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Isotopic Variations in Primitive Meteorites [and Discussion]

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Isotopic variations in primitive meteorites

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Oxygen isotopic variations in carbonaceous chondrites and in ordinary chondrites can each be interpreted as mixtures of two isotopically different reservoirs, one consisting of solids, enriched in ^{16}O, the other of a gas, depleted in ^{16}O relative to terrestrial abundances. The data suggest a common source of the solids for each of the two classes of meteorites, but a different gas reservoir for each. These conditions might prevail in gaseous protoplanets. Radiogenic ^{26}Mg is variable in abundance among some classes of Allende inclusions, implying either nebular heterogeneity with respect to ^{26}Al/^{27}Al ratios, or time differences of crystal formation of 1 or 2×10^6 a. The presence of excess ^{107}Ag from decay of extinct ^{107}Pd supports the evidence from ^{26}Mg for a time interval of at most a few million years between the last nucleosynthetic event and accretion of substantial bodies in the Solar System. The widespread small excess of ^{50}Ti in Allende inclusions is tantalizing, but unexplained. An exceptional hibonite-rich inclusion from Allende contains strongly fractionated isotopes of oxygen and calcium, but isotopically normal magnesium. Its trace elements imply association with a hot, oxidized gas. Among the volatile elements, neon-E has been shown to be essentially pure ^{22}Ne, and appears to be the decay product of extinct ^{22}Na. If so, condensation of some stellar ejecta must take place on a time scale of a year or so. The problem of reconciling the ^{26}Al time scale of about 10^6 years between nucleosynthesis and Solar System condensation with the 10^8 year scale implied by the decay of ^{129}I to ^{129}Xe and fission of ^{244}Pu requires that at most a small fraction of the ^{129}I and ^{244}Pu be formed in the most recent event. Progress has been made in establishing the carrier phases of isotopically anomalous xenon and krypton. The apparent location of anomalous xenon and ^{14}N-rich nitrogen in identical carriers supports the notion that nucleosynthetic anomalies in nitrogen are also present in Allende.

Introduction

Over the past several years, abundant evidence has been found in meteorites that proves that the matter of the Solar System was not completely homogenized before condensation and accretion of the planets. This evidence is in the form of patterns of isotopic abundances that cannot be attributed to known processes that took place *within* the solar nebula, such as isotopic fractionation, radioactive decay and transmutation by cosmic rays. These 'isotopic anomalies' apparently are attributable to the major processes of nucleosynthesis, and are observable because some atoms with different nucleosynthetic origins have maintained a chemical identity which prevented complete mixing. The study of isotopic anomalies is directed both towards a fuller understanding of nucleosynthesis itself and towards the exploitation of the variations as tracers and clocks for events in the birth of the Solar System. Observations until 1978 were reviewed by Clayton (1978) and Lee (1979). This article will emphasize more recent results.

In the discussion of isotopic anomalies, it will be convenient to subdivide the chemical elements into two categories: the rock-forming elements and the volatile trace elements. In the former, I include oxygen, magnesium, silicon, etc., which are the principal constituents of the meteoritic minerals, as well as the non-volatile trace elements that accompany them in solid

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[†] Elected F.R.S. 19 March 1981.

solution. In the second category, I include carbon, nitrogen and the noble gases, which appear to have a common chemical history in the solar nebula that is not strongly coupled to that of their associated major minerals.

Another kind of subdivision could be made on the basis of frequency of occurrence: some anomalies are widespread, and are found in all samples of particular meteorite types; others are found only in exceptional samples that have experienced unique histories, and which may, therefore, contain special information.

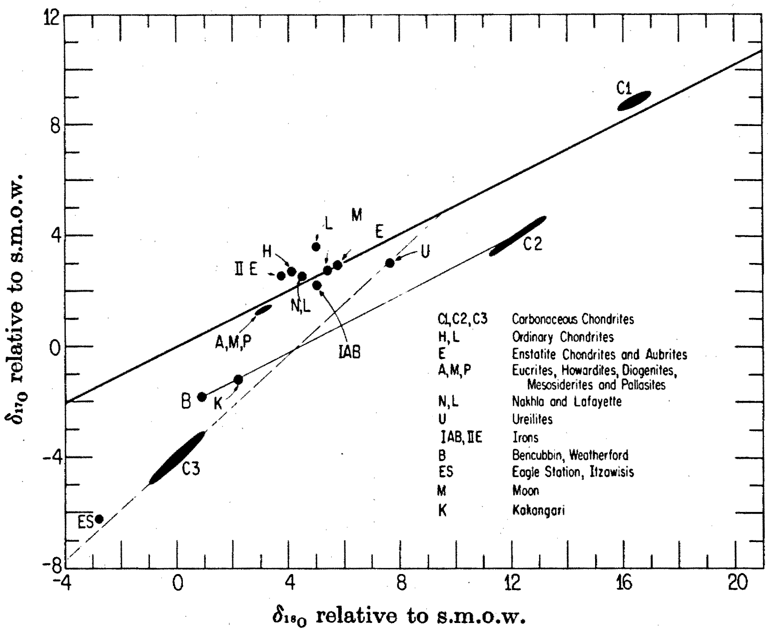

FIGURE 1. Three-isotope graph for oxygen: $\delta_{^{17}O}$ is variation in $^{17}O/^{16}O$, $\delta_{^{18}O}$ is variation in $^{18}O/^{16}O$, both relative to terrestrial s.m.o.w. (standard mean ocean water) defined to be zero on both axes. The heavy line with slope $\frac{1}{2}$ is the locus of all terrestrial samples (rocks, air, water, etc.), the variations of which are due to mass-dependent fractionation. The dashed line is the ^{16}O-mixing line defined by anhydrous minerals of C2 and C3 carbonaceous chondrites. The matrix of C2 carbonaceous chondrites plots in the region marked C2. The various meteorite groups have characteristic oxygen isotopic compositions, and lie on both sides of the terrestrial line. There is no composition that can be identified as 'normal' or 'average Solar System'.

ROCK-FORMING ELEMENTS

Oxygen

In terms of the numbers of atoms involved, oxygen shows by far the largest isotopic anomalies. Nucleosynthetic variations of oxygen isotopes are also ubiquitous among all meteorite groups, so that no preferred 'normal' isotopic composition can be defined. In particular, the isotopic composition of terrestrial oxygen is useful as a reference point only for laboratory convenience, and not because it has any broader significance for the Solar System as a whole.

The anomalies in oxygen are displayed on a three-isotope graph (figure 1). Fractionation processes, which depend almost linearly on the masses of the isotopes, produce twice as great a variation in $^{18}O/^{16}O$ ratios as in $^{17}O/^{16}O$ ratios, and thus generate lines with slope near $\frac{1}{2}$ on this graph. Data for various terrestrial samples illustrate this effect in figure 1. Similar fractionation trends, parallel to the terrestrial line, have been demonstrated for separated mineral phases of some internally equilibrated stony meteorites (Clayton *et al.* 1976). If there were no effects of nuclear origin, all Solar System samples should lie on the same fractionation line. It is evident from figure 1 that they do not, and major groups of meteorites fall on either side of that line. The largest anomalies are seen in the refractory Ca,Al-rich inclusions and other anhydrous minerals of the C2 and C3 carbonaceous chondrites. These samples are of special interest, since their chemical and mineralogical compositions are just those that were predicted as the earliest condensates from a hot gas of solar composition (Grossman 1972, 1973), and their abundances of radiogenic strontium indicate their very primitive nature (Gray *et al.* 1973). The oxygen isotopic compositions of separated minerals define a line with slope near unity. This implies that the various samples have an almost constant ratio of $^{17}\mathrm{O}/^{18}\mathrm{O}$, with variable abundances of $^{16}\mathrm{O}$. The observed range of variations corresponds to a variation of 5 % in the $^{16}\mathrm{O}$ abundance. It is a property of three-isotope graphs of this sort that samples that are mixtures in varying proportions of two end members generate a straight line between the compositions of the end members. In principle, the isotopic compositions of the end members may lie at any point on the extrapolation of the mixing line beyond the range of observed values. For the carbonaceous chondrite line, it can be argued that the compositions of the two components are, in fact, very near those of the ends of the observed range. The upper end of the line is made up of data from melilite, anorthite, olivine chondrules and dark inclusions from Allende, and iron-bearing olivine from other C3V chondrites (Vigarano, Grosnaja). This composition lies in the vicinity of those of most of the non-carbonaceous meteorites, and thus may represent a widespread Solar System component.

The lower end of the mixing line has a pile-up of data points from Allende spinel and pyroxene samples. Clayton *et al.* (1977) considered the possibility that the lower component of the mixing line might be a submicroscopic phase containing monoisotopic $^{16}\mathrm{O}$. However, to account for the data, such a phase would have to constitute at least 5 % of the spinel and pyroxene samples, and a diligent search using the electron microscope and X-ray diffraction failed to reveal any intact carrier phase of this sort. Instead, the composition given approximately by $\delta_{^{18}\mathrm{O}} = -40$‰, $\delta_{^{17}\mathrm{O}} = -42$‰ has appeared in other contexts: (1) it is found for a spinel–hibonite mixture separated from the C2 chondrite Murchison; (2) it is the initial composition from which the exceptional 'Fun' inclusions have evolved (Clayton & Mayeda 1977; Lee *et al.* 1980); (3) it is a possible end member of a mixing line for ordinary chondrites.

We can then inquire into the physical nature of the two components. Clayton *et al.* (1977) and Clayton & Mayeda (1977) proposed that the minerals of the Allende inclusions were first formed with $\delta_{^{18}\mathrm{O}}$ near -40‰ (the isotopically 'light' component), and were subsequently partially exchanged with gas in the solar nebula with $\delta_{^{18}\mathrm{O}}$ near $+5$‰ (the isotopically 'heavy' component). This choice is dictated by two types of observation: (1) spinel crystals with $\delta_{^{18}\mathrm{O}} = -38$‰ are found entirely enclosed within melilite with $\delta_{^{18}\mathrm{O}} = +2$‰, implying that the heavy component was added later; (2) the solids of the Fun inclusions were all altered by a common heavy component, again presumably the nebular gas. It should also be noted that the relative cosmic abundances of oxygen and the non-volatile major elements (magnesium, silicon, calcium, aluminium, iron, etc.) require that about 80 % of the oxygen in the solar nebula remain in gaseous molecules (CO and H_2O) after all the rocky solids have condensed, so that the overall $\delta_{^{18}\mathrm{O}}$ of the Solar System must be close to that of the gas phase.

The two-component model for minerals in the Allende inclusions is probably equally applicable to all of the minerals in Allende and the other C3 chondrites, since their isotopic compositions fall on the same mixing line as that defined by the minerals of the Ca,Al-rich inclusions. Thus these inclusions are not exceptional in the amount of ^{16}O-rich component that they originally acquired, but are exceptional in having preserved a greater fraction of that component during the subsequent exchange with the isotopically heavy gaseous reservoir.

It has recently been shown that internal oxygen isotope heterogeneities also exist in ordinary chondrites (Mayeda *et al.* 1980). Figure 2 shows a mixing line for separated fragments from the unequilibrated chondrite ALHA-76004. This line is indistinguishable from the best-fit line through the data for 33 individual chondrules from 10 ordinary chondrites (Gooding *et al.* 1980*b*; Mayeda *et al.* 1980), and the line connecting the mean of H-group chondrites and the mean of L-group chondrites (Clayton & Mayeda 1978). This line is distinctly different from the carbonaceous chondrite mixing line, being displaced towards higher ^{17}O/^{16}O by about 3‰. As for the carbonaceous chondrites, we can inquire about the physical nature and isotopic compositions of the end members of the mixing line. If we postulate that the mixing took place by a mechanism of isotopic exchange between a gas and a pre-existing solid, the evidence from ALHA-76004 suggests that the heavy component was the gas, since in a clast consisting of olivine and glass, the glass, which is more readily exchanged, has 4‰ greater $\delta_{^{18}\mathrm{O}}$ and $\delta_{^{17}\mathrm{O}}$ than the intergrown olivine. The data are still too few to make a firm assignment for the isotopic composition of the solid, light component. The most extreme composition observed is $\delta_{^{18}\mathrm{O}} = -1.9$‰ for a fragment from ALHA-76004, but lower values can be expected if analysis can be made of appropriate separated minerals. The measured slope of the mixing line in figure 2 is greater than that for the carbonaceous chondrite mixing line. The two lines intersect at a point with $\delta_{^{18}\mathrm{O}} = -37$‰. Since the intersection is at a very small angle, and the ordinary chondrite line is less well constrained due to the limited number of analyses, the uncertainty in this point of intersection may be on the order of ± 10‰. Nevertheless, it is remarkable that this intersection is indistinguishable from the inferred composition for the solid, isotopically light component of the carbonaceous chondrite mixing line. Thus, the data are compatible with a single solid end member for both mixing lines, although they have clearly exchanged with different gaseous reservoirs.

Another remarkable feature of the isotopic compositions of individual chondrules from ordinary chondrites is that there is no systematic relation between isotopic composition and the iron group (H, L or LL) of the whole meteorite, even though the whole meteorites do show distinct isotopic groupings. Thus the acquisition of the characteristic properties of the iron groups occurred after chondrule formation. This observation is entirely consistent with previous measurements of major and trace element abundances in chondrules of unequilibrated ordinary chondrites (Dodd *et al.* 1967; Gooding *et al.* 1980*a*).

A possible third ^{16}O-mixing line passes through the composition of the Earth and Moon, enstatite chondrites and aubrites, silicates of 1AB irons, and some unique stony meteorites (Mayeda & Clayton 1980). The observations appear to require several isotopically distinct gaseous reservoirs in the inner Solar System, such as might be produced in giant gaseous protoplanets (Cameron 1979).

Magnesium

Excess ^{26}Mg is common in Ca,Al-rich inclusions in Allende. Most of the samples studied are classified as coarse-grained type B1 (Wark & Lovering 1977) on the basis of mineralogy and texture. They all give excellent internal isochrons indicating *in situ* radioactive decay of ^{26}Al (half life 7.2×10^5 years). From the slope of the isochron, an initial ratio of ^{26}Al/^{27}Al, at the time of crystallization, was $(4\text{–}5) \times 10^{-5}$ (Lee 1979). An example is shown in figure 3. The same

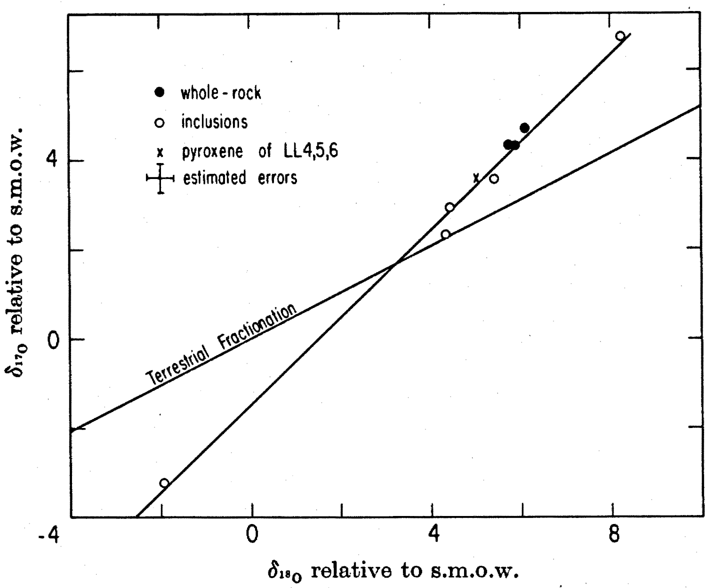

FIGURE 2. Three-isotope graph for oxygen in an unequilibrated ordinary chondrite, the Antarctic meteorite ALHA-76004. The ^{16}O-mixing line covers a range in $\delta_{^{17}O}$ and $\delta_{^{18}O}$ of 10‰. This mixing line also passes through the bulk compositions of equilibrated H, L and LL meteorites (points H and L in figure 1).

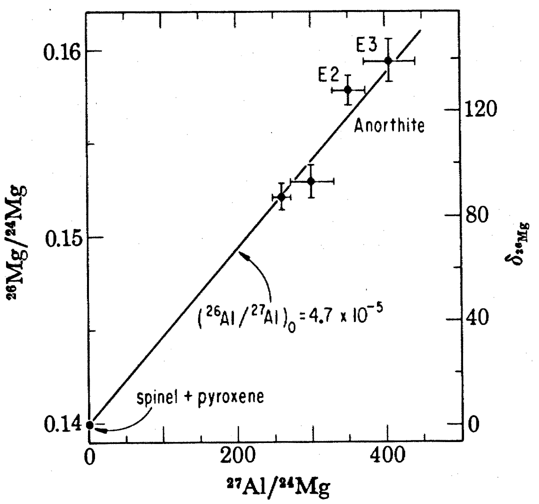

FIGURE 3. Typical ^{26}Al–^{26}Mg isochron from an Allende Ca, Al-rich inclusion of type B1. Magnesium isotopic compositions of spinel and pyroxene (magnesium-rich minerals) are indistinguishable from normal terrestrial values. The linear relation between excess ^{26}Mg and the ratio of stable isotopes ^{27}Al/^{24}Mg indicates *in situ* decay of ^{26}Al. The slope of the isochron gives the initial ratio of ^{26}Al/^{27}Al at the time of crystallization of the minerals. (Data of Steele *et al.* 1978.)

initial ratio has been found for two type B inclusions from the C3 chondrite Leoville (Hutcheon & Steele 1980) and from a small melilite-spinel inclusion from the C2 chondrite Murchison (Tanaka *et al.* 1980), and a hibonite inclusion from this same meteorite (Papanastassiou & Wasserburg 1980). This uniformity of initial ratio implies crystallization of these various objects within a time interval of about 10^5 years.

In contrast with the well defined isochrons and uniform initial ratios in type B1 inclusions, the Allende type A and B2 inclusions do not, in general, yield linear plots of ^{26}Mg/^{24}Mg against

^{27}Al/^{24}Mg (Hutcheon *et al.* 1979; Hutcheon & Steele 1980). Although many data points do lie on the B1 isochron, other parts of the same inclusion may have significantly lower ^{26}Mg contents. Several samples of hibonite from Murchison have been found to have no ^{26}Mg excesses even though they have very large Al/Mg ratios (Hutcheon *et al.* 1980). It is not clear whether these complex patterns represent initial isotopic heterogeneity in aluminium, or whether they really measure time intervals between crystallization of various minerals, which would have to be of the order of 10^6 years.

The existence of centimetre-sized rocks in Allende that have good internal ^{26}Al/^{26}Mg isochrons requires that ^{26}Al was alive at the time of crystallization of their various minerals. The inclusions themselves were formed primarily from the ordinary matter of the Solar System, at the time when meteoritic minerals first started to form, as is best indicated by the ^{87}Sr/^{86}Sr ratio (Gray *et al.* 1973). It is the presence of live ^{26}Al in the Solar System, not more than a few half lives after nucleosynthesis, that has provided the principal support for the postulate of a nearby supernova explosion just before formation of the Solar System (Cameron & Truran 1977; Schramm & Clayton 1978). This qualitative conclusion follows whether or not the ^{26}Al/^{27}Al ratio was homogenized throughout the nebula.

In the discussion of oxygen isotope heterogeneities, the possibility was put forward that the ^{16}O-rich exotic component may have been homogenized over the solid grains of the proto-solar cloud. If so, it seems very likely that the ^{26}Al/^{27}Al ratio was also homogenized, since aluminium must be virtually all condensed in solid grains. The question of uniformity of distribution of ^{26}Al is of importance for two major reasons. First, it would imply that departures from a standard isochron must represent time differences rather than primordial heterogeneities. Secondly, it would make ^{26}Al a major early heat source that could melt all condensed Solar System bodies with diameters more than a few kilometres (Lee *et al.* 1977). Resolution of this question may hinge on the results of a search for radiogenic ^{26}Mg in unequilibrated ordinary chondrites, such as those in which oxygen isotope heterogeneity has been seen.

Silver

The presence in some iron meteorites of excess ^{107}Ag from decay of the extinct radionuclide ^{107}Pd (half life 6.5×10^6 years), first reported by Kelly & Wasserburg (1978), has been confirmed by further studies of Kaiser *et al.* (1980*a*, *b*). Production of the excess ^{107}Ag by cosmic-ray spallation has been ruled out on the basis of noble gas measurements by Villa *et al.* (1980). Palladium is a siderophile element, and its decay product is only detectable in favourable cases in which the Pd/Ag ratio is enhanced by partitioning of palladium preferentially in the metal phase and silver into other phases, probably sulphides. Thus the excess ^{107}Ag can accumulate only after segregation of the metal phase in the meteorite parent body. The evidence therefore points to a time interval not greater than several million years between nucleosynthesis and iron sulphide separation in a substantial body. The observations in the ^{107}Pd–^{107}Ag system are consistent with those of the ^{26}Al–^{26}Mg system, and imply most recent nucleosynthesis of ^{26}Al and ^{107}Pd in the same event, thus extending the range of mass number of the nuclides involved in that event.

Titanium

Titanium is the only rock-forming element other than oxygen in which anomalous isotopic compositions have been found in every sample of Allende inclusion that has been analysed (Heydegger *et al.* 1979; Niederer *et al.* 1980*a*, *b*; Niemeyer & Lugmair 1980). The principal effect is an excess of the neutron-rich isotope ^{50}Ti by about 0.1 % relative to the normal abundance. Although the effect is not large, it has been measured in three laboratories and is widespread in Allende. Calcium in many of the same samples is isotopically normal (Niederer *et al.* 1980*b*). Neither the nuclear processes that produced the titanium anomaly nor the chemical processes that allow it to be observed in the Allende samples are yet understood. However, this evidence is expected to be important in understanding the general problems of isotopic heterogeneity.

Exceptional Allende inclusions

Two coarse-grained Ca,Al-rich inclusions from Allende (labelled C1 and EK1-4-1) have been found to have a remarkable array of isotopic anomalies (see Lee (1979) for a review). The usual ^{16}O excess observed in other Allende inclusions has, superimposed on it, a large mass-dependent isotopic fractionation. Both silicon and magnesium are also strongly fractionated, and have, in addition, small nuclear anomalies. They lack radiogenic ^{26}Mg. There are complicated isotopic abundance patterns for calcium and titanium, including apparent negative anomalies. Strontium, barium, samarium and neodymium have anomalous abundances which appear to result from excess of r- and p-process isotopes relative to s-process. Although it is clear that these anomalies are of nucleosynthetic origin, it is not obvious that they result from a single event, such as a supernova explosion. It is also not at all clear why they are found in two inclusions that have chemical and mineralogical characteristics indistinguishable from those of other Allende inclusions.

A third member of this exceptional group (labelled HAL) has recently been reported (Lee *et al.* 1979, 1980; Allen *et al.* 1980). Its oxygen is even more strongly fractionated than the oxygen in C1 and EK1-4-1; magnesium (of which there is very little in HAL) is isotopically normal, being unfractionated and devoid of radiogenic ^{26}Mg; calcium is strongly fractionated. Isotopic data are not yet available on other elements. HAL has very unusual chemical and mineralogical compositions in that it consists predominantly of hibonite ($CaAl_6O_{19}$) with minor perovskite ($CaTiO_3$), and, in its coarsely crystalline interior, has no silicates. These compositions are consistent with a very high temperature of condensation or a high temperature of evaporation of previously solid material. Another indicator of the conditions of formation of HAL is the marked depletion in the concentration of cerium relative to the adjacent rare earths (Tanaka *et al.* 1979), which can only be understood in terms of equilibration or exchange with a highly oxidizing gas phase. A fundamental question yet to be answered for this class of exceptional rocks is whether the isotopically anomalous matter has been added to an initially homogeneous substrate, or whether it has been *revealed* by selective removal of material from an initially heterogeneous substrate.

VOLATILE ELEMENTS

Primitive meteorites, both carbonaceous and ordinary chondrites, contain noble gases that frequently are found to have isotopic abundances that are not attributable to any of the three principal components: solar, planetary and cosmogenic. Most of these gases are contained within fine-grained carbonaceous carrier phases, and their association with the major minerals of the meteorites appears to be more or less accidental, in contrast with the rock-forming elements described above. However, genetic relationships may be expected between the trace quantities of noble gases and the more abundant elements of the carrier phases: carbon, nitrogen, and probably hydrogen.

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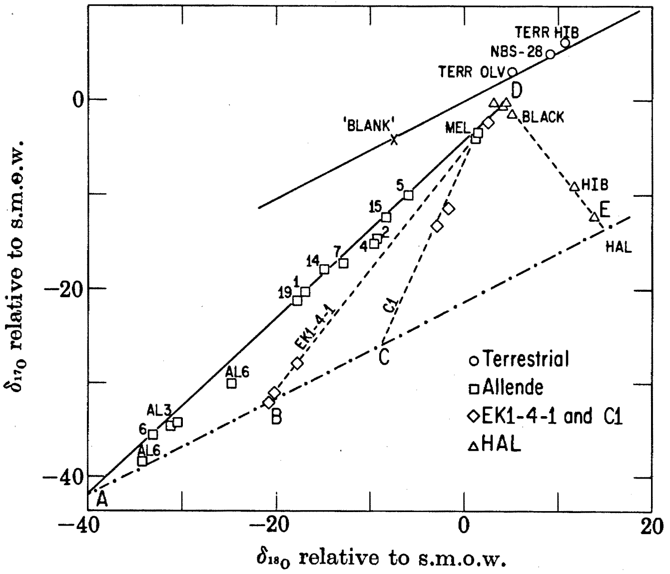

FIGURE 4. Three-isotope graph of oxygen from the exceptional Allende inclusions: EK 1-4-1, C1 and HAL. The terrestrial fractionation (solid line, slope ½) and 'normal' Allende (solid line, slope 1) lines are shown for reference. The history of minerals in these inclusions appears to have been: (1) initial crystallization with isotopic composition near point A; (2) large mass-dependent fractionation and loss of lighter isotopes, perhaps by evaporation, giving compositions B, C and E for EK 1-4-1, C1 and HAL, respectively; and (3) exchange with a gas with composition near D, with spinel and pyroxene only slightly exchanged, and melilite almost completely exchanged. 'Normal' Allende inclusions, indicated by numbered square symbols, had similar histories, except that they lacked process (2). (Data of Lee *et al.* 1980.)

Neon

Neon-E, recognized as a component enriched in ^{22}Ne, was postulated by Black (1972) to have been derived from a source outside the Solar System. It has now been established, by physical concentration of the host phases, that neon-E is $> 99\,\%$ pure ^{22}Ne (Jungck *et al.* 1979). A strong case can be made against production of neon-E by nuclear reactions within the Solar System (D. D. Clayton *et al.* 1977). Even stellar nucleosynthesis is hard put to produce such an isotopically pure component (Arnould & Nørgaard 1978). The favoured explanation at the present time is that the ^{22}Ne is a decay product of ^{22}Na (half life 2.6 years) (Jeffery & Anders 1970; D. D. Clayton 1975). A scheme that may be astrophysically plausible is the condensation of solid sodium-bearing crystals in the cooling, expanding ejecta of a supernova on the time scale of about 1 year. Such grains would contain negligible amounts of the other neon isotopes, and would therefore become carriers of pure ^{22}Ne. Neon-E is found in some ordinary chondrites as well as carbonaceous chondrites (Niederer & Eberhardt 1977), and has been found in two different carrier phases, one that releases neon in the laboratory at relatively low temperatures (< 800 °C), probably a carbonaceous phase, the other that releases neon at high temperatures (1200–1400 °C), perhaps spinel or hibonite (Alaerts *et al.* 1980). The relationship between these carriers and the supernova scheme is obscure.

Xenon

The isotopic variations of xenon in the Earth, the Moon and meteorites are the subject of a recent manuscript by D. Phinney & R. O. Pepin which runs to > 100 pages. It is obviously impossible to do justice to the topic in this brief review. Two topics will be discussed: (1) the interpretation of radiogenic ^{129}Xe in light of the time scales implied by ^{26}Al and ^{107}Pd, and (2) the siting of CCF-xenon.

Reynolds's (1960) discovery of excesses of ^{129}Xe due to decay of the extinct nuclide ^{129}I led to an estimate of about 2×10^8 years for the interval between the last major nucleosynthetic event and the formation of solids in the Solar System. This time period is attractive since it is about the time necessary for the Sun to pass from one galactic spiral arm to the next. Since the spiral arms are regions of active star formation, they provide a natural location for accumulation of freshly synthesized nuclei ejected by explosions of short-lived stars. Reeves (1979) and Kelly & Wasserburg (1978) have shown that the ^{129}I time scale of the order of 10^8 years and the ^{26}Al time scale of the order of 10^6 years are not necessarily incompatible if the 10^6 year event contributed only a small percentage of the ^{129}I in the solar nebula. This requires a relatively low production rate of r-process nuclei in the last event.

Meteoritic xenon contains a component, known as CCF-xenon, that has the characteristic signature of enrichments of both the lightest isotopes (124, 126) and the heaviest (134, 136) (Reynolds & Turner 1964). Although there is no concensus concerning the origin of this component, most current theories invoke stellar nucleosynthetic processes to produce some or all of the excess nuclei. In recent years, much attention has been given to the search for carrier phases of both normal and exotic noble gases in meteorites (see, for example, Lewis *et al.* 1975). Carbonaceous carrier phases have been identified in several instances. An important recent development was the identification of carbynes as noble gas carriers in the carbonaceous chondrites Allende and Murchison (Whittaker *et al.* 1980). The carbynes are allotropes of carbon containing chains of carbon atoms with alternating single and triple bonds (Sladkov & Koudrayatsen 1969; Whittaker 1978). This structure is intriguingly similar to that of the cyanoacetylene molecules which are observed in space by radio telescope (Kroto *et al.* 1978; Walmsley *et al.* 1980). The association of carbon, nitrogen and noble gases in meteorites is shown by the experiments of Frick & Pepin (1980), who showed that their acid residues from Allende (presumably mostly carbynes) undergo oxidation with molecular oxygen below 600 °C, and release isotopically anomalous xenon in the same narrow temperature range as ^{14}N-rich nitrogen. Thiemens & Clayton (1980) had previously found ^{14}N-rich nitrogen in stepwise heating of a bulk sample of Allende. Since nitrogen has only two stable isotopes, there is no unambiguous way to distinguish between nuclear effects and fractionation effects in producing isotopic variability. Hence, only if its isotopic variations are very large, and are clearly correlated with nucleosynthetic variations in other elements, can nuclear effects in nitrogen (and carbon) be recognized. This may turn out to be the case in the carbonaceous carrier phases in unequilibrated meteorites.

SUMMARY

New observations of isotopic variations in meteorites continue to be made, and attempts to put them into appropriate astrophysical contexts naturally follow. The presence of large internal ^{16}O variability in ordinary chondrites greatly extends the range of meteorite types in which this phenomenon has been observed. These results may lead to identification of major gas and dust reservoirs in the cloud from which the Solar System formed. The demonstration that live ^{107}Pd was present in the differentiated parent bodies of some iron meteorites supports the million year time scale between a major nucleosynthetic event and Solar System formation, as implied by the presence of live ^{26}Al in carbonaceous chondrites. However, the variability of radiogenic ^{26}Mg abundances in these meteorites makes it clear that the data cannot be interpreted simply in terms of time variations. Models of nucleosynthesis for elements from calcium to the iron peak should be aided by the new observations of abundances of titanium isotopes. The recent progress toward identification of carrier phases for the isotopically anomalous noble gases, particularly Ne-E and CCF-Xe is encouraging, and leads to the expectation that their astrophysical sources may soon be identified. The possible relationship between carbynes in meteorites and cyanoacetylenes in cold clouds in space is especially exciting.

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Discussion

W. H. McCrea, F.R.S. (*Astronomy Centre, University of Sussex, Brighton BN*1 9*QH, U.K.*) Butler *et al.* (1978) have suggested that much of the neon on the Earth and the other planets may have been accreted directly onto these bodies from dense interstellar clouds during an estimated dozen or so passages of the Solar System through such clouds in its past motion through the Galaxy. Could Professor Clayton say whether this suggestion is supported by the isotopic evidence concerning neon? The novelty of the suggestion is the possible significance of accretion by the planets themselves, as distinct from accretion by the Sun.

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R. N. Clayton. Butler *et al.* (1978) proposed that a large fraction of the Earth's atmospheric neon was derived from interstellar clouds, and suggested that a ^{22}Ne/^{20}Ne ratio of about 0.10 (like that on Earth) might be found on Mars and Venus. Measurement of neon isotopic ratios by the Viking and Pioneer mass spectrometers was exceedingly difficult due to interference of doubly charged ions CO_2^{2+} and $^{40}Ar^{2+}$. There is therefore no satisfactory measurement of ^{22}Ne/^{20}Ne for Mars, and the value of 0.07 ± 0.02 for Venus (Hoffman *et al.* 1980) is in agreement with the solar wind value (Geiss *et al.* 1972). One feature not accounted for by the process of Butler *et al.* (1978) is the large variation of neon abundances of the terrestrial planets, with a decrease of about two orders of magnitude in each step from Venus to Earth to Mars.

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