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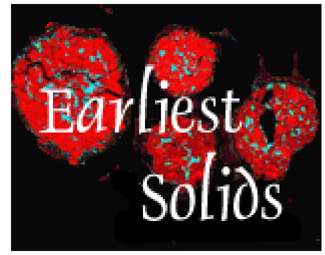


Dating the Earliest Solids in our Solar System

--- Lead isotopic analyses give absolute formation ages of Ca-Al-rich inclusions and chondrules.

Written by Alexander N. Krot
Hawai'i Institute of Geophysics and Planetology

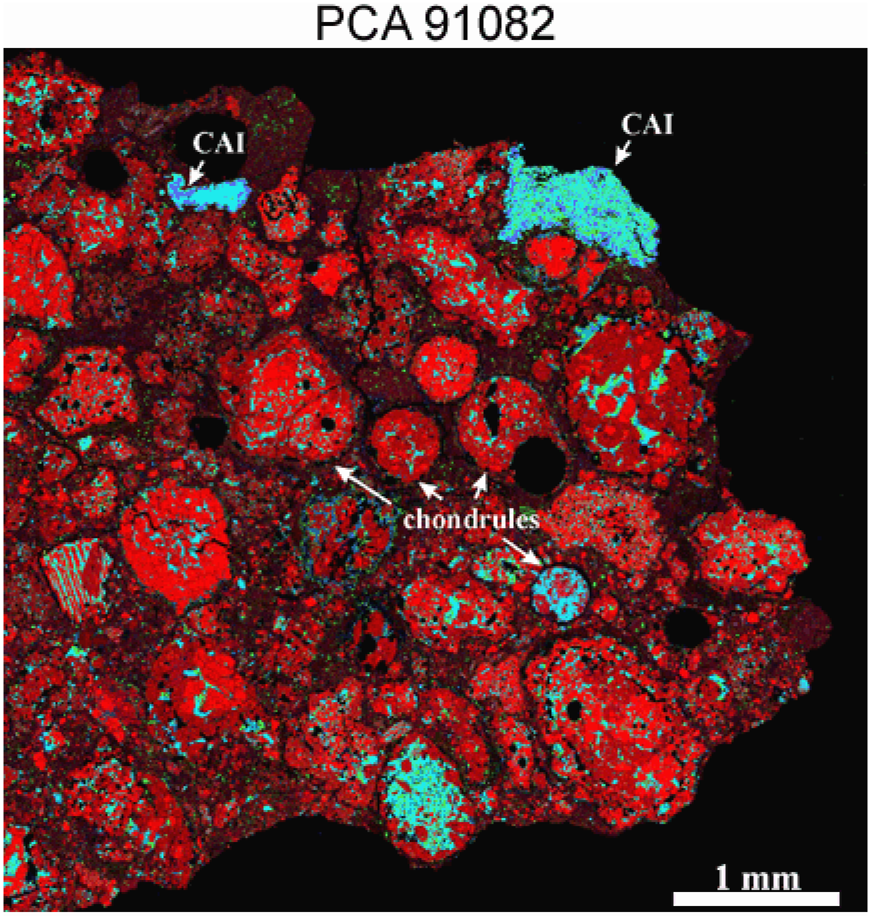
Chondritic meteorites (chondrites), the oldest rocks in our solar system, provide a significant record of the processes that transformed a disk of gas and dust into a collection of planets, moons, asteroids, and comets. They are considered to be the building blocks of the inner planets, Mercury, Venus, Earth, and Mars. Chondrites are aggregates of three major components: refractory Ca-Al-rich inclusions (CAIs), less refractory ferromagnesian silicate spherules called chondrules, and a fine-grained matrix. We know that CAIs and chondrules formed at nearly the same time as the Sun (4.56 billion years ago), but we don't know the details of how or where the CAIs and chondrules formed. The timing and duration of their formation remains obscure. My colleagues, Yuri Amelin (Royal Ontario Museum), Ian Hutcheon (Lawrence Livermore National Laboratory), Alexander Ulyanov (Moscow State University), and I set out to resolve these unknowns by determining the absolute formation ages of CAIs and chondrules using lead isotopic analyses.

Reference:

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

High Temperature Processing

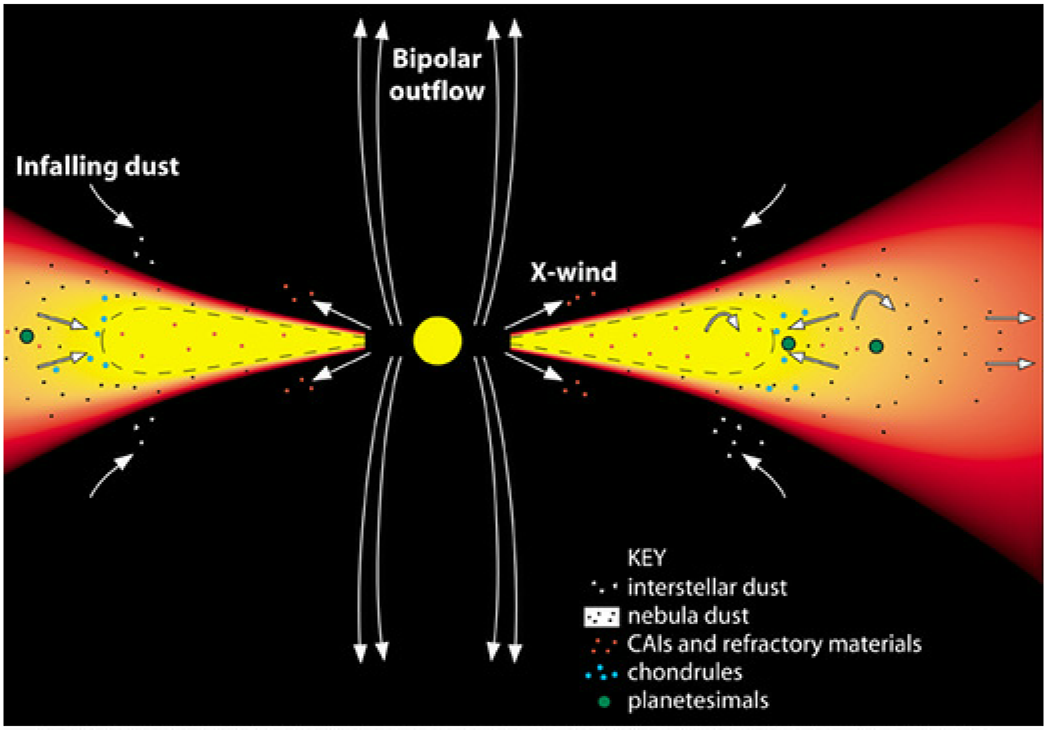
Most meteorite experts believe that CAIs and chondrules formed in the solar nebula by high temperature processes. These processes included condensation, evaporation, and, for all chondrules and many CAIs, subsequent melting during multiple brief heating episodes.



(Alexander Krot, University of Hawaii)

This combined X-ray elemental map shows Mg (red), Ca (green) and Al (blue) of the CR carbonaceous chondrite PCA 91082. CAIs and chondrules are labeled. Rocks like these preserve a record of the processes and timing of events in the solar nebula.

There are two mechanisms proposed for CAI and chondrule formation: shock waves and jet flows. According to the shock models, for example by S. J. Desch (Carnegie Institution of Washington) and H. C.Connolly, Jr. (Kingsborough College-CUNY), chondrules and CAIs were heated by shock waves that originated in the asteroid belt region. These shock waves moved through the dusty cloud at supersonic speeds, produced frictional heating, and melted the dust particles. According to the jet flow model developed by Frank Shu (University of California, Berkeley), chondrules and CAIs formed near the Sun (at ~0.04-0.08 AU) by sunlight and radiation associated with solar flares and were transported later to the asteroid belt region by a bipolar outflow [see PSRD articles Relicts from the Birth of the Solar System and The Oldest Metal in the Solar System for more information.] Ages (relative or absolute) of CAIs and chondrules can provide important constraints on their origin, but past calculations are either controversial or insufficiently precise.



(PSRD graphic by Nancy Hulbirt, based on a conceptual drawing by Edward Scott, Univ. of Hawaii.)

This drawing depicts some of the processes that might have operated in the nebular disk surrounding the young Sun. It shows the jet flow model of CAI and chondrule formation. The yellow region near the Sun is very hot, which vaporizes all the dust falling into the nebula. The young Sun emits vast quantities of energetic particles, which create winds in the nebula. Rising plumes above the dashed lines are blown out to cooler parts of the disk. According to Shu, powerful jets accelerate CAIs and chondrules to hundreds of kilometers per second, allowing them to reach the asteroid belt in only a day or two.

Relative Ages

The age relationship between CAIs and chondrules can be established using the short-lived radioactive isotope ^{26}Al, which has a half-life ($t_{1/2}$) of ~ 0.73 million years. Most aluminum is in the form of the isotope ^{27}Al, which is not radioactive. ^{26}Al decays to an isotope of magnesium, ^{26}Mg. The tricky thing about determining age differences is that some ^{26}Mg was already present in CAIs and chondrules, so not all the ^{26}Mg originated from the decay of radioactive ^{26}Al. We look for an excess of ^{26}Mg (designated $^{26}Mg^*$) by comparing the $^{26}Mg/^{27}Mg$ ratio to that of other solar system materials.

CAIs and chondrules formed with different initial contents of ^{26}Al. Most CAIs show large excesses of $^{26}Mg^*$, corresponding to an initial $^{26}Al/^{27}Al$ ratio of ~4-5x10^{-5}. Chondrules, in contrast, show only small or undetectable $^{26}Mg^*$, implying an initial $^{26}Al/^{27}Al$ of less than or equal to 1.5x10^{-5}.

Glenn MacPherson (Smithsonian Institution) and colleagues suggest that the difference in the initial $^{26}Al/^{27}Al$ indicates that CAIs formed at least 1-2 million years (My) earlier than chondrules. This chronological interpretation is based on the assumption that ^{26}Al had an external stellar origin and was injected and homogenized in the solar nebula over a time scale shorter than its half-life. A second school of thought proposed by Gounelle (CSNSM-Université, Paris) and colleagues involves a local origin of ^{26}Al by energetic particle irradiation near the forming Sun. This would result in a radial heterogeneity of ^{26}Al distribution and limit the utility of using ^{26}Al as a chronometer.

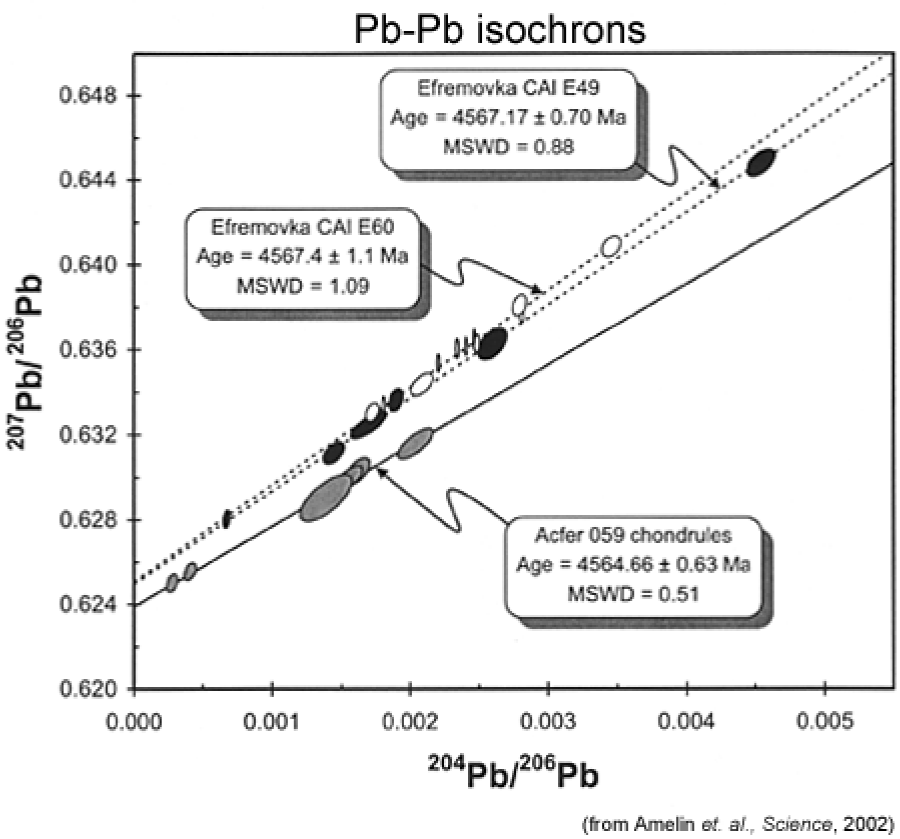
Absolute Ages

In contrast to the relative age dating achieved with ^{26}Al-^{26}Mg radioactive decay, absolute formation ages of CAIs and chondrules may be measured with the $^{207}Pb/^{206}Pb$ chronometer. This lead-lead age is based on radioactive decay of two long-lived radioactive isotopes ^{235}U and ^{238}U. The uncertainties of $^{207}Pb/^{206}Pb$ dates can be as low as 0.5-1.5 My, thus the $^{207}Pb/^{206}Pb$ chronometer may be suitable for resolving a potential 2-3 My age difference between CAIs and chondrules. C. Allégre, G. Manhes, and C. Göpel (Paris Geophysical Institute) report an impressively precise Pb-Pb age of 4566±2 Ma for CAIs from the Allende CV chondrite. Unfortunately, this is not quite precise enough.

My colleague, Yuri Amelin, has developed an even more precise technique for determining Pb-Pb ages. The key to improving the precision of the age determinations comes from Amelin's ability to analyze many small samples. This allows him to find the samples that have the least amount of common (or initial) lead, the lead that was in a chondrule or CAI during its formation and subsequent modification in an asteroid. For example, a chondrule sample could be contaminated with the fine-grained, relatively lead-rich matrix of a chondrite. Or lead might have migrated into the chondrule when the rock was heated in an asteroid. A smaller amount of common lead means that there is a smaller correction required to determine how much lead is due to radioactive decay of uranium. By analyzing many tiny samples, researchers can choose those with the least amount of common lead, hence the largest amount of lead formed by radioactive decay. This decreases the scatter on the Pb-Pb diagrams, leading to much higher precision.

In our recently published paper in *Science* magazine, we report Pb-Pb isochron ages for two CAIs (E60 and E49) from the CV carbonaceous chondrite Efremovka and a similarly precise Pb isotopic age for chondrules from the CR carbonaceous chondrite Acfer 059. We also report the ^{26}Al-^{26}Mg systematics for the CAI E60.

The Pb-Pb isochron age for the Acfer 059 chondrules is 4564.7±0.6 Ma. The weighted average Pb-Pb isochron age for the Efremovka CAIs is 4567.2±0.6 Ma.



On lead isotope plots, materials with the same age will fall along a single line. The data for chondrules from Acfer 059 (solid line) and for CAIs from Efremovka (dashed lines) define precise lines and indicate ancient ages. Error ellipses are 2-sigma; isochron age errors are 95% confidence intervals; MSWD is mean square weighted deviation.

Combining the age of the Acfer 059 chondrules with the age of the Efremovka CAIs gives an interval of 2.5±1.2 My between formation of the CV CAIs and CR chondrules. This indicates that CAI- and chondrule-forming events in the solar nebula continued for at least 1.6 My. This estimate of the interval during which CAIs and chondrules formed is within the range of the jet flow and shock-wave models of chondrule formation.

Implications of the Age Dates

It appears that ^{26}Al can be used as a clock to measure small time differences, allowing us to understand more about the formation of the first solids in the solar system. Preliminary Al-Mg results for chondrules from the CR and CV chondrites by K. K. Marhas (Physical Research Lab, India) and colleagues suggest a range of initial ^{26}Al /^{27}Al from $\sim 1\text{x}10^{-5}$ to less than $3\text{x}10^{-6}$. Our analyses and those of Marhas and J. N. Goswami show initial ^{26}Al/^{27}Al ratios of $\sim$4-$5\text{x}10^{-5}$ for the CR CAIs and Efremovka CAI E60. This suggests a 2-3 My age difference between CAIs and chondrules in these chondrite groups. Ernst Zinner and Christa Göpel [see **PSRD** article Using Aluminum-26 as a Clock for Early Solar System Events] have also shown a correspondence between Pb-Pb ages and ^{26}Al.

Together, the Pb-Pb and Al-Mg isotopic studies support the chronological significance of ^{26}Al-^{26}Mg systematics. These isotopic age results are inconsistent with a local origin of ^{26}Al by energetic particle irradiation. This implies uniform mixing of ^{26}Al and perhaps other isotopes with short half lives [see **PSRD** article Supernova Debris in the Solar System]. Using the Pb-Pb dating technique, we are planning to date chondrules from other chondrite groups. This will help to define the total duration of chondrule formation in the early Solar System, and possibly discriminate between the jet flow and shock-wave formation models.

Additional Resources

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

Taylor, G. J. "Supernova Debris in the Solar System." *PSR Discoveries.* March 2000. <http://www.psrd.hawaii.edu/Mar00/supernovaDebris.html>.

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Zinner, E. "Using Aluminum-26 as a Clock for Early Solar System Events." *PSR Discoveries.* September 2002. <http://www.psrd.hawaii.edu/Sept02/Al26clock.html>.

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