PART 10.

Inner Solar Nebula, Meteorites and IDPs

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Constraints on the Origin of the Solar System from Meteorites

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Abstract. Primitive meteorites have preserved material that was present in the presolar nebula and record processes that occurred as evolution proceeded from the earliest solids. The discovery of isotopic anomalies in these samples led to the isolation of presolar grains and allowed the presence of short-lived radionuclides in the early solar system to be inferred. Isotopic anomalies in oxygen may reflect non-linear chemical fractionation rather than a nuclear effect, but the theory is as yet insufficiently developed to be rigorously assessed.

Analyses of individual SiC and refractory oxide presolar grains reveal that a large number of distinct nucleosynthetic sites contributed material to the solar nebula, and much progress has been made in identifying the various environments in which they formed. Isotopic anomalies associated with nanometre-size diamonds are best explained by supernova nucleosynthesis but it is clear that several sub-populations exist.

The extinct nuclides ^{26}Al, ^{53}Mn and ^{129}I have each been used to establish the relative timing of events in the formation of the solar system. Calibrations of the Mn-Cr and I-Xe systems against the Pb-Pb system (based on decay of uranium isotopes) have been proposed, and Al-Mg data can be included through a calibration with the I-Xe scheme. Assuming these calibrations to be valid allows a tentative chronology of the early solar system to be developed, the plausibility of which can be seen as a test of the calibrations. In this chronology, the first solids to form in the solar system were refractory inclusions. Chondrules (rapidly cooled silicate droplets) appear to have formed later than CAIs over a period of a few million years. Parent body processing began early in solar system history and was ongoing as chondrules formed.

1. Introduction

The origin and history of our solar system can be investigated through the study of the chemical and isotopic compositions of meteorites. The insights gained complement those obtained from astronomical observations of solar system formation around other stars and data from interplanetary probes. A com-

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prehensive review of this area is impossible in a short paper; my aims are to introduce the subject and the techniques employed, and to highlight some results and outstanding questions that may interest the astrochemistry community. Accordingly, in the next section I introduce some of the basic concepts and terminology of meteoritics, while in subsequent sections some topics I believe to be of particular relevance to astrochemistry are discussed. To aid the reader interested in learning more, recent papers with a significant review content have been cited where possible.

2. Fundamentals of Meteoritics

McSween (1999) is an excellent introduction to the issues summarised in this section.

Meteorites are categorised as either 'irons', 'stony-irons' or 'stones'; stones are subdivided into 'achondrites' and 'chondrites'. Typical crystallisation ages are $>$4.5 Ga (Minster et al. 1982), while cosmic ray exposure ages, which measure how long the sample has been part of a body $\sim$1 m radius are typically less than 100 Ma (Crabb & Schultz 1981). This shows that meteorites are recent fragments of larger 'parent bodies' that formed in the early solar system. Those meteorites for which orbital data exist appear to have originated in the asteroid belt. Studies of asteroid spectra and orbital dynamics have allowed some meteorite sources to be tentatively identified with individual asteroids, notably Vesta (the Howardite, Eucrite and Diogenite achondrites) and Hebe (H chondrites).

Irons, stony-irons and achondrites together make up differentiated meteorites - samples of parent bodies large enough and heated sufficiently (early in their history) to allow separation of silicate and metal melts. When such differentiation occurred, it erased most traces of earlier events. Chondrites, which are undifferentiated, make up approximately 85% of the meteorites observed to fall. The proportion of chondrites in the total inventory (which includes 'finds' as well as 'falls') is lower because of the greater resistance to terrestrial weathering of less primitive meteorites.

Most chondrites fall into one of several well defined groups (Figure 1). When different properties are examined (e.g. oxidation state, oxygen isotope ratios, volatile content, chondrule and metal grain size distributions) the same groupings are observed. This is explicable if these properties reflect the source of each chondrite group as a single parent body in the early solar system. While different properties lead to the same groups, the trend from group to group varies. This suggests that parent body properties were not determined by a single simple parameter (Clayton 1993).

A primitive meteorite can be thought of as a sediment made up of solid material present in the solar nebula. After compaction, parent body processes operated which modified this material to varying extents. In addition to group, meteorites are classified by 'petrologic type' (Van Schmus & Wood 1967). This is a number which categorises the type and extent of parent body processing. The least processed meteorites are assigned type 3. Increasing degree of thermal metamorphism (being hotter for longer) in the enstatite (EH and EL) and ordinary (H, L, LL) chondrites is represented by types 4–7, while type 2 and 1 carbonaceous chondrites experienced increasing degrees of aqueous alteration.

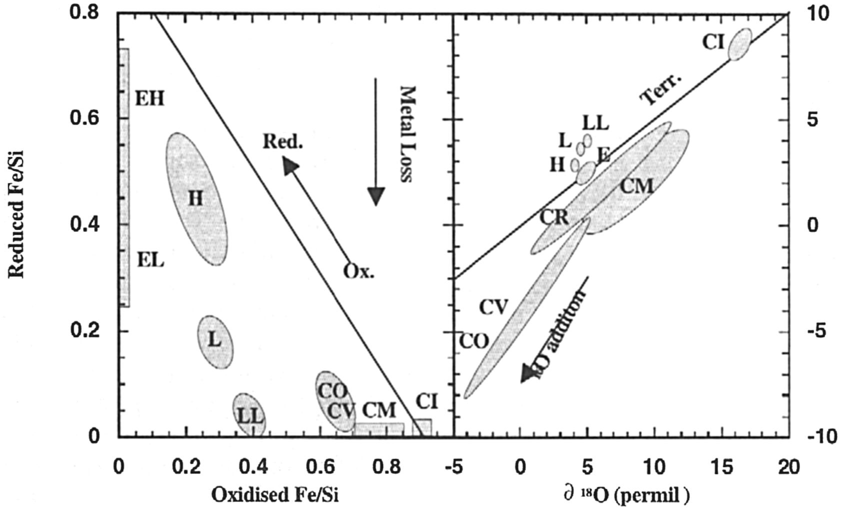

Figure 1. Examination of several chondrite properties leads to the same groups being defined. On the left, relative proportions of reduced iron (iron as metal or sulphide) and oxidised iron (iron present in the silicate phase) to silicon are used revealing the oxidation state of the chondrite group. Varying fractionation between iron and silicon may be a consequence of the size sorting of chondrules and metal grains. Mechanisms capable of producing the oxygen isotope groupings (right) are discussed in the text. (Figure loosely adapted from McSween 1999. The delta notation indicates variations in the ratio between the isotope indicated and ^{16}O in parts per thousand.)

Type 3 chondrites are further subdivided into 10 divisions (3.0–3.9), 3.0 being the most unprocessed (Sears et al. 1980) . It seems likely that, within a group such as the H chondrites, higher petrologic type meteorites are samples from closer to the centre of a parent body than lower petrologic type meteorites. Some meteorites also show the effects of shock (for instance in modification of the lattice structure of olivine grains). A comprehensive discussion of these issues can be found in Kerridge & Matthews (1988).

To gain information about the origin of the solar system, the properties of the material that was compacted to form the parent body must be studied. This is simplest when unshocked samples of the lowest petrologic type (low type 3 meteorites) are chosen.

3. Constituents of Primitive Meteorites

Chondrules are roughly spherical objects, typically 0.2 mm to 1 mm diameter. They are composed of ferromagnesian silicates, primarily $(Mg,Fe)_2SiO_4$ (olivine) and $(Mg,Fe)_2Si_2O_6$ (pyroxene) with some (originally) glassy Al-rich (feldspathic) mesostasis. Their petrology and mineralogy demonstrate that they were made when pre-existing solid material was flash heated from below 650 K to between 1850 K and 2050 K, and rapidly cooled (at rates up to 2000 K hr^{-1}). However, the nature, timing and environment of the heating process are still debated vigorously (Hewins et al. 1996).

In each meteorite group there is a similarity between the size distributions of chondrules and metal grains, suggesting the operation of a sorting mechanism (Akridge & Sears 1999). The sorting mechanism may also be responsible for the depletion in metal of most meteorite groups relative to the 'cosmic' abundance (Figure 1). The chondrule forming process was manifestly important in the solar nebula; some meteorites are composed almost entirely of chondrules and chondrule fragments, and it has been argued that much of the material of the terrestrial planets was processed into chondrules at some stage (Clayton 1993).

Refractory Inclusions, also known as Calcium- Aluminium-rich Inclusions (CAI), are composed of minerals such as corundum (Al_2O_3), perovskite ($CaTiO_3$) and melilite ($Ca_2Al_2SiO_7$ - $Ca_2MgSi_2O_7$) - the first equilibrium condensates expected in a cooling gas of solar composition. Refractory inclusions experienced temperature in excess of 2000 K and cooled at a few 10s K hr^{-1}. Relatively large excesses of the daughter products of extinct radionuclides may be evidence that these are the oldest solar system objects so far identified (Russell et al. 1996).

Chondrules, metal grains and refractory inclusions are surrounded by matrix. This is a fine grained material composed of presolar grains, chondrule fragments and material not processed into chondrules during the early solar system. Some meteorites seem unusually rich in amorphous and crystalline silicate and aluminosilicate grains of varying compositions, which may be the meteoritic material most closely resembling the dust original present in the presolar nebula (Brearley 1993).

Several species of presolar grains have been identified by the isotopically anomalous compositions of some of their constituent elements. They were first isolated by tracing the isotopic signature of their presence as samples of bulk meteoritic material were chemically dissolved, though some have now been identified in situ. The grains record the chemical environment and nucleosynthetic history of stars that existed before the solar system formed. Grains have been attributed to AGB stars (SiC, graphite, corundum), red giants (corundum), novae (graphite) and supernovae (Si_3N_4, nanodiamonds) (Zinner 1997). Nanodiamonds are $\sim$100 times more abundant than any other presolar grain (up to $\sim$0.05 % in primitive meteorites). They are the carriers of an isotopically anomalous xenon component enriched in both heavy and light isotopes known as Xe-HL. However, isotopic studies show that several sub-populations exist (Figure 2) and it is only necessary that a fraction be presolar to account for the concentration of isotopically anomalous xenon. The Xe-HL component itself is enigmatic—the heavy and light isotopic enrichments require separate processes that are believed to have occurred in different regions of a supernova (Ott 1996), yet the various attempts to isolate separate diamond populations in which the ratio of H to L components varies have been unsuccessful. Recently, however, evidence has been presented that there are spectroscopic differences between the carriers of the H and L components, though the chemical source of these spectroscopic differences is unclear (Meshik et al. 1998).

The preservation of demonstrably presolar grains shows that a significant fraction of solar system material did not suffer heating and homogenisation. Those grains that have been identified are refractory - their separation required severe chemical processing of meteoritic material. It seems likely that comparable proportions of less chemically resistant material also survived processing in the solar nebula and may retain information about the pre-existing molecular cloud.

4. Extinct Radionuclides and Early Solar System Chronology

Presolar grains were identified through the isotopic anomalies that they carry. A second, distinct source of isotopic anomalies in meteorites is the short-lived radionuclides that were present in the early solar system. These were incorporated into minerals as they formed and decayed in situ to produce excesses of single isotopes. The excesses are detectable because the parent element was concentrated relative to the daughter element. This occurred naturally when minerals formed in which the parent element is part of the structure but the daughter element is not. For example, studies of aluminium-rich minerals in refractory inclusions show that ^{26}Al, which decays to ^{26}Mg with a half-life of 7.4×10^5 years, was present in the early solar system with an initial $^{26}\mathrm{Al}/^{27}\mathrm{Al}$ ratio $\sim 5 \times 10^{-5}$ (MacPherson et al. 1995). Thus only $\sim 4 \times 10^{-5}$ of the total ^{26}Mg was present as ^{26}Al when the solar system formed. Its presence would never have been detected had mineral formation not chemically separated some aluminium from magnesium.

In addition to ^{26}Al, the presence of several other extinct radionuclides has been inferred (Podosek & Nichols 1997). They are generally believed to be evidence of recent stellar nucleosynthesis in the vicinity of the early solar system. The shortest-lived so far identified is ^{41}Ca, which decays to ^{41}K. If all the ^{41}K present in the solar system today was initially present as ^{41}Ca the interval between the introduction of ^{41}Ca to the formation of the refractory inclusions was at most ~ 1.5 Ma. If the source of ^{41}Ca was a nucleosynthesis in a supernova, this drastically limits the time available for transport of material to the solar system and subsequent mixing. In part to overcome these difficulties, a rival theory suggests that some extinct radionuclides were produced by interaction with cosmic rays as material was processed through stellar outflows in the early sun (Lee et al. 1999). The theory may also be able to account for the formation of the refractory inclusions in which the anomalies with the most short-lived precursors have been observed and the observation that inclusions that appear to have preserved isotopic anomalies from nucleosynthesis, and which are thus presumably the most primitive, do not contain any evidence for extinct ^{26}Al (MacPherson et al. 1995). The extension of this model to chondrule formation remains more controversial.

The presence of anomalies produced by in-situ decay allows the relative abundance of the parent isotope to a stable isotope of the same element to be deduced. On the assumption that the solar system was well mixed, at least in the region in which meteorites formed, it is possible to deduce a chronology based

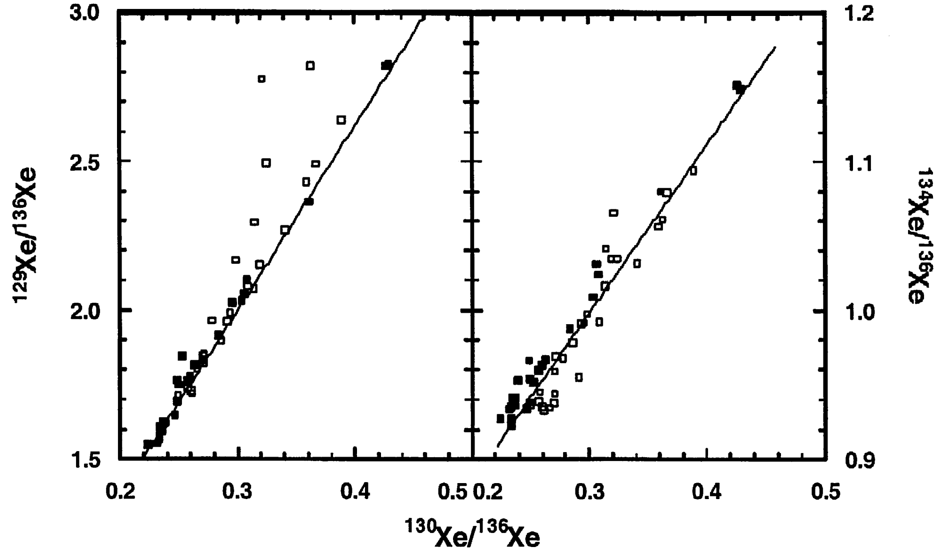

Figure 2. In 3-isotope plots, such as those shown here, simple mixing between two isotopically distinct components results in an array of data points along a straight line joining the two end-members. Each data point in these figures represents the gas released at one temperature during stepwise heating of sample of nanodiamonds. Data from two samples are displayed; solid symbols represent data from a fine grain size separate while open symbols represent that from a coarse grain size separate (J.D. Gilmour & A.B. Verchovsky, unpublished data; sample descriptions in Verchovsky et al. 1998). The size of the plotted symbols is similar to the uncertainty in the ratios. The straight lines represent mixing between an isotopically 'normal' component (upper right) and the anomalous xenon component Xe-HL (lower left). It is clear that other components are present and are not distributed equally between the two grain size separates. In particular, the coarse fraction is notable for a low temperature release of gas enriched in ^{129}Xe, while some variation in the high temperature ratio of ^{134}Xe/^{136}Xe is apparent between the two separates.

on the evolution of these ratios. Three extinct radionuclides are particularly significant for this purpose. In addition to ^{26}Al, these are ^{53}Mn, which decays to ^{53}Cr with a half-life of 3.7 Ma, and ^{129}I which decays to ^{129}Xe with a half life of 15.7 Ma. Figure 3 is an attempt to reconcile chronologies derived from these three isotopic systems.

Absolute calibrations of ages derived from each system can be attempted with reference to samples in which more than one chronometer has been determined. As yet there are few such samples. Separate calibrations of the I-Xe and Mn-Cr systems against the Pb-Pb chronometer, which is an absolute chronometer based on decay of uranium isotopes, have been employed. A single phase, feldspar from the H4 chondrite Ste Marguerite, from which both I-Xe and Al-Mg data are available has been used to incorporate data from ^{26}Al decay (references in figure caption).

Chronological interpretation of variations in relative abundance of unstable isotopes is only possible if the isotope was homogeneously distributed in the region in which the samples were formed. The variation in ages of feldspar separates determined in the I-Xe system correlates well with petrologic type suggesting that a chronological interpretation is valid for this system (Figure 3). There is evidence of radial inhomogeneity in ^{53}Mn (Lugmair & Shukolyukov 1998), but not within the source region of the ordinary chondrites. If extinct radionuclides, most notably ^{26}Al, were synthesised by cosmic ray interactions in stellar outflows, chronological interpretation of initial aluminium ratios would be questionable at best.

A chronometer based on decay of an unstable isotope records the time at which the system analysed last ceased equilibrating with its surroundings - the event recorded may be cooling through a 'closure temperature' at which diffusive redistribution of the daughter isotope ceased. In calibrating one chronometer against another it is assumed that the time of closure of each chronometer in a single phase is identical. This might be true if, for instance, cooling was rapid compared to the half-lives of the radioisotopes in question (certainly true during formation of chondrules and refractory inclusions) but in general must be considered questionable.

While the chronology proposed in Figure 3 cannot be considered definitive, its implications are interesting. Aqueous processing on parent bodies began very early in solar system history, possibly even at the same time as formation of refractory inclusions. This shows that parent bodies were assembled within at most 1 million years of the formation of refractory inclusions. This is also reflected in the ages recorded by the earliest resetting of minerals in thermal metamorphism. The earliest minerals dated from differentiated meteorites record the cooling of these bodies from peak temperatures and are less than 10 Ma later than refractory inclusion formation. Chondrule formation is spread over around five millions years and began no later than 1 Ma after CAI formation - the larger spread in ages observed in chondrules from some meteorites may reflect post formational processing.

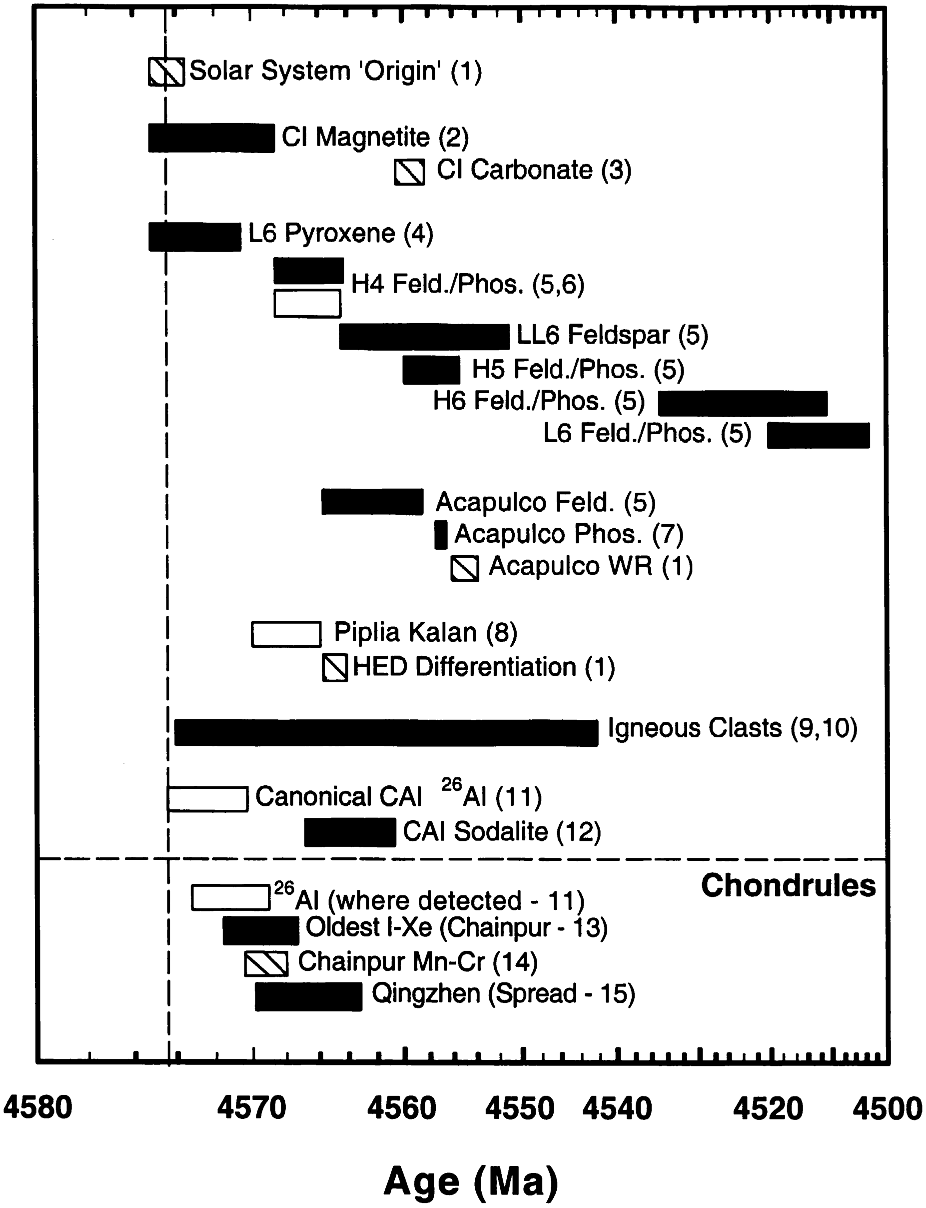
Solar System 'Origin' (1)
CI Magnetite (2)
CI Carbonate (3)
L6 Pyroxene (4)
H4 Feld./Phos. (5,6)
LL6 Feldspar (5)
H5 Feld./Phos. (5)
H6 Feld./Phos. (5)
L6 Feld./Phos. (5)
Acapulco Feld. (5)
Acapulco Phos. (7)
Acapulco WR (1)
Piplia Kalan (8)
HED Differentiation (1)
Igneous Clasts (9,10)
Canonical CAI 26Al (11)
CAI Sodalite (12)
Chondrules
26Al (where detected - 11)
Oldest I-Xe (Chainpur - 13)
Chainpur Mn-Cr (14)
Qingzhen (Spread - 15)
4580
4570
4560
4550
4540
4520
4500
Age (Ma)

Figure 3. A tentative absolute chronology of the early solar system based on the radioactive decay of the extinct radionuclides ^{26}Al, ^{53}Mn and ^{129}I. Absolute ages have been derived for the I-Xe (solid bars) and Mn-Cr (hatched bars) systems by assuming the identity of closure ages of the systems and the Pb-Pb system in Acapulco phosphate (Nichols et al. 1994; Göpel et al. 1994) and the Angrite LEW86010 (Lugmair & Shukolyukov 1998) respectively. The Al-Mg system (open bars) has been calibrated assuming the identity of its closure age with that of the I-Xe system in St Marguerite feldspar (Brazzle et al. 1999; Zinner & Göpel 1992). Finally, interpretation of each system chronologically is only valid if the unstable nuclide was homogeneously distributed throughout the formation region of the samples. Errors bars of individual samples are usually dominated by the uncertainty in the calibration. The plausibility or otherwise of this chronology may be viewed as a test of these assumptions, and in this context the figure is encouraging. The earliest samples in each system are consistent and there is reasonable agreement for the earliest chondrule ages. Aqueous alteration and igneous processes, both of which are associated with sizable planetary bodies, commenced early in solar system history and continued for more than 10 Ma, an interval during which differentiation of some parent bodies took place. References: 1 - Lugmair & Shukolyukov (1998), 2 - Lewis & Anders (1975), 3 - Endress et al. (1996), 4 - Pravdivtseva & Hohenberg (1999), 5 - Brazzle et al. (1999 - representative data have been chosen), 6 - Zinner & Göpel (1992), 7 - Nichols et al. (1994), 8 - Srinivasan et al. (1999), 9 - Hutchison et al. (1988) 10 - Gilmour et al. (1999), 11 - Macpherson et al. (1995), 12 - Brazzle et al. (1996), 13 - Swindle et al. (1991), 14 - Nyquist et al. (1997), 15 - Whitby et al. (1999 - bar encompasses complete range of chondrule data).

5. Isotopic Anomalies in Oxygen

Isotopic anomalies arising from the preservation of grains formed around other stars before the solar system formed and from the presence in the presolar nebula of short-lived radionuclides are both traceable to nucleosynthesis. It has been suggested that isotopic anomalies in oxygen, specifically the presence of a component enriched in ^{16}O, represents a third category.

In Figure 1 the variations in bulk oxygen isotopes of chondrite groups are displayed. Conventional mass fractionation of a single reservoir would produce variation along lines of gradient 0.5, parallel to the line labelled 'terr. frac.'. Such processes are unable to account for all the data; there is clear evidence of a component enriched in ^{16}O alone. Studies of CAI led to the proposal that they were formed from a dust component enriched in ^{16}O, their constituent minerals then equilibrating to varying extent with a ^{16}O poor volatile phase. It was originally envisaged that the ^{16}O rich dust phase had preserved the signature of nucleosynthesis (Clayton 1993). Several objections have been made to this being the source of the excess ^{16}O—notably that those presolar oxide grains so far identified are not normally enriched in ^{16}O and that isotopic variations in other elements are not observed to accompany variations in ^{16}O content.

An alternative mechanism capable of producing ^{16}O enrichments has been proposed (Thiemens 1999). It invokes a non-linear isotopic effect similar to that observed between ozone and residual oxygen in the upper atmosphere. The similarity between the effects observed here and in meteorites is striking (Clayton 1993). However, the details of the mechanism by which it arises in the upper atmosphere are far from clear (some dependence on the differing symmetries of the ^{16}O^{16}O^{16}O and ^{17}O^{16}O^{16}O and ^{18}O^{16}O^{16}O isotopomers seems implicated). As yet the reaction responsible for producing a similar effect in the early solar system has not been identified. Thus this model has not reached the level of detail at which similar criticisms to those leveled at the nucleosynthetic model can be made; for instance, what correlation might be expected between ^{16}O excess and chemistry? Furthermore, the absence of individual grains enriched in ^{16}O may be equally critical for both theories. Finally, whether nucleosynthesis would be expected to have left traces in other elements is debatable. Oxygen is present in both volatile and refractory reservoirs, so oxygen isotopic homogeneity requires equilibration between the reservoirs while large scale homogeneity of elements present in only one reservoir requires only wide scale mixing of the nebula. The difficulties associated with the proposed nucleosynthetic origin of the ^{16}O rich dust reservoir are not as yet so great as to require it to be abandoned in favour of the non-linear chemical fractionation model until a better defined mechanism for the latter has been proposed.

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References

Akridge, D.G. & Sears, D.W.G. 1999, J. Geophys. Res, 104, 11, 853
Brazzle, R.H., Davis, A.M., MacPherson, G.J., & Hohenberg, C.M. 1996, Meteoritics, 31, A21
Brazzle, R.H., Pravdivtseva, O.V., Meshik, A.P., & Hohenberg, C.M. 1999, Geochim. Cosmochim. Acta, 63, 739
Brearley, A.J. 1993, Geochim. Cosmochim. Acta, 57, 1521
Clayton, R.N. 1993, Annu. Rev. Earth Planet. Sci., 21, 115
Crabb, J. & Schultz, L. 1981, Geochim. Cosmochim. Acta, 45, 2151
Endress, M., Zinner, & Bischoff A. 1996, Nature, 379, 701
Gilmour, J.D., Whitby, J.A., Turner, G., Bridges, J.C., & Hutchison, R. 1999, Meteoritics, (submitted)
Göpel, C., Manhès, G., & Allègre, C.J. 1994, Earth Planet. Sci. Lett, 121, 153
Hewins, R.H, Jones, R.H., & Scott, E.R. D., eds. 1996, Chondrules and the Protoplanetary Disk (Cambridge University Press: Cambridge)
Hutchison, R.H., Williams, C.T., Din, V.K., Clayton, R.N., Kirschbaum, C., Paul, R.L., & Lipschutz M.E. 1988, Earth Planet. Sci. Lett., 90, 105
Kerridge, J.F. & Matthews, M.S., eds. 1988, Meteorites and the Early Solar System (University of Arizona: Tucson)

Lee, T., Shu, F.H., Shang, H., Glassgold, A.E., & Rehm, K.E. 1999, ApJ, 506, 898
Lewis, R.S. & Anders, E. 1975, Proc. Nat. Acad. Sci. USA, 72, 268
Lugmair, G.W. & Shukolyukov, A. 1998, Geochim. Cosmochim. Acta, 62, 2863
MacPherson, G.J., Davis, A.M., & Zinner, E.K. 1995, Meteoritics, 30, 365
McSween Jr., H.Y. 1999, Meteorites and Their Parent Planets (Cambridge University Press: Cambridge)
Meshik, A.P., Pravdivtseva, O.V., & Hohenerg, C.M. 1998, Meteoritics, 33, A106
Minster, J.F., Birck, J.L., & Allègre, C.J. 1982, Nature, 300, 414
Nichols Jr., R.H., Hohenberg, C.M., Kehm, K., Kim, Y., & Marti, K. 1994, Geochim. Cosmochim. Acta, 58, 2553
Nyquist, L., Lindstrom, D., Shih, C.-Y., Wiesmann, H., Mittlefehldt, D., Wentworth, S., & Martinez, R. 1997, Proc. Lunar Planet. Sci. Conf., XXVII, 1093
Podosek, F.A. & Nichols Jr., R.H. 1997, in Astrophysical Implications of the Laboratory Study of Presolar Materials, eds. T.J. Bernatowicz & E. Zinner, AIP Conf. Proc., 402, 617
Pravdivtsva, O.V. & Hohenberg, C.M. 1999, Proc. Lunar Planet. Sci. Conf. XXX, abstract #2047
Russell, S.S., Srinivasan, G., Huss, G.R., Wasserburg, G.J., & MacPherson, G.J. 1996, Science, 273, 757
Sears, D.W.G., Grossman, J.N., Melcher, C.L., Ross, L.M., & Mills, A.A. 1980, Nature, 287, 791
Srinivasan, G., Goswami, J.N., & Bhandari, N. 1999, Science, 284, 1349
Swindle, T.D., Caffee, M.W., Hohenberg, C.M., Lindstrom, M.M., & Taylor G.J. 1991, Geochim. Cosmochim. Acta, 55, 861
Ott, U. 1996, ApJ, 463, 344
Thiemens, M.H. 1999, Science, 283, 341
Van Schmus, W.R. & Wood, J.A. 1967, Geochim. Cosmochim. Acta, 31, 747
Verchovsky, A.B., Fisenko, A.V., Semjonova, L.F., Wright, I.P., Lee, M.R., & Pillinger, C.T. 1998, Science, 281, 116
Whitby, J.A., Gilmour, J.D., Turner, G., & Ash, R.D. 1998, Geochim. Cosmochim. Acta, submitted
Zinner, E. 1997, in Astrophysical Implications of the Laboratory Study of Presolar Materials, eds. T.J. Bernatowicz & E. Zinner, AIP Conf. Proc., 402, 3
Zinner, E. & Göpel, C. 1992, Meteoritics, 27, 311

Discussion

Y. Aikawa: Can you elaborate on current objections to the 'X-wind model' from the meteorites researchers? The X-wind model has a big impact on the interpretation of meteoritic data; meteoritic data may carry information about the region very close to the star, rather than the outer 'planet-forming region.'

J. D. Gilmour: The 'X-wind model' is one of the competing explanations for the presence of short-lived radionuclides. Each has problems. Notable for the X-wind model are the overproduction of ^{41}Ca by 2 orders of magnitude (Lee et al. ApJ, 506, 898), the 'matching' of chondrules matrix in various groups and the variation in chondrule properties (e.g. ^{16}O anomalies) between various chondrite groups. Acceptance of any model at this point is premature, in my view.

E. Herbst: What specific objections are there to the view that ^{16}O enhancement comes from symmetry-breaking in chemical reactions?

J. D. Gilmour: I have no specific objections, but as yet there is no specific theory to object to. A major objection to the 'nucleosynthesis' theory is the absence of other expected isotope anomalies. The competing symmetry-breaking or SIKIE reaction theory as yet makes no other predictions against which to test it. Of course, it could be correct nevertheless.

J. M. Greenberg: I have wondered for some time if the presence of hydrated silicates is correlated with the presence of carbonates and organic carbon. Are there enough meteorite samples to show, on the other hand, that non-hydrous silicates are not accompanied by carbonates and organic carbon? My reason for asking this question is that if the H_2O from cloud interstellar dust is preserved, it contains CO_2 which then leads to carbonates if the heating proceeds (liquid water).

J. D. Gilmour: I do not as yet know the answer to this question. However, I am sure that carbonates produced by aqueous alteration will be accompanied by other alteration products such as hydrated silicates.

D. Williams: What kind of sorting processes operate in the sorting of chodrules?

J. D. Gilmour: Sorting processes are invoked to explain metal-silicate fractionation and chondrule size distributions, which vary among groups. A huge variety of processes, many depending on aerodynamic sorting, have been proposed. See Akridge & Sears (1999, J. Geophys. Res., 104, E5, 11853) for a recent summary and description of one possible sorting process.