI and CM2 matrices was also essentially unfractionated. The absence of fractionations indicates that CI chondrites

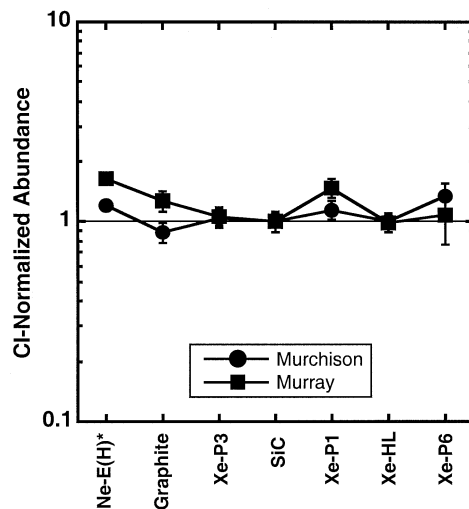


Fig. 1. Abundances of several presolar components in CM2 chondrite matrix are compared to the abundances in CI chondrites, represented by Orgueil. The components are arranged in order of increasing resistance to thermal destruction from left to right. Xe-P3, Xe-HL, and Xe-P6 are carried in presolar diamonds. The carrier for Ne-E(H)\* is unknown (see Huss *et al.*, 2003). The carrier for Xe-P1, the dominant xenon component in primitive chondrites, is not known, but it correlates with other presolar components and is likely presolar as well (see, Huss and Alexander, 1987; Huss *et al.*, 1996). Note that all of the components are present in CM2 matrix at essentially the same abundance as in CI chondrites, independent of thermal resistance. Abundance data from Huss and Lewis (1994b, 1995) and Huss *et al.* (2003).

and CM2 matrices were never exposed to high temperature, either in the nebula or on the meteorite parent body. The major mineralogy of CI chondrites and CM2 matrices is no longer that of molecular cloud material, however. Aqueous processes on the meteorite parent bodies have almost completely transformed the mineralogy of these fine-grained materials and have destroyed most or all of the presolar silicates. This extensive aqueous alteration may also be a reflection of low nebular temperatures, which permitted the accretion of water into the meteorite parent bodies. For the purposes of the following discussion, I will consider the CI chondrites and CM2 matrix to be most representative of the raw material for the solar system, both in terms of bulk composition and in terms of the mixture of presolar components. For simplicity and because the characteristics of CI chondrites are better constrained, I will compare the other classes to CI chondrites below. Minor differences between CI chondrites and CM2 matrices do not affect my conclusions.

### 5. Correlated fractionations of presolar grains and chondrite bulk compositions

Chondritic meteorites and their components exhibit two major types of chemical fractionations: 1) a metal-silicate fractionation in which metal has been mechanically added to or removed from the formation regions of various types of chondrites, and 2) volatility-controlled fractionation in which volatile elements are depleted and refractory elements are enriched to varying degrees relative to CI chondrites (*e.g.*, Larimer and Anders, 1967, 1970). Some meteorites show only volatility-based chemical fractionations, others show both metal-silicate and volatility-based fractionations, and still others formed from batches of material that experienced different levels of one or both of these fractionations were then mixed together in varying proportions.

The bulk compositions of chondrites reflect two main components, the chondrules, CAIs, and metal, which experienced temperatures at or above their melting points, and matrix, which saw much lower temperatures. Chondrule formation was almost certainly accompanied by the loss of volatile elements, but the short time scale for melting probably prevented complete volatile loss (*e.g.*, Yu *et al.*, 1996). Grossman and Wasson (1983) argued convincingly that chondrule compositions primarily reflect the composition of the precursors, not the chondrule-forming process. Connolly *et al.* (2001) argued that CR2 chondrule precursors were already depleted in volatile elements such as gold before chondrule formation. CR2 metal grains that apparently formed by recondensation of siderophile elements evaporated from chondrules are depleted in gold relative to CI chondrites. Such condensates would be enriched in gold and other volatile siderophiles if they had condensed from a gas produced by incomplete evaporation of material with CI-like abundances. Thus, the volatility-based fractionations observed among chondrite groups primarily reflect processes that occurred prior to chondrule formation, with a minor overprint of the chondrule-forming process. On the other hand, metal-silicate fractionation, which may have been initiated through reduction of iron and expulsion of metal during chondrule formation (*e.g.*, Connolly *et al.*, 2001), probably post-dates the major volatility-based fractionations.

In contrast to the bulk compositions, presolar components can only provide information about the matrices of chondrites, because presolar grains cannot survive

melting events such as chondrule formation. Presolar grains are found in the matrices of all classes of chondrites, in the meteorites that have experienced little parent body metamorphism. Within each meteorite class, differences in the abundances and characteristics of presolar grains primarily reflect parent-body metamorphism, and the abundances patterns indicate that all chondrite classes sampled the same mixture of presolar grains (Huss, 1990; Huss and Lewis, 1995). However, Huss and Lewis (1995) had already noticed abundance anomalies between the least metamorphosed members of several meteorite classes that seemed to reflect a pre-accretionary thermal history. It is this pre-accretionary history that I wish to discuss here, so I will focus only on the least metamorphosed members of each meteorite class. Low metamorphic temperatures have been inferred from various thermometers for the meteorites discussed below [e.g., Semarkona (LL3.0),  $< 250^{\circ}\text{C}$  (Alexander *et al.*, 1989); Bishunpur (LL3.1),  $< 350^{\circ}\text{C}$  (Rambaldi *et al.*, 1981); Renazzo (CR2),  $< 150^{\circ}\text{C}$  (Zolensky, 1991); ALHA 77307 (CO3.0) and Colony (CO3.0),  $\sim 200^{\circ}\text{C}$  (Scott and Jones, 1990; Huss *et al.*, 2003); Leoville (CV3) and Vigarano (CV3),  $\sim 300^{\circ}\text{C}$  (Huss and Lewis, 1994b, 1995); Acfer 214 (CH);  $\sim 150^{\circ}\text{C}$  (Huss *et al.*, 2003)]. In most cases, the metamorphic temperatures inferred for the host meteorite are significantly lower than the temperatures inferred for the thermal processing reflected in the bulk compositions and presolar grains. Additional discussions of the metamorphism issue can be found in Huss and Lewis (1994b, 1995) and Huss *et al.* (2003).

### 5.1. LL chondrites

The LL chondrites are one of the three classes of ordinary chondrites that together make up the vast majority of chondrites. I discuss LL chondrites in this paper because, of the three classes of ordinary chondrites, LL3 chondrites have the most extensive data on presolar components. Figure 2a shows bulk compositional data for LL3 chondrites. The data are normalized to the abundances in CI chondrites and are arranged in order of decreasing volatility from left to right. In a plot like Fig. 2a, elements present in the same abundance as in CI chondrites will plot on the horizontal line at "1". The first thing to notice is that the lithophile elements (solid symbols) are uniformly enriched relative to CI chondrites by  $\sim 40\%$ . These elements have CI-chondrite-like (=un-fractionated) relative abundances, and the enrichments relative to CI reflect depletions of other elements, because the total of all elements must add up to 100%. Also note that siderophile elements (open symbols), those found primarily in metal, are systematically depleted relative to the lithophile elements and are slightly depleted relative to CI chondrites. This systematic difference between lithophile and siderophile elements is an example of metal-silicate fractionation; here some of the metal has been removed from the system. The third thing to notice is the relative depletions of the most volatile elements. This is an example of volatility-controlled fractionation. For comparison with other classes of meteorites, note the left-most element on the unfractionated plateau for the lithophile elements (sodium). Depletions of volatile siderophile elements start at elements more volatile than gold and may reflect vaporization during chondrule melting, during which metal was expelled from chondrules (e.g., Connolly *et al.*, 2001).

The right panel for LL3 chondrites (Fig. 2b) shows the abundances of the same seven presolar components that were shown for CM2 chondrites in Fig. 1. Again the



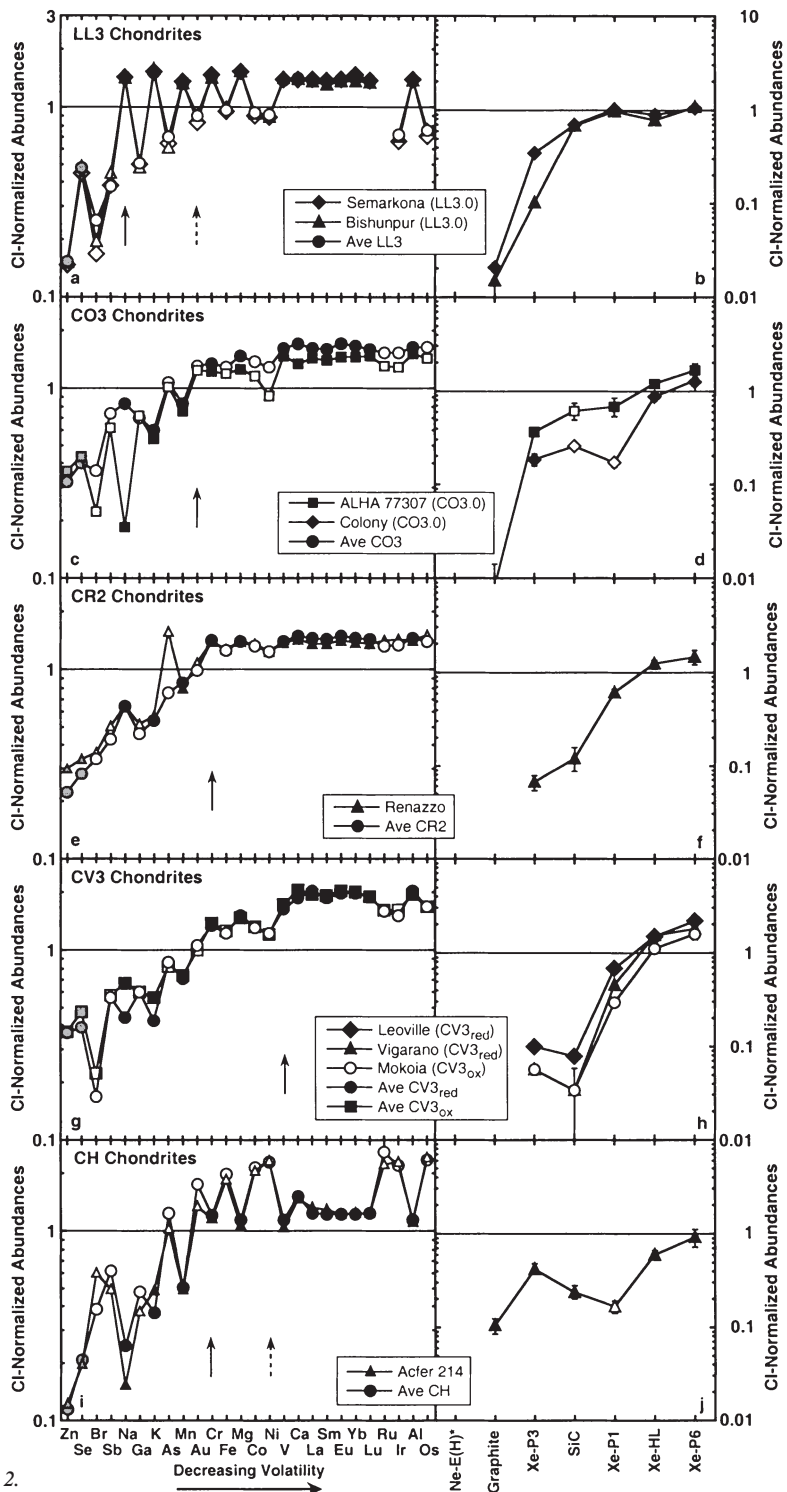


Fig. 2.

data are arranged with the easiest types to destroy on the left and the most resistant presolar materials on the right. Notice that the easy-to-destroy types are depleted relative to CI chondrites, but the four more-resistant components are present in essentially CI abundances. Both the bulk compositional data and the data for presolar grains show depletions of the most labile components relative to CI chondrites.

### 5.2. CR2 chondrites

The CR2 chondrites (Fig. 2e, f) show volatility-based fractionations, but no evidence of metal-silicate fractionation. Both lithophile and siderophile elements more refractory than chromium are unfractionated from each other and are systematically enriched by 40–43% relative to CI chondrites. Elements more volatile than chromium show increasing depletions with increasing volatility relative to this refractory-element plateau, and most are depleted relative to CI chondrites (these depletions produce the ~40% enrichment of refractory elements). The left-most element on the refractory-element plateau is chromium. Thus, CR2 chondrites have lost more of their original (CI-like) inventory of volatile elements than have LL3 chondrites.

The presolar grains in CR2 chondrites (Fig. 2f) show depletions in all but the two most resistant components relative to CI chondrites. The Xe-HL and Xe-P6 are enriched relative to CI, reflecting the loss of more reactive components, many of which are not part of this plot. CR2 chondrites have lost more of their reactive presolar components than have LL3 chondrites (*cf.*, Figs. 2b and 2f). Thus, both the bulk compositional data and the surviving mixture of presolar grains indicate that the precursors of CR2 chondrites were heated more severely than those of LL3 chondrites.

### 5.3. CO3 chondrites

The elemental abundance patterns for CO3 chondrites (Fig. 2c) show some additional complications, although they are still dominated by volatility-based fractionations. First, the enrichments of refractory elements for ALHA 77307 are smaller than those for Colony and average CO3 chondrites. This is due to a significantly higher matrix content in ALHA 77307 (~43%, Scott *et al.*, 1981) compared to other CO3 chondrites (30–33%, McSween, 1977a; Rubin *et al.*, 1985). However, the *relative*

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Fig. 2 (opposite). Bulk compositional data and abundances of the same presolar components as in Fig. 1 are shown for five classes of chondrites. Panels a, c, e, g, and i, show abundances of the elements in the bulk meteorite normalized to CI chondrites (Anders and Grevesse, 1989) and arranged in order of decreasing volatility from left to right. Lithophile elements are shown as black filled symbols, siderophile elements as open symbols, and chalcophile elements as gray symbols. Arrows mark the least volatile element on the refractory-element plateau (see text). Panels b, d, f, h, and j show abundance data for presolar components normalized to matrix content and presented in the same format as in Fig. 1. Open symbols for SiC in panel d indicate higher than normal uncertainty (see Huss *et al.*, 2003). Open symbols for Xe-P1 in panels d and j indicate an anomalously low abundance due to terrestrial weathering. Compositional data from Kallemeyn and Wasson (1981, 1982), Kracher *et al.* (1985), Kallemeyn *et al.* (1989, 1994), and Bischoff *et al.* (1993). Abundances of presolar components from Huss and Lewis (1994b, 1995) and Huss *et al.* (2003). The extreme depletions of bromine and sodium in ALHA 77307 are probably due to Antarctic weathering (Kallemeyn and Wasson, 1982).

abundance patterns of the refractory elements are the same for all CO3s. To avoid confusion due to different matrix contents, I will use the data for average CO3 and Colony to discuss enrichment factors because their matrix abundances (30–33%) are similar to those for CR2 chondrites (*e.g.*, 31% for Renazzo, McSween, 1977b) and CV 3 chondrites (35–38%, McSween, 1977b). For average CO3 chondrites, elements from vanadium to osmium show a nearly constant enrichment of 60–65% relative to CI, while elements from gold to nickel are enriched by 30–35%. Elements more volatile than gold show increasing depletions with increasing volatility. The higher abundances of the most refractory elements are most likely due to the presence of ~2% CAIs (McSween, 1977a), which are enriched to ~20–100×CI in the most-refractory elements (*e.g.*, Russell *et al.*, 1998). The elements from gold to nickel, which include magnesium and iron (and would include silicon if it could be measured by INAA), reflect the abundances in the chondrules, the dominant component of the meteorites. For CO3 chondrites, the left-most unfractionated element in this “chondrule-element” suite is gold, which, along with the lesser degree of enrichment of chondrule elements (30–35%), suggest that CO3 meteorite precursors were heated less than those of CR2 chondrites.

The presolar grain abundances for the most primitive CO3 chondrites show a smooth pattern of depletions. Only a hint of graphite remains in ALHA 77307 (Fig. 2d). The slope of the depletions is less than that of CR2 chondrites, but steeper than that of LL3 chondrites. The Xe-HL and Xe-P6 components are enriched in ALHA 77307, but in Colony, only Xe-P6 is enriched relative to CI chondrites. The shift to higher abundances for ALHA 77307 is probably due to the use of a matrix abundance to matrix-normalize the data that was too low (33.7%; Huss *et al.*, 2003). Normalizing with a matrix abundance of 43% (Scott *et al.*, 1981) would put the ALHA 77307 pattern essentially on top of the Colony pattern (Fig. 2d). Plotted this way, the enrichments of resistant components are also intermediate between LL3 and CR2 chondrites. Thus, both in terms of bulk composition and in terms of presolar grains, CO3 chondrites lie between LL3 and CR2 chondrites.

#### 5.4. CV3 chondrites

Figure 2g shows elemental abundance patterns for average reduced and oxidized CV3 chondrites. The two patterns are almost identical, except for slightly higher alkali-element abundances in CV3<sub>ox</sub> chondrites, reflecting the higher degree of metasomatism experienced by the components of these meteorites (*e.g.*, Krot *et al.*, 1995). The CV3 chondrites show a slight depletion of refractory siderophiles compared to refractory lithophiles, and a slight relative enrichment of the volatile siderophiles. The refractory lithophiles found in CAIs, which make up 4–9% of CV chondrites (*e.g.*, McSween, 1977b), are enriched to ~2×CI. The chondrule elements, from chromium to vanadium, do not show the flat pattern that they do in CR chondrites, but instead show increasing depletions with increasing volatility relative to the most refractory elements. In fact, vanadium, which is typically part of the CAI-element plateau, is depleted relative to calcium, the least refractory element not to show a depletion relative to more refractory elements. In spite of the fractionation among chondrule elements, magnesium is more enriched (~1.5×CI) than in either

CO3 or CR2 chondrites.

The presolar-component abundances for CV3 chondrites (Fig. 2h) show steeply fractionated patterns. The CV3<sub>red</sub> matrices are enriched relative to CI in both Xe-HL and Xe-P6. The abundance of Xe-P3 is higher than one might expect based on the patterns for CO3 and CR2 chondrites. Huss and Lewis (1994b, 1995) suggested, on the basis of the release pattern for the P3 noble gases, that reduced CV3 chondrites contain two components of presolar grains, a main component heated to high temperature in which P3 gases and SiC have been mostly destroyed, and a smaller low-temperature component heated to no more than ~300°C that provides most of the P3 gases and some SiC. The least metamorphosed CV3<sub>ox</sub> meteorites studied, Mokoia, is slightly depleted relative to reduced CV3s in all components and it shows a slightly steeper slope. These lower abundances may reflect the much-more-extensive metasomatism experienced by the matrix prior to accretion (Krot *et al.*, 1995).

### 5.5. CH chondrites

The most striking thing about the bulk compositions of CH chondrites is the very large enrichments of siderophile elements, up to  $2.2 \times \text{CI}$  for the most refractory siderophiles (Fig. 2i). Lithophile elements more refractory than chromium have an essentially unfractionated pattern, and they are slightly enriched relative to CI, in spite of the enrichment of siderophile elements. The most volatile lithophile element that is undepleted relative to more-refractory lithophiles is chromium. The most volatile siderophile element that is undepleted relative to more-refractory siderophiles is nickel.

The presolar-component abundances for Acfer 214 do not show a smooth decrease with increasing susceptibility to destruction. This pattern is almost certainly due to a bi-modal mixture of dark inclusions made up of matrix-like material that was apparently never heated above ~150°C and normal matrix material that was processed to high temperature (*cf.*, Huss *et al.*, 2003). The high abundances of graphite, Xe-P3, and SiC reflect the dark inclusions, while the minor depletion of Xe-P6 and the depletion in bulk diamonds reflects the bulk of the silicates. The Xe-P1 abundance may be too low due to terrestrial weathering (Huss *et al.*, 2003).

### 5.6. CM2 chondrites

As already discussed above, matrices of CM2 chondrites are very similar to bulk CI material and are among our best samples of primitive nebula material. The bulk compositions of CM2 chondrites (Fig. 3) reflect a two-component mixture of the primitive matrix and a high-temperature component consisting of chondrules and CAIs. The elements more volatile than about potassium are almost uniformly depleted by ~40% relative to CI, corresponding to the ~40% of chondrules and CAIs in these meteorites. The high-temperature component shows the same stepped structure as CO3 and CV3 chondrites, with elements more refractory than uranium, those that make up CAIs, enriched slightly more (~32% relative to CI) than the elements normally found in chondrules (~14% relative to CI). Direct comparison of the degree of enrichment of moderately volatile elements between Figs. 2 and 3 is not valid because of the factor-of-two difference in matrix content between the CM2s and the other carbonaceous chondrites. However, dividing the matrix content by two so that it approximates

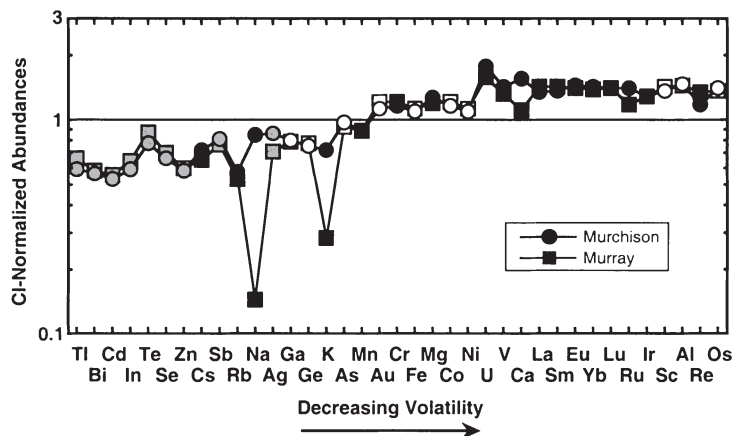


Fig. 3. Abundances of 37 elements in Murchison and Murray CM2 chondrites normalized to the abundances in CI chondrites (Anders and Grevesse, 1989) and arranged in order of decreasing volatility from left to right. Lithophile elements are shown in black filled symbols, siderophile elements as open symbols, and chalcophile elements as gray symbols. Elements more volatile than potassium are systematically depleted by ~40%, gold through nickel are enriched by ~14%, and elements more refractory than uranium are enriched by ~32% relative to CI chondrites. Data from Kallemeyn and Wasson (1981) and Krähenbühl *et al.* (1973). Low sodium and potassium abundances for Murray are attributed to leaching after the fall (Kallemeyn and Wasson, 1982).

those of the carbonaceous chondrites in Fig. 2 would give an enrichment factor for chondrule elements similar to that for CO3 chondrites. The left-most element on the refractory-element plateau is gold, as it is in CO3 chondrites. These data imply that the high-temperature component of CM2 chondrites had a similar nebular history to the CO3 chondrite precursors.

## 6. Model: Differential partial evaporation of average molecular cloud material

Table 2 summarizes the observations in the previous section using five parameters for the bulk compositional data and three parameters for presolar components. Most parameters are normalized to CI chondrites and values of all parameters are given for CI chondrites at the top of the table. The first group of entries consists of chondrite types whose bulk compositions and presolar grains reflect relatively simple histories dominated by volatility-based fractionations. Mixing of components with different thermal histories is minor. Note that all parameters show essentially the same sequence from CI to LL to CO to CR to  $CV_{red} \approx CV_{ox}$ . The only reversals can be understood in terms of metal-silicate fractionation (enrichment of chondrule forming elements in LL chondrites), alkali-iron metasomatism in  $CV_{ox}$  chondrites (*e.g.*, Krot *et al.*, 1995), or minor late addition of primitive material ( $CV$  chondrites, see above). Thus, for these meteorites, there are strong correlations between the abundances and characteristics of presolar grains and the bulk compositions of the host meteorites. Because the correlations affect both matrix and high-temperature components, they must have been

Table 2. Summary of indicators for pre-accretionary nebular processing.

| Meteorite Class   | Enrichment Chondrule El. <sup>1</sup> | Fractionation Chondrule El. <sup>1</sup> | Lowest T Undep. El. <sup>2</sup> | Na/Mg <sup>3</sup> CI | Mn/Mg <sup>3</sup> CI | Xe-P3 <sup>4</sup> CI Diam. | SiC <sup>5</sup> SiC in CI | Xe-P6 <sup>4</sup> CI Diam. |
|---|---------------------------------------|--|----------------------------------|-----------------------|-----------------------|-----------------------------|----------------------------|-----------------------------|
| CI  | 1                                     | No                                       | ~300 K                           | 1                     | 1                     | 1                           | 1                          | 1                           |
| <b>Chondrites with relatively simple fractionation histories and only minor component mixing.</b> |                                       |  |                                  |                       |                       |                             |                            |                             |
| LL  | 1.4 <sup>7</sup>                      | No                                       | Na ≈ 861 K                       | ~-0.93                | ~-0.87                | 0.45                        | 0.7                        | 1.3                         |
| CO  | 1.30-1.35                             | No                                       | Au ≈ 1074 K                      | ~-0.57                | ~-0.57                | ~0.3                        | 0.6                        | 1.6                         |
| CR  | 1.40-1.43                             | No                                       | Cr ≈ 1137 K                      | ~-0.46                | ~-0.60                | 0.07                        | 0.12                       | 1.6                         |
| CV <sub>red</sub>   | 1.34-1.65                             | Yes                                      | Ca ≈ 1382 K                      | ~-0.24                | ~-0.47                | 0.09 <sup>9</sup>           | 0.08 <sup>9</sup>          | 2.0                         |
| CV <sub>ox</sub>  | 1.37-1.73                             | Yes                                      | Ca ≈ 1382 K                      | ~-0.45                | ~-0.50                | 0.07 <sup>9</sup>           | 0.03 <sup>9</sup>          | 1.9                         |
| <b>Chondrites that mix components with different fractionation histories.</b>                     |                                       |  |                                  |                       |                       |                             |                            |                             |
| CM Chondrites   | ~1.14                                 | No                                       |                                  | 0.68                  | 0.70                  | 1                           | 1                          | 1.4                         |
| CM Matrix (0.57) <sup>6</sup>   | 1                                     | No                                       | ~300 K                           | 1                     | 1                     | 1                           | 1                          | 1                           |
| CM Hi-T (0.43) <sup>6</sup>   | ~1.32                                 | No                                       | Au ≈ 1074 K                      | ~-0.25                | ~-0.30                | low                         | low                        | high                        |
| CH Chondrites   | ~1.10; 1.3-2.3 <sup>7,8</sup>         | No; Yes <sup>8</sup>                     |                                  | ~-0.13                | ~-0.44                | 0.43                        | 0.24                       | 0.93                        |
| CH Incl. (0.04) <sup>6</sup>  | ~1                                    | No                                       | ~400 K                           | ~1                    | ~1                    | ~1                          | ~1                         | ~1                          |
| CH Hi-T Lith. (0.78) <sup>6</sup>   | ~1.40                                 | No                                       | Cr ≈ 1137 K                      |                       |                       | ~-0.07                      | ~-0.12 <sup>10</sup>       | ~1.6                        |
| CH Metal (0.18) <sup>6</sup>  | 0.2-1.2                               | Yes                                      | Ni ≈ 1202 K                      | -                     | -                     | -                           | -                          | -                           |

<sup>1</sup> Chondrule elements are those that dominate chondrules, the largest component in most chondrites. They include chromium, iron, magnesium, silicon, cobalt, and nickel, among others. The enrichment and fractionation of chondrule elements listed in this table refer to lithophile elements, except in case of CH chondrites, where values for both lithophile and siderophile elements are listed.

<sup>2</sup> Temperatures are 50% condensation temperatures in a gas of solar composition at 10<sup>-6</sup> atm. Data from Wasson (1985).

<sup>3</sup> Calculated relative to the same ratio in CI chondrites.

<sup>4</sup> Calculated relative to the abundance of the component in CI diamonds.

<sup>5</sup> Abundance normalized to matrix content and to abundance in CI chondrites.

<sup>6</sup> Numbers give approximate fraction of meteorite the component makes up as determined from point counting a thin section.

<sup>7</sup> Enrichment level affected by metal-silicate fractionation.

<sup>8</sup> First entry refers to lithophile elements, second entry refers to siderophile elements.

<sup>9</sup> May reflect in part a minor addition of low-temperature material (see text).

<sup>10</sup> Abundance may be somewhat low due to the presence of solar Ne in Acfer 214.

established prior to the chondrule-forming event(s). These correlations are not likely to be accidental and probably reflect a single process acting on all chondritic parent material, producing fractionations in the bulk compositions and in the mixtures of presolar grains.

As discussed in the Introduction, many, if not most models of volatility-based fractionations among chondrites have been based on different degrees of condensation from a gas of solar composition, followed by separation of the solids from the gas (*e.g.*, Larimer and Anders, 1967, 1970; Boynton, 1985). However, if the same process that produced the chemical fractionations also modified the abundances of the presolar components, then condensation from a gas of solar composition *cannot* be that process. This is because complete vaporization of pre-existing dust, a necessary step to produce a gas of solar composition, would destroy the presolar grains, leaving nothing to correlate with the bulk compositions. The simplest alternative is that the chemical fractionations and the fractionations among presolar components reflect different degrees of heating of bulk nebular dust inherited from the Sun's parent molecular cloud.

This heating evaporated volatile elements, and the volatile-rich gases were largely lost from the system. The evaporation was probably not controlled by strict gas-solid equilibrium, because most elements are expected to condense over very short temperature intervals (*e.g.*, Boynton, 1985). Under equilibrium conditions, only a very few elements would be partially in the gas phase, and a pattern like that for CR2 chondrites (Fig. 2e) would not be produced. Instead, evaporation was probably controlled in large part by the mineralogy of the dust, with phases carrying a single element releasing that element over a range of temperatures. Much of the fractionated solid material was then subjected to chondrule formation, and in some cases a subsequent metal-silicate fractionation. The resulting high-temperature solids then mixed with thermally processed dust that did not experience chondrule formation (matrix), and with CAIs or unprocessed material in some cases, to form the chondrites we observe today.

The temperatures under which these fractionations occurred are currently rather poorly constrained. The temperatures experienced by precursors to LL3 chondrites are constrained by the survival of P3 gases in diamonds to have been no more than  $\sim 200^\circ\text{C}$ , because temperatures only slightly higher than this outgas the P3 component in the laboratory. Of course chondrules subsequently experienced heating sufficient to melt silicates, but the matrix did not. Laboratory studies of the kinetics of SiC destruction under nebula conditions indicate that temperatures in excess of  $\sim 700^\circ\text{C}$  are required to efficiently destroy SiC under a variety of  $f\text{O}_2$  conditions in the solar nebula (Mendybaev *et al.*, 2002). This would imply that CO3 chondrite precursors were perhaps not heated to quite  $700^\circ\text{C}$ , while CR2-chondrite precursors were heated to  $\sim 700^\circ\text{C}$ , and CV3 precursors were heated to  $> 700^\circ\text{C}$  (their SiC is most likely from the low-T component). These temperatures are somewhat lower than the 50% condensation temperatures of the most-volatile undepleted element in each class (Table 2). This discrepancy means that much more work is required to understand the kinetics of vaporization from non-equilibrium phase assemblages and the kinetics of destruction of presolar grains.

Of course, a simple vaporization model cannot explain all aspects of chondritic meteorites. But then neither did equilibrium condensation from a gas of solar composition. For example, in both evaporation and condensation models, it is necessary to mix components with different thermal histories to explain some kinds of meteorites. The lower part of Table 2 summarizes data for two classes of chondrites where such mixing clearly occurred. Consider the CM2 chondrites, which have the textural and compositional characteristics of a two-component mixture (*e.g.*, McSween, 1979; Wolf *et al.*, 1980). Inferred characteristics of the two components are shown in Table 2, along with the compositional characteristics of the bulk meteorite and the presolar grains characteristics of the matrix. A simple model, in which the matrix has its full complements of volatile elements and fragile presolar components and the high-temperature component has characteristics much like that of CO3 chondrites, provides a good description of bulk CM2 chondrites (Table 2).

The CH chondrites can be understood as a mixture of material heated to about the same degree as CR2 chondrites, dark inclusions made of CI-like material, and metal heated to somewhat higher temperature and enriched by  $\sim 20\%$  in refractory siderophile elements relative to iron and compared to CI chondrites (*e.g.*, Meibom *et al.*, 1999).

Most of the main silicate fraction experienced chondrule formation, but the matrix portion did not. My modal analysis of a thin section from the piece adjacent to the one used for presolar-grain abundances gave: chondrules and other large silicates 66%, matrix ~12%, metal ~18%, troilite ~1%, and dark inclusions ~3%. Bischoff *et al.* (1993) give higher matrix and dark inclusion abundances and a lower metal abundance. The modal proportions that roughly match both the bulk composition and the abundances of presolar grains are given in Table 2. Because the abundances of presolar grains shown in Fig. 2j are normalized to the measured matrix content of 12%, they do not accurately reflect the siting of the grains in the dark inclusions. If the matrix contains only ~7% of the amount of P3 noble gases as the Orgueil matrix (like CR2 chondrites), but the meteorite also contains ~4% dark inclusions with a CI-like P3 content, the bulk meteorite would give the observed  $0.43 \times \text{CI}$  if everything was assumed to be in the 12% matrix. In a matrix with only 7% of its original P3 gas remaining, graphite would be absent and SiC would be highly depleted, so the observed graphite and SiC should be almost entirely from the dark inclusions. But the depletions appear larger for graphite and SiC than for Xe-P3 (Fig. 2j). This is most likely due to the presence in Acfer 214 of solar neon, whose high  $^{20}\text{Ne}/^{22}\text{Ne}$  ratio masks Ne-E during deconvolution of neon components (*cf.*, Huss and Lewis, 1995). The relative abundances of the three most resistant presolar components are similar to those of CR2 chondrites (although Xe-P1 might be too low due to terrestrial weathering, Huss *et al.*, 2003), but the pattern is displaced to lower abundances. This would be easiest to understand if the matrix abundance has been over-estimated due to terrestrial weathering. A matrix abundance of ~9–10% would bring the pattern for Acfer 214 into line with expectations based on CR2 chondrites. Although the story is not as clean as one would like, the elemental abundance pattern and the abundances of presolar components seem best understood in terms of mixing of a major component with that experienced nebular processing similar to CR2 chondrites, a metal component that experienced somewhat higher temperature and was enriched in the accretion zone relative to silicates, and 3–4% dark inclusions with CI-like bulk compositions and abundances of presolar grains.

## 7. Conclusions

Isotopic anomalies are widespread in primitive chondritic meteorites. Most of these anomalies can be traced directly to surviving presolar material from the Sun's parent molecular cloud. After accounting for parent-body metamorphism, the abundances and characteristics of presolar components in the different chondrite classes can be understood in terms of thermal processing of bulk molecular cloud dust in the solar nebula. Strong correlations between the degree of processing of presolar components and volatility-controlled elemental fractionations in the host chondrite indicate that the same thermal processing was responsible for both sets of characteristics. If this is true, then condensation from a gas of solar composition cannot be the primary mechanism for volatility-controlled fractionation among chondrites, because the evaporation of presolar materials required to produce a gas of solar composition would have destroyed all presolar grains. Instead, a model of different degrees of evaporation from bulk



molecular-cloud material seems to explain the volatility-based elemental fractionations and the fractionations among known presolar components. It is likely that the evaporation of the different elements was governed in part by kinetic factors due to the mineralogy of the molecular-cloud dust, not simply by gas-solid equilibrium. Following these fractionations, chondrule formation occurred, followed in some cases by metal-silicate fractionation and/or mixing together of components with different thermal histories, and finally by accretion and parent-body processing. Although much work remains to be done, this framework seems to be consistent with the majority of the observations.

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