ISOTOPE COSMOCHEMISTRY

INTRODUCTION

Meteorites are our primary source of information about the early Solar System. Chemical, isotopic and petrological features of meteorites reflect events that occurred in the first few tens of millions of years of Solar System history. Observations on meteorites, together with astronomical observations on the birth of stars and the laws of physics, are the basis of our ideas on how the Solar System, and the Earth, formed.

Meteorites can be divided into two broad groups: primitive meteorites and differentiated meteorites. The chondrites constitute the primitive group: most of their chemical, isotopic, and petrological features resulted from processes that occurred in the cloud of gas and dust that we refer to as the solar nebula. All chondrites, however, have experienced at least some metamorphism on "parent bodies", the small planets (diameters ranging from a few km to a few hundred km) from which meteorites are derived by collisions. The differentiated meteorites, which include the achondrites, stony irons, and irons, were so extensively processed, by melting and brecciation, in parent bodies that any information about nebular processes has largely been lost. On the other hand, the differentiated meteorites provide insights into the early stages of planet formation.

Chondrites are so-called becuase the contain "chondrules", small (typically a mm diameter) round bodies that were clearly once molten. The other main consitutents of chondirtes are the matrix, which is generally very fine grained, and refractory, or Ca-Al, inclusions (called CAI's or RI's), which are evaporative resides or high-temperature condesates. Chondrites are divided into carbonaceous (C), H, L, LL (collectively called ordinary, or O chondrites), and E classes classes. The carbonaceous chondrites are, as their name implies, rich in carbon (as carbonate, graphite, organic matter, and, rarely, microdiamonds) and other volatiles and are further divided into classes CI, CV, CM, and CM. The CI chondrites lack chondrules and are considered the compositionally the most primitive of all objects. The classification of the remaining chondrites is based on their content of iron oxidation state of the iron. Chondrites are further a petrographic grade on the basis of the extent of metamorphism they have experienced in parent bodies. Grades 4, 5, and 6 have experienced increasing degrees of high-temperature metamorphism, while grades 1 and 2 experienced low-temperature aqueous alteration. Grade 3 is the least altered. Achondrites are in most cases igneous rocks, some roughly equivalent to terrestrial basalt, others appear to be cummulates. Other achondrites are highly brecciated. Irons, as they name implies, consist mainly of Fe-Ni metal (Ni content around 5%), and can also be divided into a number of classes. Stony-irons are, as their name implies, mixtures of iron metal and silicates.

In these two lectures, we focus on the question of the age of meteorites and variations in their isotopic composition.

COSMOCHRONOLOGY

Conventional methods

Meteorite ages are generally taken to be the age of Solar System. The oft cited value for this age is 4.556 Ga. Before we discuss meteorite ages in detail, we need to consider the question of precisely what event is being dated by radiometric chronometers. Radioactive clocks record the last time the isotope ratio of the daughter element, e.g., $^{87}Sr/^{86}Sr$, was homogenized. This is usually some thermal event. In the context of what we know of early Solar System history, the event dated might be (1) the time solid particles were removed from a homogeneous solar nebula, (2) thermal metamorphism in meteorite parent bodies, or (3) crystallization (in the case of chondrules and achondrites), or (4) impact metamorphism of meteorites or their parent bodies. In some cases, the nature of the event being dated is unclear.

The oldest reliable high precision age is from CAI inclusions of *Allende*, a CV3 meteorite. These give a Pb isotope age of 4.568±0.003 Ga. The matrix of Allende seems somewhat younger, although this is uncertain. Thus this age probably reflects the time of formation of the CAI's. Precise Pb-Pb ages of 4.552 Ga have been reported by several laboratories for the *St. Severin* LL chondrite. The same age (4.552±0.003 Ga) has been reported for 2 L5 chondrites. U-Pb ages determined on phosphates in equilibrated (i.e., petrologic classes 4-6) ordinary chondrites range from 4.563 to 4.504 Ga. As these phosphates are thought to be secondary and to have formed during metamorphism, these ages apparently represent the age of metamorphism of these meteorites. Combined whole rock Rb-Sr ages for H, E, and LL chondrites are 4.498±0.015 Ga. However, within the uncertainty of the value of the ^{87}Rb decay constant, this age could be 4.555 Ga (uncertainties normally reported on ages are based only on the scatter about the isochron and the uncertainty associated with the analysis, they do not include uncertainty associated with the decay constant). The age of *Allende* CAI's thus seems 5 Ma older than the best ages obtained on ordinary chondrites. No attempt has been made at high-precision dating of CI chondrites as they are too fine-grained to separate phases.

Pb isotope ages of the unusual achondrite *Angra dos Reis,* often classed by itself as an 'angrite' but related to the Ca-rich achondrites, give a very precise age of 4.5578±0.0004 Ma. Ibitira, a unique unbrecciated eucrite, has an age of 4.556±0.006 Ga. Perhaps surprisingly, these ages are the same as those of chondrites. This suggests that the parent body of these objects formed, melted, and crystallized within a very short time interval. Not all achondrites are quite so old. A few other high precision ages (those with quoted errors of less than 10 Ma) are available and they range from this value down to 4.529±0.005 Ga for *Nueve Laredo*. Thus the total range of the few high precision ages in achondrites is about 30 million years.

K-Ar ages are often much younger. This probably reflects Ar outgassing as a result of collisions. These K-Ar ages therefore probably date impact metamorphic events rather than formation ages.

The present state of conventional meteorite chronology may be summarized by saying that it appears the meteorite parent bodies formed around 4.56±0.005 Ga, and there is some evidence that high-temperature inclusions (CAI's: calcium-aluminum inclusions) and chondrules in carbonaceous chondrites may have formed a few Ma earlier than other material. Resolving events on a finer timescale than this has proved difficult using conventional techniques. There are, however, other techniques which help to resolve events in early solar system history, and we now turn to these.

Initial Ratios

Attempts have been made to use initial isotope ratios to deduce a more detailed chronology, but these have been only moderately successful. Figure 24.1 shows initial ^{87}Sr/^{86}Sr ratios of meteorites and lunar rocks and a time scale showing how ^{87}Sr/^{86}Sr should evolve in either a chondritic or solar reservoir. The reference 'initial' ^{87}Sr/^{86}Sr of the solar system is taken as 0.69897±3, based on the work of Papanastassiou and Wasserburg (1969) on basaltic achondrites (this value is known as BABI: basaltic achondrite best initial). Basaltic achondrites were chosen since they have low Rb/Sr and hence the initial ratio (but not the age) is well constrained in an isochron. Subsequent high precision analyses of individual achondrites yield identical results, except for Angra Dos Reis and Kapoeta, which have slightly lower ratios: 0.69885. This suggests their parent body(ies) were isolated from the solar system somewhat earlier. CAI's and Rb-poor chondrules from Allende have an even lower initial ratio: 0.69877±3. Allende chondrules appear to be among the earliest formed objects. The parent body of the basaltic achondrites appears to have formed 10 to 20 Ma later. Note there is no distinction in the apparent age of the oldest lunar rocks and the basaltic achondrites: from this we may conclude there was little or no difference in time of formation of the moon, and presumably the Earth, and the basaltic achondrite parent body.

The initial ^{143}Nd/^{144}Nd ratio of the solar system is taken as 0.506609±8 (normalized to ^{143}Nd/^{144}Nd = 0.72190) based on the work on chondrites of Jacobsen and Wasserburg (1980). Achondrites seem to have slightly higher initial ratios, suggesting they formed a bit later.

The initial isotopic composition of Pb is taken from the work of Tatsumoto et al. (1973) on troilite from the Canyon Diablo iron meteorite as ^{206}Pb/^{204}Pb: 9.307, ^{207}Pb/^{204}Pb: 10.294, ^{208}Pb/^{204}Pb: 29.476.

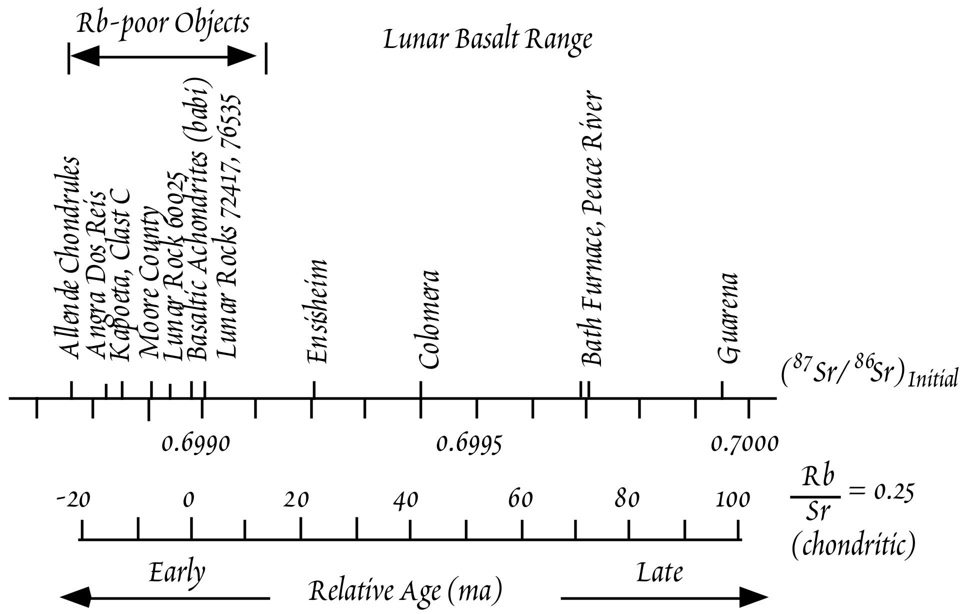

Figure 23.1. Initial Sr isotope ratios plotted against a time scale for $^{87}Sr/^{86}Sr$ assuming a chondritic Rb/Sr ratio. After Kirsten (1978).

These values are in agreement with the best initial values determined from chondrites, including Allende chondrules. More recent work by Chen and Wasserburg (1983) confirms these results, i.e.: 9.3066, 10.293, and 29.475 respectively.

EXTINCT RADIONUCLIDES

There is evidence that certain short-lived nuclides once existed in meteorites. This evidence consists of the anomalous abundance of nuclides, for example, ^{129}Xe, known to be produced by the decay of short-lived radionuclides, e.g., ^{129}I, and correlations between the abundance of the radiogenic *isotope* and the parent *element*. Consider, for example, ^{53}Cr, which is the decay product of ^{53}Mn. The half-life of ^{53}Mne, only 3.7 million years, is so short that any ^{53}Mn produced by nucleosynthesis has long since decayed. If ^{53}Mn is no longer present, how do we know that the anomalous ^{53}Cr is due to decay of ^{53}Mn? We reason that the abundance of ^{53}Mn, when and if it was present, should have correlated with the abundance of other isotopes of Mn. ^{55}Mn is the only stable isotope of Mn. So we construct a plot similar to a conventional isochron diagram (isotope ratios vs. parent/daughter ratio), but use the stable isotope, in this case ^{55}Mn as a proxy for ^{53}Mn. An example is shown in Figure 23.2.

Starting from our basic equation of radioactive decay, we can derive the following equation:

$$D = D_0 + N_0(1 - e^{-\lambda t}) \qquad 23.1$$

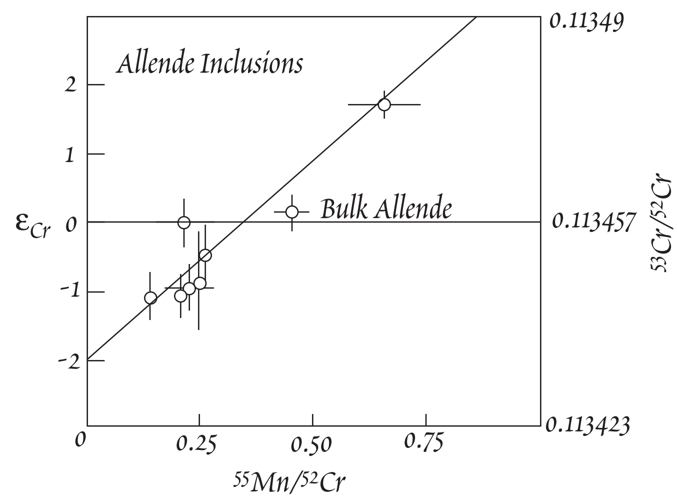

Figure 23.2. Correlation of the $^{53}Cr/^{52}Cr$ ratio with $^{55}Mn/^{52}Cr$ ratio in inclusions from the Allende CV3 meteorite. After Birck and Allegre (1985).

This is a variation on the isochron equation we derived in lecture 4. Written for the example of the decay of ^{53}Mn to ^{53}Cr, we have:

$$\frac{^{53}Cr}{^{52}Cr} = \left(\frac{^{53}Cr}{^{52}Cr}\right)_0 + \left(\frac{^{53}Mn}{^{52}Cr}\right)_0 (1 - e^{-\lambda t} \qquad 23.2$$

where the subscript nought denotes an initial ratio, as usual. The problem we face is that we do not know the initial ^{53}Mn/^{52}Cr ratio. We can, however, measure the ^{55}Mn/^{53}Cr ratio. Assuming that initial isotopic composition of Mn was homogeneous in all the reservoirs of interest; i.e., $^{53}Mn/^{55}Mn_0$ is constant, the initial ^{53}Mn/^{52}Cr ratio is just:

$$\left(\frac{^{53}Mn}{^{52}Cr}\right)_0 = \left(\frac{^{55}Mn}{^{52}Cr}\right)_0 \left(\frac{^{53}Mn}{^{55}Mn}\right)_0 \qquad 23.3$$

Of course, since ^{55}Mn and ^{52}Cr are both non-radioactive and non-radiogenic, the initial ratio is equal to the present ratio (i.e., this ratio is constant through time). Substituting 23.3 into 23.2, we have:

$$\frac{^{53}Cr}{^{52}Cr} = \left(\frac{^{53}Cr}{^{52}Cr}\right)_0 + \left(\frac{^{55}Mn}{^{52}Cr}\right)\left(\frac{^{53}Mn}{^{55}Mn}\right)_0 (1 - e^{-\lambda t}) \qquad 23.4$$

Finally, for a short-lived nuclide like ^{53}Mn, the term λt is very large after 4.55 Ga, so the term $e^{-\lambda t}$ is 0 (this is equivalent to saying all the ^{53}Mn has decayed away). Thus we are left with:

$$\frac{^{53}Cr}{^{52}Cr} = \left(\frac{^{53}Cr}{^{52}Cr}\right)_0 + \left(\frac{^{55}Mn}{^{52}Cr}\right)\left(\frac{^{53}Mn}{^{55}Mn}\right)_0 \qquad 23.5$$

On a plot of ^{53}Cr/^{52}Cr vs. ^{55}Mn/^{52}Cr, the slope is proportional to the initial ^{53}Mn/^{55}Mn ratio. Thus correlations between isotope ratios such as these is evidence for the existance of extinct radionuclides.

In this way, many extinct radionuclides have been identified in meteorites from variations in the abundance of their decay products. These include ^{26}Al (7.2×10^5 a), ^{41}Ca (1×10^5 a), ^{53}Mn (3.7×10^6 a), ^{60}Fe (1.5×10^6 a), ^{107}Pd (6.5×10^6 a), ^{129}I (1.6×10^7 a), ^{146}Sm (1.03×10^8 a), ^{182}Hf (9×10^6 a) and ^{244}Pu (8.1×10^7 a) (Table 23.1). Clearly, the existence of these nuclides in meteorites requires that they must have been synthesized shortly (on geological time scales) before the solar system formed.

To understand why these short-lived radionuclides require a nucleosynthetic event, consider the example of ^{539}Mn. Its half-life is 3.7 Ma. Hence 3.7 Ma after it was created only 50% of the original number of atoms would remain. After 2 half-lives, or 7.4 Ma, only 25% would remain, after 4 half-lives, or 14.8 Ma, only 6.125% of the original ^{53}Mn would remain, etc. After 10 half lives, or 37 Ma, only $1/2^{10}$ (0.1%) of the original amount would remain. The correlation between the Mn/Cr ratio and the abundance of ^{53}Cr indicates some ^{53}Mn was present when the meteorite, or its parent body, formed. From this we can conclude that an event which synthesized ^{53}Mn occurred not more than roughly 30 million years before the meteorite formed.

^{129}I–^{129}Xe

Among the most useful of these short-lived radionuclides, and the first to be discovered, has been ^{53}I, which decays to ^{129}Xe. Figure 23.3 shows the example of the analysis of the meteorite Khairpur. In this case, the analysis in done in a manner very analagous to ^{40}Ar-^{39}Ar dating: the sample is first irradiated with neutrons so that ^{128}Xe is produced by neutron capture. The amount of ^{128}Xe produced is proportional to the amount of ^{127}I present (as well as the neutron flux and reaction cross section). The sample is then heated in vacuum through

Table 23.1. Short-Lived Radionuclides in the Early Solar System

Radio-nuclide	Half-life Ma	Decay	Daughter	Abundance Ratio
^{26}Al	0.7	β	^{26}Mg	$^{26}Al/^{27}Al \sim 5 \times 10^{-5}$
^{41}Ca	0.13	β	^{41}K	$^{41}Ca/^{40}Cal < 10^{-6}$
^{53}Mn	3.7	β	^{53}Cr	$^{53}Mn/^{55}Mn \sim 4 \times 10^{-5}$
^{60}Fe	1.5	β	^{60}Ni	$^{60}Fe/^{56}Fe \sim 5 \times 10^{-10}$
^{107}Pd	9.4	β	^{107}Ag	$^{107}Pd/^{108}Pd \sim 2 \times 10^{-5}$
^{129}I	16	β	^{129}Xe	$^{129}I/^{127}I \sim 1 \times 10^{-4}$
^{146}Sm	103	α	^{142}Nd	$^{146}Sm/^{144}Sm \sim 0.005$
^{182}Hf	9	β	^{182}W	$^{182}Hf/^{180}Hf \sim 2.6 \times 10^{-4}$
^{244}Pu	82	α, SF	Xe	$^{244}Pu/^{238}U \sim 0.005$

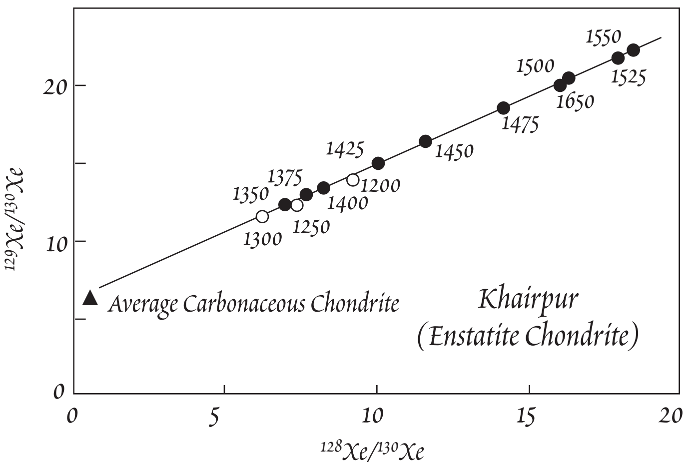

Figure.23.3. Correlation of $^{129}Xe/^{130}Xe$ with $^{128}Xe/^{130}Xe$. The ^{128}Xe is produced from ^{127}I by irradiation in a reactor, so that the $^{128}Xe/^{130}Xe$ ratio is proportional to the $^{127}I/^{130}Xe$ ratio. Numbers adjacent to data points correspond to temperature of the release step.

a series of steps and the Xe released at each step analyzed in a mass spectrometer. As was the case in Figure 23.2, the slope is proportion to the $^{129}I/^{127}I$ ratio at the time the meteorite formed.

In addition to ^{129}Xe produced by decay of ^{129}I, the heavy isotopes of Xe are produced by fission of U and Pu. ^{244}Pu is of interest because it another extinct radionuclide. Fisson, of course, does not produce a single nuclide, rather there is a statistical distribution of nuclides produced by fission. Each fissionable isotope produces a different distribution. The distribution produced by U is similar to that produced by ^{244}Pu, but the difference is great enough to demonstrate the existance of ^{244}Pu in meteorites, as is shown in Figure 23.4. Fission tracks in excess of the expected number of tracks for a known uranium concentration are also indicative of the former presence of ^{244}Pu.

These extinct radionuclides provide a means of relative dating of meteorites and other bodies. Of the various systems, the ^{129}I–^{129}Xe decay is perhaps most useful. Figure 23.5 shows relative ages based on this decay system. These ages are calculated from $^{129}I/^{127}I$ ratios, which are in turn calculated from the ratio of excess ^{129}Xe to ^{127}I. Since the initial ratio of $^{129}I/^{127}I$ is not known, the ages are relative to an arbitrary value, which is taken to be the age of the Bjurböle meteorite, a L4 chondrite.

The ages 'date' closure of the systems to Xe and I mobility, but it is not clear if this occurred at condensation or during metamorphism. Perhaps both are involved. The important point is that there is only slight systematic variation in age with meteorite types. Carbonaceous chondrites do seem to be older than ordinary and enstatite chondrites, while LL chondrites seem to be the youngest. Differentiated meteorites are generally younger. These are not shown, except for silicate in the El Taco iron, which is not particularly young. The bottom line here is that all chondrites closed to the I-Xe decay system within about 20 Ma.

An interesting aspect of Figure 23.5 is that the achondrites, which are igneous in nature, and the irons do not appear to be substantially younger than the chondrites. Irons and achrondrites are both products of melting on meteorite parent bodies. That they appear to be little younger than chondrites indicates that and melting and differentiation of those planetismals must have occurred very shortly after the

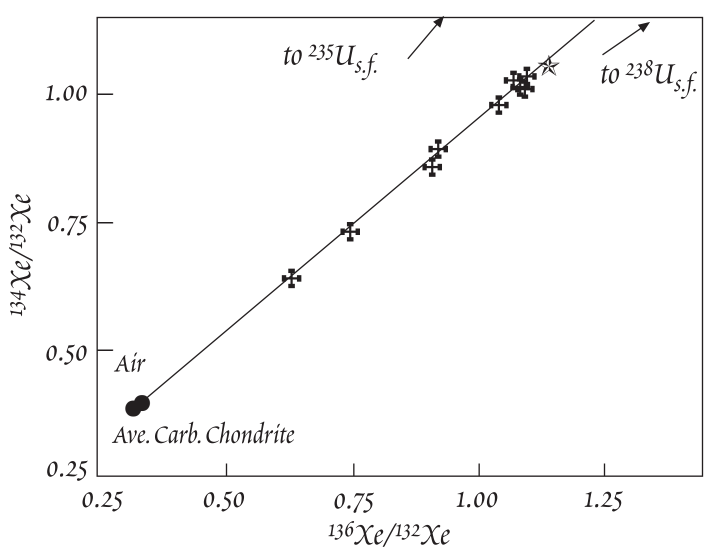

Figure 23.4. Variation of $^{134}Xe/^{132}Xe$ and $^{136}Xe/^{132}Xe$ in meteorites (✠). The isotopic composition of man-made fission products of ^{244}Pu is shown as a star (✯). After Podosek and Swindle (1989).

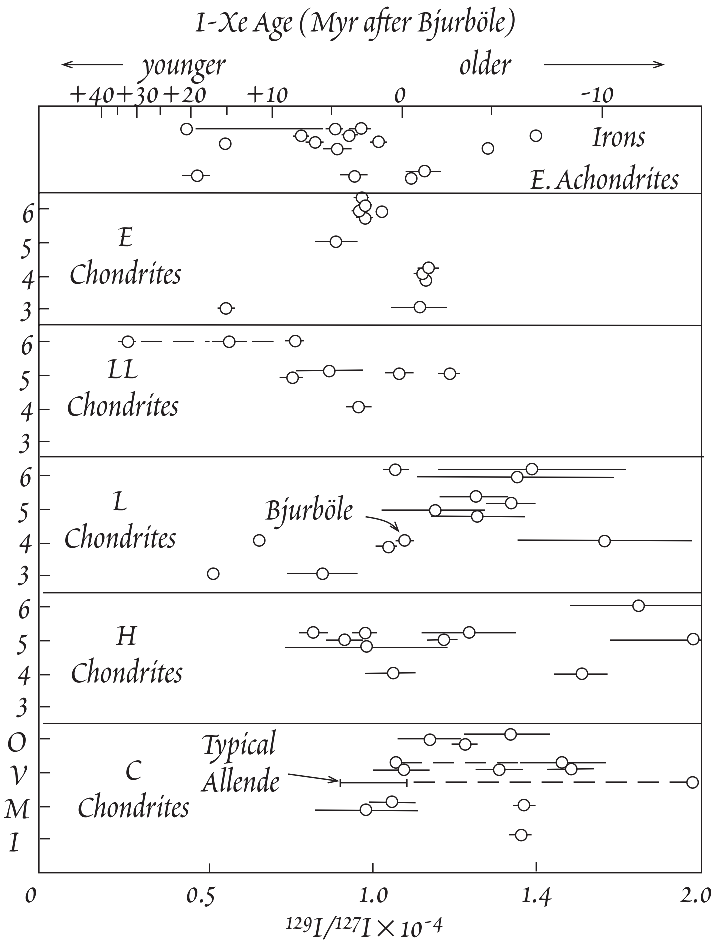

Figure 23.5. Summary of I-Xe ages of meteorites relative to Bjurböle. After Swindle and Podosek (1989).

solar system itself formed and within tens of millions of years of the synthesis of ^{129}I.

^{107}Pd–^{107}Ag

The existence of variations isotopic composition of silver, and in particular variations in the abundance of ^{107}Ag that correlate with the Pd/Ag ratio in iron meteorites indicates that ^{107}Pd was present when the irons formed. The half life of ^{107}Pd is 9.4 million years, hence the irons must have formed within a few tens of millions of years of synthesis of the ^{107}Pd. This in turn implies that formation of iron cores within small planetary bodies occurred within a few tens of millions of years of formation of the solar system.

Fractions of metal from the meteorite Gibeon (IVA iron) define a fossil isochron indicating an initial ^{107}Pd/^{108}Pd ratio of 2.4×10^{-5} (Chen and Wasserburg, 1990). Other IVA irons generally fall along the same isochron (Figure 23.6). IIAB and IIAB irons, as well as several anomalous irons show ^{107}Ag/^{109}Ag–^{108}Pd/^{109}Ag correlations that indicate ^{107}Pd/^{108}Pd ratios between 1.5 and 2.4 $\times 10^{-5}$. Assuming these differences in initial ^{107}Pd/^{108}Pd are due to time and the decay of ^{107}Pd, all of these iron meteorites would have formed no more than 10 million years after Gibeon (Chen and Wasserburg, 1996).

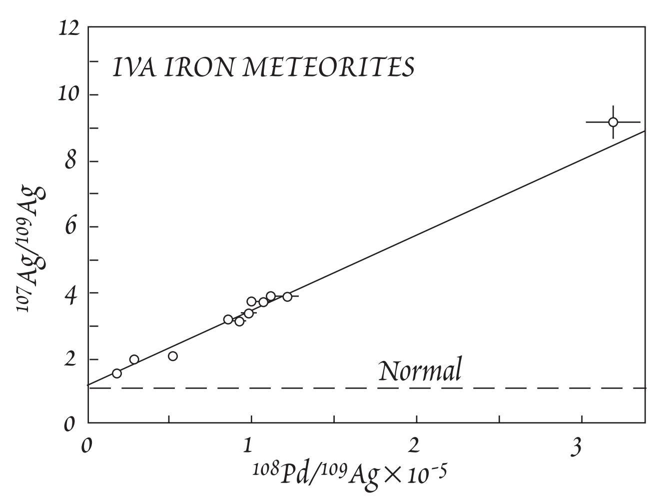

Figure 23.6. Correlation of ^{107}Ag/^{109}Ag with ^{108}Pd/^{109}Ag in Group IVA iron meteorites, demonstrating the existance of ^{107}Pd at the time these irons formed. After Chen and Wasserburg (1984).

^{26}Al–^{26}Mg

Another key extinct radionuclide has been ^{26}Al. Because of its short half-life (0.72 Ma), it provides much stronger constraints on the amount of time that could have passed between nucleosynthesis and processes that occurred in the early solar system. Furthermore, the abundance of ^{26}Al was such that it's decay could have been a significant source of heat. ^{26}Al decays to ^{26}Mg; an example of the correlation between ^{26}Mg/^{24}Mg and ^{27}Al/^{24}Mg is shown in Figure 23.7.

Because of the relatively short half-life of ^{26}Al and its potential importance as a heat source, considerable effort has been devoted to measurement of Mg isotope ratios in meteorites. Most of this work has been carried out with ion microprobes, which allow the similtaneous measurement of $^{26}Mg/^{24}Mg$ and $^{27}Al/^{24}Mg$ on spatial scales as small as 10 μ. As a result, there are some 1500 measurements on 60 meteorites reported in the literature, mostly on CAI's. The reason for the focus on CAI's is, of course, because their high Al/Mg ratios should produce higher $^{26}Mg/^{24}Mg$ ratios.

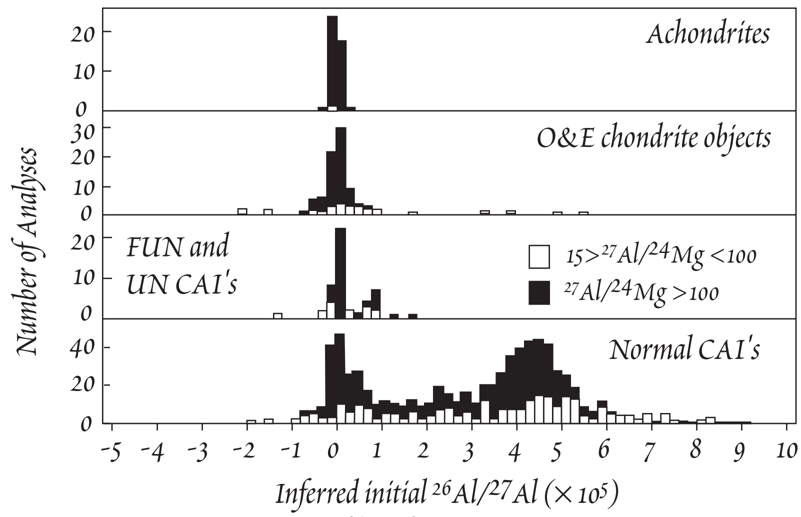

Figure 23.8. Inferred initial $^{26}Al/^{27}Al$ for all available meteoritic data. After MacPherson et al. (1995).

Figure 23.7 summarizes these data. These measurements show a maximum in the $^{26}Al/^{27}Al$ ratio of around 4.5×10^{-5}. Significant ^{26}Mg anomalies, which in turn provide evidence of ^{26}Al, are mainly confined to CAI's. This may in part reflect the easy with with the anomalies are detected in this material and the focus of research efforts, but it almost certainly also reflects real differences in the $^{26}Al/^{27}Al$ ratios between these objects and other materials in meteorites. This in turn probably reflects a difference in the timing of the formation of the CAI's and other materials, including chondrules. The evidence thus suggests that CAI's formed several million years before chondrules and other materials found in meteorites.

^{182}Hf–^{182}W and Core Formation

The Hf-W pair is particularly interesting Hf is lithophile while W is moderately siderophile. Thus the ^{182}Hf-^{182}W decay system should be useful in "dating" silicate-metal fractionation, including core formation in the terrestrial planets and asteroids. Both are highly refractory elements, while has the advantage the one can reasonably assume that bodies such as the Earth should have a chondritic Hf/W ratio, but the disadvantage that both elements are difficult to analyse by conventional thermal ionization. Anomalous W isotopic compositions were first found in the IA iron Toluca by Harper et al. (1991). They found the $^{182}W/^{183}W$ ratio in the meteorite was 2.5 epsilon units (i.e., parts in 10,000) lower than in terrestrial W. This value was revised to -3.9 epsilon units by subsequent, more precise, measurements (Jacobsen and Harper, 1996). This indicates Toluca metal was separated from Hf-bearing silicates before ^{182}Hf had entirely decayed. Because of the difference between "terrestrial" W (the terrestrial tungsten is representative of W in the silicate Earth, but not the entire Earth), Jacobsen and Harper (1996) concluded the Earth's core must have segregated rapidly. However, without data on chondritic meteorites and the initial $^{182}Hf/^{180}Hf$ ratio in the solar nebula, such a conclusion is highly speculative.

Lee and Halliday (1995) reported W isotope ratios for 2 carbonaceous chondrites (Allende and Murchison), two additional iron meteorites (Arispe, IA, and Coya Norte, IIA) and one lunar basalt. They found the iron meteorites showed depletions in ^{182}W (ε_W = -4.5 and -3.7 for Arispe and Coya Norte respectively) that were similar to that observed in Toluca reported by Jacobsen and Harper (1996). The chondrites, however, had ε_w values that were only slightly positive, about +0.5, and were analytically indistiguishable from "terrestrial" W, as was the lunar basalt. Lee and Halliday (1995) inferred an initial $^{182}Hf/^{180}Hf$ for the solar nebula of 2.6×10^{-4}, much higher than assumed by Jacobsen and Harper. Lee and Halliday interpreted their data to indicate that the minimum time required for formation of the Earth's core was 62 million years.

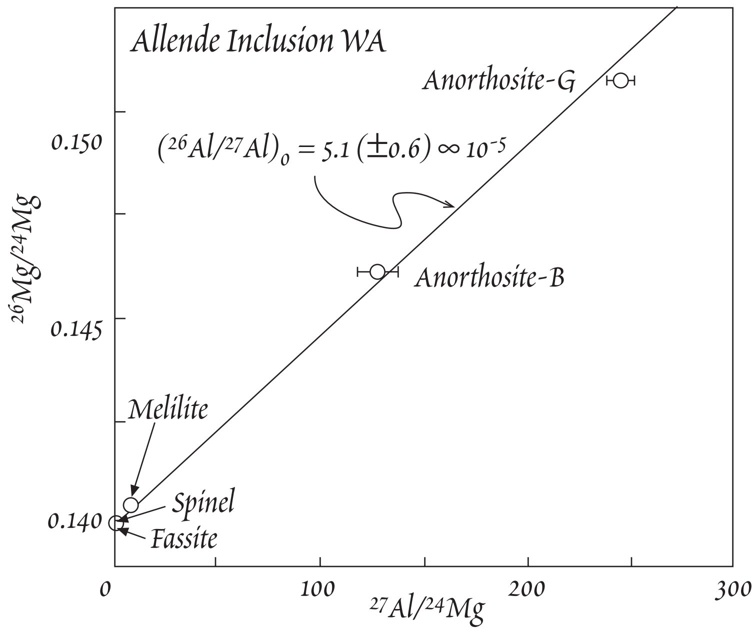

Figure 23.7. Al-Mg evolution diagram for Allende CAI WA. Slope of the line corresponds to an initial $^{26}Al/^{27}Al$ ratio of $^{26}Al/^{27}Al$ ratio of 5.1×10^{-4}. After Lee et al. (1976).

More recently, Lee and Halliday (1998) reported ε_W values in the range of +2 to +3 in 3 SNC meteorites (thought to have come from Mars) and ε_W values of +32 and +22 in the achondrites Juvinas and ALHA78132. They concluded that metal-silicate fractionation occurred quite early in the achondrites parent bodies. Interestingly, the data indicate that the Martian core formed relatively early. The heterogeneity in tungsten isotopes indicates in Martian mantle was never fully homogeneized.

Original of Short-lived Nuclides

The mere existence of radiogenic ^{129}Xe requires the time span between closure of the presolar nebula to galactic nucleosynthesis and formation of the solar system be no more than about 150 Ma. This time constraint is further reduced by the identification of radiogenic ^{26}Mg, produced by the decay of ^{26}Al. Apparent $^{26}Al/^{27}Al$ ratios in CAI's around 10^{-5}, together with the half-life of ^{26}Al of 0.72 Ma and theoretical production ratios for $^{26}Al/^{27}Al$ of around 10^{-3} to 10^{-4}, suggests nucleosynthethesis occurred less than several million years before formation of these CAI's.

What this nucleosynthetic "event" was remains a matter of debate. The most likely site of ^{26}Al synthesis is in asymtopic giant branch stars (sometimes called AGB stars, or more commonly red giants). Red giants inject a enormous amount of material into surrounding space through greatly enhanced solar winds. Thus the ^{26}Al may have been injected into the cloud that ultimately collapsed to form the solar system by a red giant. ^{107}Pd is produced principally in the s process, and so may also have originated in a red giant. However, other extinct nuclides, such as ^{60}Fe, ^{129}I, ^{182}Hf, and ^{244}Pu are "r" nuclides and therefore likely to have been produced in supernova explosions.

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