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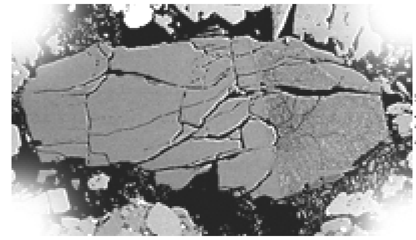
Hot Idea

posted September 30, 2002

Using Aluminum-26 as a Clock for Early Solar System Events

--- Correspondence between ^{26}Al and Pb-Pb ages shows that ^{26}Al records a detailed record of events in the early solar system.

Feldspar grain from



ordinary chondrite Forest Vale

Written by Ernst Zinner
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Our solar system formed 4.6 billion years ago. Primitive meteorites provide samples that were formed in its earliest days and thus can give us information about this period. To establish the sequence of events during solar system formation on a time scale of a million years radioactive isotopes that decay with half-lives comparable to this time scale can potentially serve as clocks for dating these events. ^{26}Al, which has a half-life of 0.73 million years appeared to be an ideal chronometer. However, for this to be the case, ^{26}Al had to be uniformly distributed in the early solar system and this fact had not been clearly established. Comparison measurements with two different clocks, ^{26}Al and the decay of uranium isotopes, in refractory Ca-Al-rich inclusions (CAIs) and in feldspar crystals from ordinary chondrites indicate that both techniques give the same ages. It appears that ^{26}Al can indeed be used as a fine-scale chronometer for early solar system events.

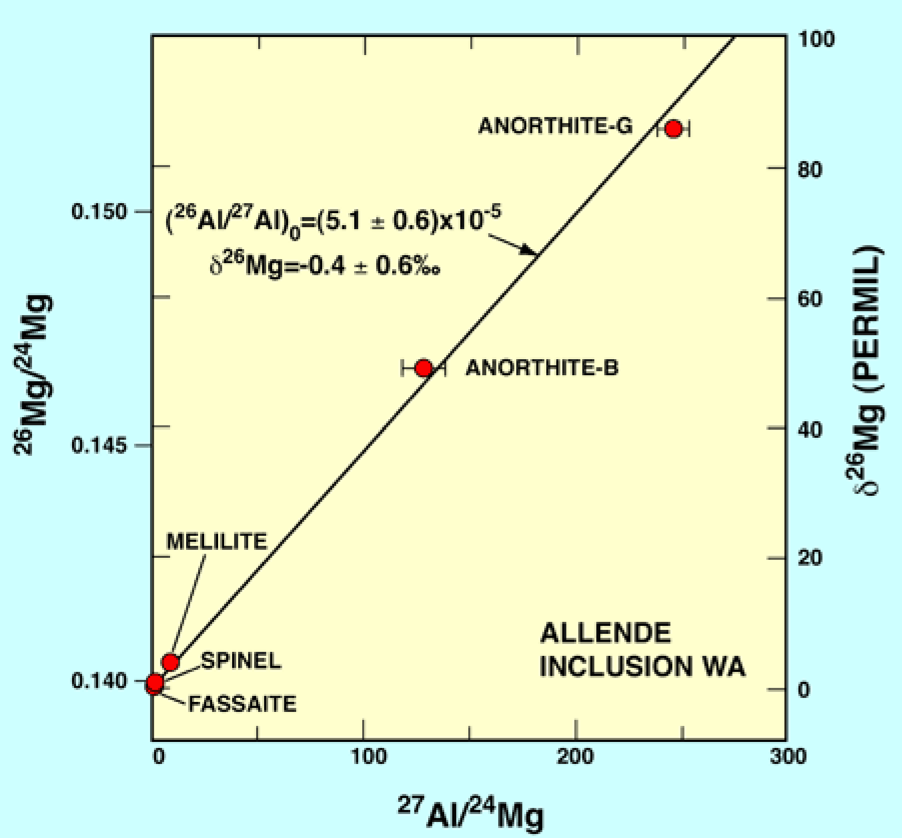
References:

Zinner E. and Göpel C. (2002) Aluminum-26 in H4 chondrites: implications for its production and its usefulness as a fine-scale chronometer for early-solar-system events. *Meteoritics and Planetary Science,* v. 37, p. 1001-1013.

Zinner E., Hoppe P. and Lugmair G. (2002) Radiogenic ^{26}Mg in Ste. Marguerite and Forest Vale plagioclase: can ^{26}Al be used as chronometer? *Lunar Planet. Sci. XXXIII,* Abstract #1204.

A Clock and a Heat Source

^{26}Al is a radioactive isotope that decays into ^{26}Mg, a stable isotope, with a half-life of 0.73 million years. Although this is so short that all of it has decayed billions of years ago, its presence at the beginning of the solar system has been conclusively established by the discovery of excesses of its daughter isotope ^{26}Mg in the most primitive solar system objects. If these objects containing ^{26}Al at the time of their formation remained relatively undisturbed (i.e., did not experience high temperatures), the decay product ^{26}Mg was frozen in and today provides a record of the original ^{26}Al. The ratio of ^{26}Mg excess measured now relative to the amount of the stable isotope ^{27}Al yields the original $^{26}Al/^{27}Al$ ratio.



(From Lee *et.al., Geophys. Res. Lett.*, 1976)

Magnesium isotopic ratios measured in different minerals with different ratios of aluminum to magnesium from a refractory inclusion in the meteorite Allende. Magnesium shows excesses in the isotope 26 that are correlated with the aluminum/magnesium ratio, indicating that the ^{26}Mg excesses originated from the decay of the radioactive isotope ^{26}Al. This finding is evidence for the initial presence of ^{26}Al in early solar system objects.

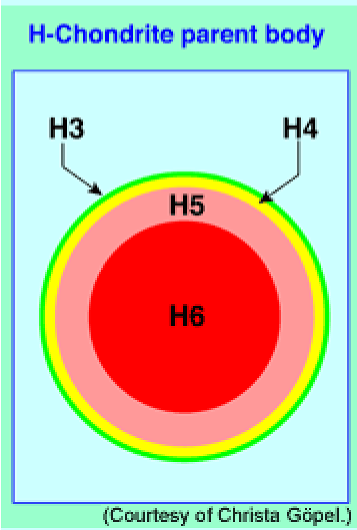
The discovery of evidence for ^{26}Al in the 1970s offered two very exciting prospects. The first was that this isotope could be used as a clock. The reason is that because of its radioactive decay, the ^{26}Al/^{27}Al ratio varies in objects that formed at different times. By measuring the aluminum-magnesium system today, the relative ages of these objects can be established. The second was that the radioactive decay of ^{26}Al produces heat and this heat could have melted small asteroidal bodies. We have evidence for the melting of such bodies from certain types of meteorites that were produced from magmas. However, for ^{26}Al to serve as a clock and as a heat source, two conditions had to be satisfied. The ^{26}Al had to be distributed uniformly in the solar system (otherwise different ^{26}Al/^{27}Al ratios cannot be uniquely interpreted as being due to a time difference) and enough of it had to be present to provide the heat necessary for melting.

Was ^{26}Al Uniformly Distributed?

Measurements in refractory Ca-Al-rich inclusions (CAIs) from primitive meteorites established an initial ^{26}Al/^{27}Al ratio of 5x10^{-5}. This would have been enough for asteroidal melting as long as ^{26}Al was uniformly distributed throughout the solar system and not concentrated only in CAIs and as long as small asteroids formed within a couple of million years after CAIs. It was assumed that ^{26}Al, together with other short-lived radioisotopes, had been produced by nuclear processes (nucleosynthesis) in stars prior to the collapse of the nebular cloud giving birth to our solar system. Other primitive objects from meteorites such as chondrules show initial ^{26}Al/^{27}Al ratios of approximately 10^{-5} and smaller. This has generally been interpreted as indicating that chondrules formed approximately 2 million years after CAIs. However, it could also have meant that chondrules formed at the same time as CAIs but were endowed with less ^{26}Al. Thus, nagging doubts remained whether ^{26}Al was uniformly distributed. These nagging doubts were amplified by the recent discovery by Kevin McKeegan (University of California, Los Angeles) and colleagues that another short-lived isotope, beryllium-10 (half-life 1.5 million years) was also originally present in CAIs. This radioisotope is not produced by stellar nucleosynthesis but most likely formed as energetic particles from the early sun bombarded material in the accretion disk. This bombardment could, in principle, also have produced other short-lived isotopes including ^{26}Al. If this happened mostly in CAIs, as was proposed by Frank Shu (University of California, Berkeley) and collaborators, a uniform distribution of ^{26}Al was not assured.

Feldpars from H4 Chondrites to the Rescue

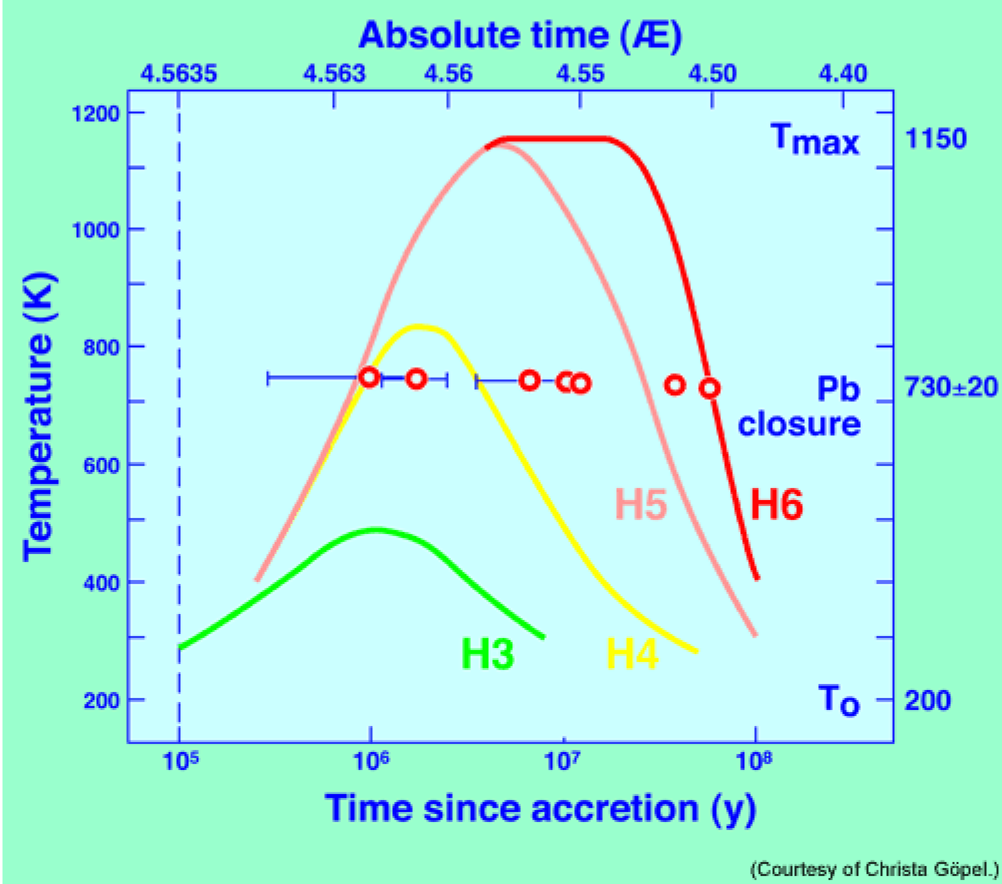
One way to establish whether ^{26}Al can be used as a clock was to compare it to a different radioactive clock where a uniform distribution in the solar system is not in doubt. Such a clock is uranium whose isotopes ^{235}U (half-life 0.7 billion years) and ^{238}U (half-life 4.5 billion years) decay into lead isotopes. One fundamental difference with respect to ^{26}Al is that the uranium half-lives are long enough that these isotopes are still around today. As a consequence, absolute ages can be measured by the uranium clock, while only relative ages can be determined with the ^{26}Al clock. Furthermore, uranium is the only clock based on long-lived isotopes that has a precision (less than a million years) that allows the resolution of different events in the early solar system. Because lead isotopes are the daughter products of uranium decay, uranium ages are usually called Pb-Pb ages.



Onion shell model of the parent asteroid of ordinary chondrites of type H.

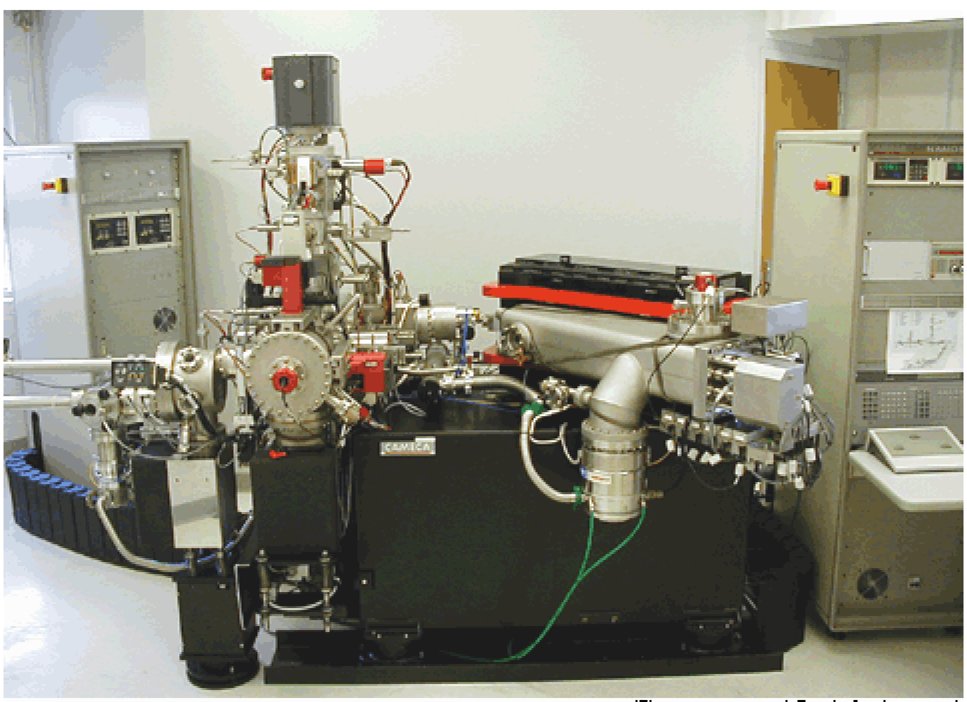
With my collaborators Christa Göpel (Laboratoire Géochimie et Cosmochimie, Paris, France) and Peter Hoppe (Max-Planck-Institut für Chemie, Mainz, Germany) I selected feldspar grains from two ordinary chondrites of type H4, Ste. Marguerite and Forest Vale, for such a comparative study. There were several reasons for the selection of H4 chondrites. H chondrites are believed to come from a parent body that was heated (presumably by the decay of ^{26}Al). This heating was the cause of metamorphic changes in the rocks making up this asteroid. Rocks from different depths experienced different peak temperatures and duration of heating. Correspondingly, H chondrites exhibiting different metamorphic grades are assumed to come from different depths in this parent body.

Another reason was that Christa Göpel had previously used the uranium clock on phosphate crystals from Ste. Marguerite and Forest Vale and had obtained absolute ages of 4562.7±0.6 and 4560.9±0.7 million years. These ages are so-called metamorphic ages because phosphates are metamorphic minerals that formed during heating of the H4 region on the parent body. The uranium clock thus measures a time when the temperature became low enough that the uranium and lead isotopes did not equilibrate any more with their surroundings. Compared to a uranium age of 4567.2±0.6 million years for CAIs, the time differences given by these ages are such that we could expect to find evidence for initial ^{26}Al in H4 chondrites provided that they contain phases with a very high aluminum to magnesium ratio. This is because the ^{26}Mg excess from ^{26}Al decay is proportional to this ratio. Fortunately, the two H4 chondrites of our study contain fairly large (up to 0.2 millimeter) feldspar crystals with aluminum/magnesium ratios exceeding 10,000.



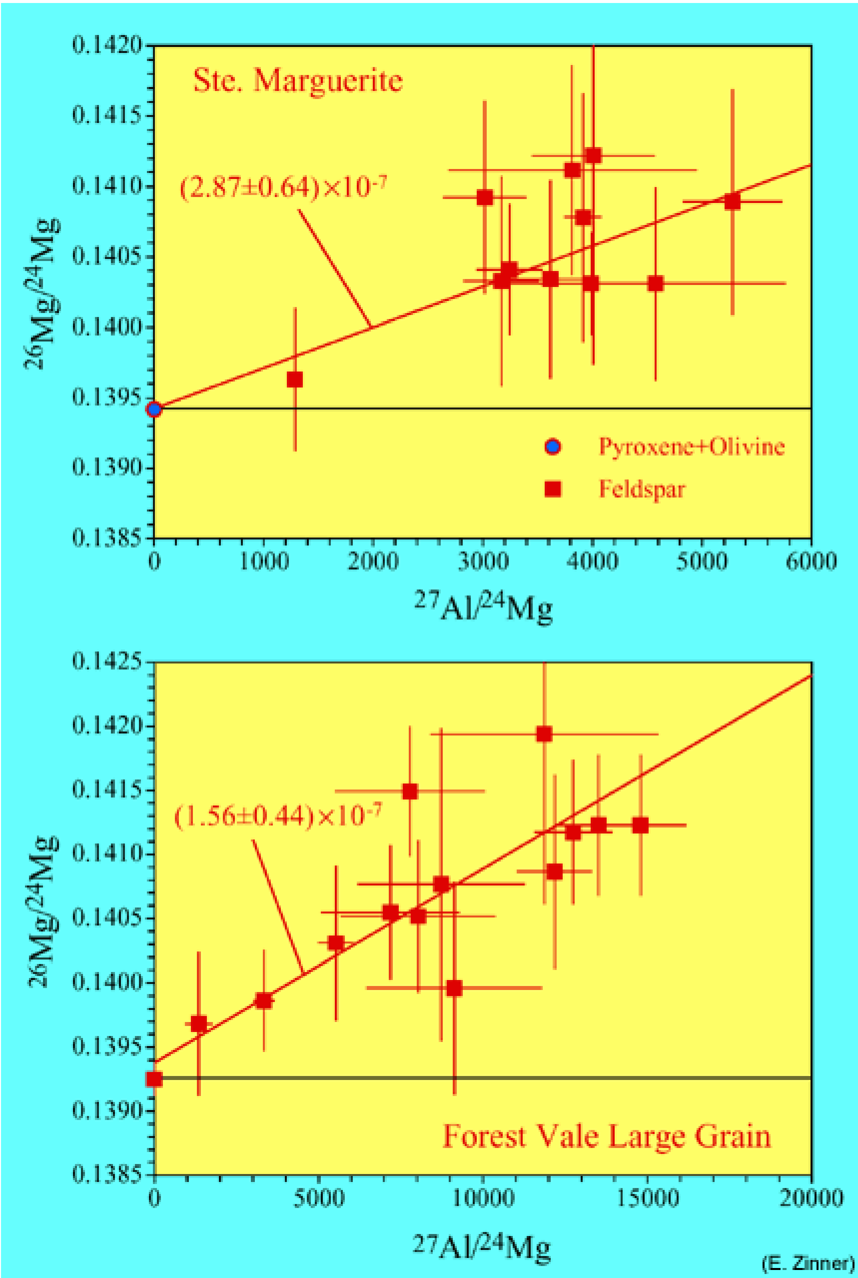
Models of the temperature profiles experienced by different metamorphic grades of the H ordinary chondrites. The temperature at which the uranium-lead system stops being equilibrated during decreasing temperature is believed to be approximately 730 degrees Kelvin. This temperature is reached at different times for different H chondrites.

Ion Microprobe Measurements of Initial $^{26}Al/^{27}Al$ Ratios


(Photo courtesy of Frank Stadermann.)

This picture shows the recently installed NanoSIMS at Washington University. The NanoSIMS is a new type of ion microprobe that allows elemental and isotopic analysis with very high spatial resolution and with high sensitivity. Peter Hoppe and I measured the magnesium isotopic ratios and the aluminum/magnesium ratios in many different spots on a single feldspar crystal with such an instrument at the Max-Planck-Institute for Chemistry in Mainz, Germany.

The determination of ^{26}Mg excesses as a function of aluminum/magnesium ratios was made with a special type of mass spectrometer, the ion microprobe. In this instrument a finely focused ion beam (in our case oxygen) bombards the surface of the sample to be analyzed (in our case polished thin sections of the meteorites). This ion bombardment results in the emission of atoms and ions from the sample. The ions are accelerated and analyzed for their mass in a mass spectrometer. This analysis technique is therefore called secondary ion mass spectrometry (SIMS). The ion probe allows the elemental and isotopic analysis of small samples and even measurements of many different spots on a given crystal.



Ion microprobe measurements of the aluminum-magnesium system in feldspar crystals from the H4 chondrites Ste. Marguerite and Forest Vale show ^{26}Mg excesses that are correlated with the aluminum-magnesium ratio in both meteorites. The slopes of the correlation lines yield initial $^{26}Al/^{27}Al$ ratios.

We measured the ratios of all three stable magnesium isotopes (^{24}Mg, ^{25}Mg, and ^{26}Mg) and ^{27}Al (the only stable isotope of aluminum) in several crystals from the two meteorites. On a large crystal from Forest Vale we could make these measurements in many different areas. Measurements are made by changing the magnetic field of the mass spectrometer to different values so that only ions of a given isotope are transmitted and counted. This is done through many cycles. Because of the very low magnesium concentrations, measurements take up to 10 hours for a single spot. Comparison with the magnesium isotopic ratios in terrestrial rocks revealed clear ^{26}Mg excesses in the feldspar grains from both meteorites. The inferred initial $^{26}Al/^{27}Al$ ratios obtained from these measurements are $(2.87\pm0.64)\text{x}10^{-7}$ for Ste. Marguerite and $(1.55\pm0.32)\text{x}10^{-7}$ for Forest Vale.

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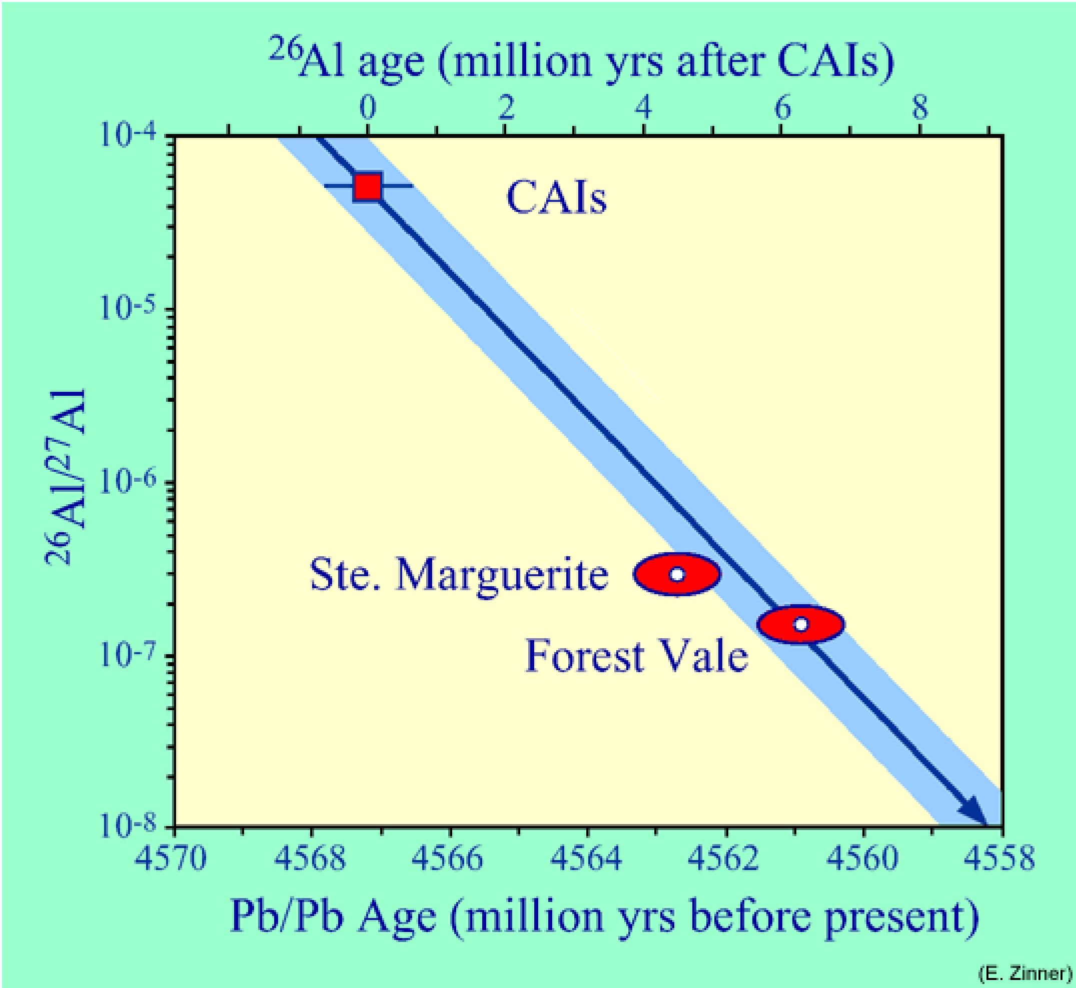
^{26}Al and Uranium Age Differences Between CAIs and H4 Chondrites Agree

If we interpret the differences between the widespread ("canonical") initial $^{26}Al/^{27}Al$ ratio of $5\text{x}10^{-5}$ for CAIs and the ratios determined for the H4 chondrites of the present study as being due to a time difference, then we obtain for the ^{26}Al ages of these meteorites relative to CAIs 5.4±0.1 million years for Ste Marguerite and 6.1±0.1 million years for Forest Vale. This compares to differences of 4.5±0.9 and 6.3±0.9 million years, respectively, obtained with the uranium clock. The ages obtained by the two methods are in excellent agreement.



$^{26}Al/^{27}Al$ ratios measured in CAIs and in Ste. Marguerite and Forest Vale as well as the ages of these objects determined with the uranium clock (Pb-Pb ages). The lower scale indicates the absolute ages, the upper scale ages relative to CAIs. The line with the arrow indicates the decrease of the $^{26}Al/^{27}Al$ ratio because of the decay of ^{26}Al, the blue area around this line is due to the uncertainty in the absolute age of CAIs. The ellipses around the data points for the two H4 chondrites express the uncertainties of their uranium ages and $^{26}Al/^{26}Al$ ratios. Within these uncertainties the difference in the ages between CAIs and the two H4 chondrites measured by the uranium and inferred from the ^{26}Al clock agree.

Remaining Questions

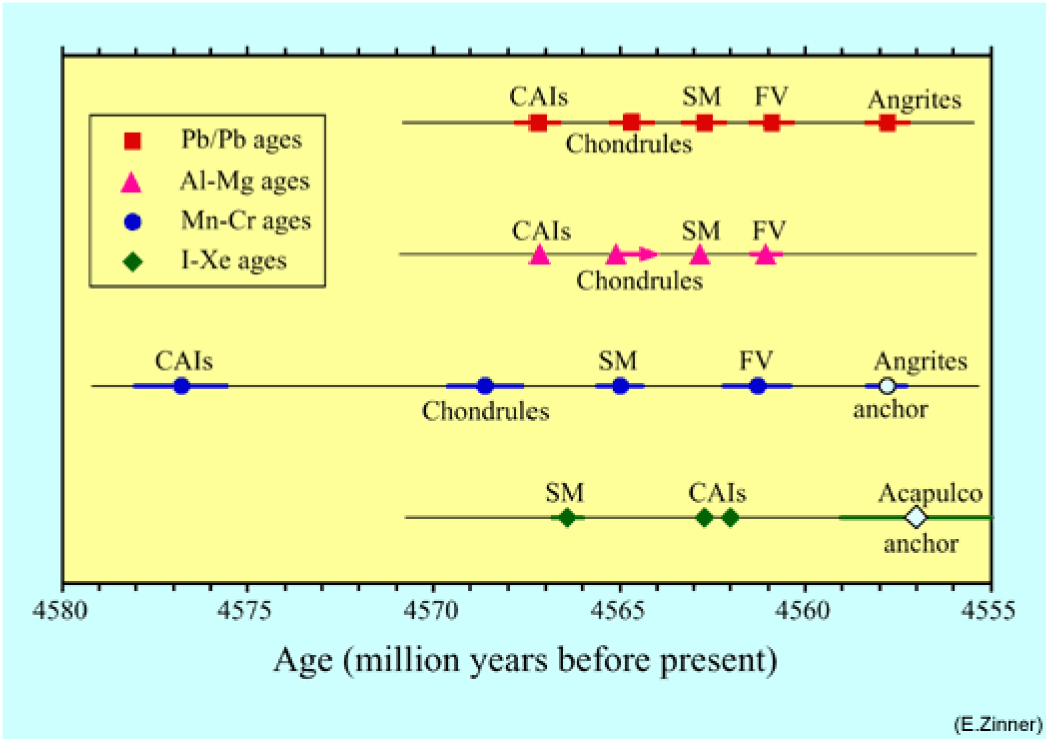
From our analysis we have obtained an affirmative answer to our original question whether or not ^{26}Al can be used as a fine-scale clock for early solar system events. However there are several remaining questions.

1. Are the feldspar crystals of our study of metamorphic or igneous origin? We have already mentioned that there is little doubt that the phosphate used for uranium dating of the H4 chondrites is of metamorphic origin. The question is whether also feldspar in these meteorites formed from preexisting other phases during metamorphic heating of the parent body and the ^{26}Al age measures the ceasing of equilibration of the aluminum-magnesium system during parent body cooling. The relatively high concentrations of sodium and the extremely low concentrations of magnesium, much lower than any observed in feldspar from CAIs and chondrules, indicate a metamorphic origin.

2. Do the ^{26}Al and uranium chronometers measure the same event? Not necessarily. The start of the clock, namely the time when the parent-daughter system becomes frozen in (this is called "closure" of the system by scientists working on geo- and cosmochronology) depends on the temperature when the respective isotopic systems stop equilibration. Unfortunately,

the diffusive behavior of aluminum and magnesium in feldspar has not been determined. Thus the start of the two clocks could be different and, in principle, one cannot compare radiometric ages based on different chronometers. What helps in our case is that previous measurements indicated a high cooling rate of more than 1000 degrees Kelvin per million years for the H4 chondrites. If this is correct, then the difference in the start of the ^{26}Al and uranium clocks must have been much less than a million years and the general agreement still holds within the experimental errors involved.

3. Do the relative ages obtained from the ^{26}Al and uranium clocks agree with those obtained from other short-lived isotopes? Besides ^{26}Al, manganese-53 (^{53}Mn, half-life 3.7 million years) and iodine-129 (^{129}I, half-life 16 million years) have also been used for radiometric dating of early solar system events. However, while there is some agreement between the ^{53}Mn and ^{129}I chronometers, inconsistencies remain between them and the ^{26}Al and uranium systems.



Ages of different objects from the early solar system determined with different clocks. Only the uranium (Pb-Pb) clock gives absolute ages. The other chronometers have to be anchored to the uranium clock by measuring both systems in the same object or a set of objects. For the manganese-chromium (Mn-Cr) clock that has been done on a type of meteorite called angrites, for the iodine-xenon (I-Xe) clock the age calibration has been made on the meteorite Acapulco. For the ^{26}Al clock we assigned absolute ages by anchoring the relative ^{26}Al ages to the uranium age of CAIs. As can be seen, while the ^{26}Al ages of chondrules, Ste. Marguerite (SM) and Forest Vale (FV) agree well with their uranium ages, this is not the case for the other clocks based on short-lived isotopes. For example, the ^{53}Mn ages of Ste. Marguerite, chondrules, and especially CAIs are much older than their uranium (Pb-Pb) ages. These inconsistencies are still not understood.

Supporting Evidence

Two recent experimental findings support our tentative conclusion that ^{26}Al can indeed be used as a chronometer. First, Amelin (Royal Ontario Museum) and coworkers used the uranium clock to determine the absolute ages of CAIs and chondrules. [See PSRD article Dating the Earliest Solids in our Solar System.] According to their measurements, CAIs are 2.5 million years older than chondrules. This is in good agreement with the relative age difference inferred from the ^{26}Al chronometer. Second, Marhas (Physical Research Lab, India) and colleagues reported ion microprobe measurements in unusual refractory inclusions that show the initial presence of beryllium-10 (^{10}Be) but lack any evidence of ^{26}Al. This indicates that ^{26}Al was not produced together with ^{10}Be by irradiation with energetic particles in the early solar system and removes a constraint on its uniform distribution.

While the detailed chronology of early solar system events is still far from being consistently established, our and other recent experimental studies indicate that ^{26}Al is after all an important clock. We hope that its further usefulness can be shown in future studies.

Additional Resources

Krot, A. N. "Dating the Earliest Solids in our Solar System." *PSR Discoveries.* September 2002. <http://www.psrd.hawaii.edu/Sept02/isotopicAges.html>.

MacPherson G. J., Davis A. M., and Zinner E. K. (1995) The distribution of aluminum-26 in the early Solar System-A reappraisal. *Meteoritics,* v. 30, p. 365-386.

McKeegan K. D., Chaussidon M., and Robert F. (2000) Incorporation of short-lived ^{10}Be in a calcium-aluminum-rich inclusion from the Allende meteorite. *Science,* v. 289, p. 1334-1337.

Shu F. H., Shang H., Gounelle M., Glassgold A. E., and Lee T. (2001) The Origin of Chondrules and Refractory Inclusions in Chondritic Meteorites. *Astrophys. J.,* v. 548, p. 1029-1050.

Zinner E. and Göpel C. (2002) Aluminum-26 in H4 chondrites: implications for its production and its usefulness as a fine-scale chronometer for early-solar-system events. *Met. & Planet. Sci.,* v. 37, p. 1001-1013.

Zinner E., Hoppe P. and Lugmair G. (2002) Radiogenic ^{26}Mg in Ste. Marguerite and Forest Vale plagioclase: can ^{26}Al be used as chronometer? *Lunar Planet. Sci. XXXIII,* Abstract #1204.

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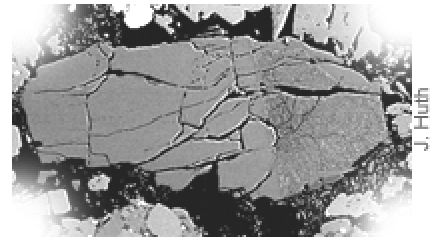

ordinary chondrite Forest Vale

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Technical References List

Amelin Y., Krot A. N., Hutcheon I. D., and Ulyanov A. A. (2002) Lead isotopic ages of chondrules and calcium-aluminum-rich inclusions. *Science,* v. 297, p. 1678-1683.

Gilmour J. (2002) The solar system's first clocks. *Science,* v. 297, p. 1658-1659.

Göpel C., Manhés G., and Allégre C. (1994) U-Pb systematics of phosphates from equilibrated ordinary chondrites. *Earth Planet. Sci. Lett.,* v. 121, p. 153-171.

Lee T., Panastassiou D. A., and Wasserburg G. J. (1976) Demonstration of ^{26}Mg excess in Allende and evidence for ^{26}Al. *Geophys. Res. Lett.,* v. 3, p. 109-112.

Lipschutz M. E., Gaffey M. E., and Pellas P. (1989) Meteoritic parent bodies: nature, number, size and relation to present-day asteroids. In *Asteroids II,* ed. (eds. R. P. Binzel, T. Gehrels and M. S. Matthews), Univ. of Arizona Press, Tucson, p. 740-778.

MacPherson G. J., Davis A. M., and Zinner E. K. (1995) The distribution of aluminum-26 in the early Solar System-A reappraisal. *Meteoritics,* v. 30, p. 365-386.

Marhas K.K., Goswami J. N., and Davis A. M. (2002) A limit on the energetic particle irradiation of the solar nebula. *Meteoritics & Planet. Sci. ,* v. 37, p. A94.

McKeegan K. D., Chaussidon M., and Robert F. (2000) Incorporation of short-lived ^{10}Be in a calcium-aluminum-rich inclusion from the Allende meteorite. *Science,* v. 289, p. 1334-1337.

Pellas P. and Storzer D. (1981) ^{244}Pu fission track thermometry and its application to stony meteorites. *Proc. R. Soc. Lond.,* v. A374, p. 253-270.

Shu F. H., Shang H., Gounelle M., Glassgold A. E., and Lee T. (2001) The Origin of Chondrules and Refractory Inclusions in Chondritic Meteorites. *Astrophys. J.,* v. 548, p. 1029-1050.

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