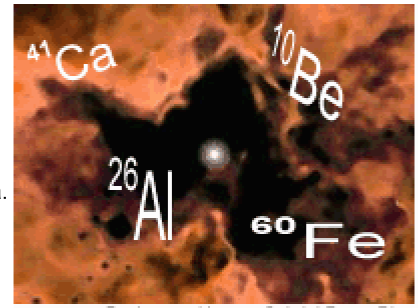
Hot Idea

posted May 21, 2003

Triggering the Formation of the Solar System

--- New data from meteorites indicates that formation of the Solar System was triggered by a supernova.



Background image,Gabriel Peres Diaz, Instituto de Astrofisica Ecanarias

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One of the most amazing discoveries in space science is the unambiguous evidence from meteorites that the solar nebula (the cloud of gas and dust in which the Sun and planets formed) contained radioactive isotopes with half-lives so short that they no longer exist. These include isotopes with very short half-lives, such as calcium-41, ^{41}Ca, (100,000 years) and aluminum-26, ^{26}Al, (740,000 years), and those with longer half-lives such as plutonium-244, ^{244}Pu, (81 million years). The short-lived isotopes are particularly interesting. If they formed in an exploding star, that explosion might have triggered the collapse of the huge interstellar cloud in which the Sun formed. On the other hand, if they formed in the solar nebula by intense radiation close to the Sun, then it would prove some hypotheses about the young Sun and jets of radiation from it.

As synthesized and lucidly explained by Ernst Zinner (Washington University in St. Louis), recent data from ancient objects in meteorites point strongly to the supernova trigger idea. K. K. Marhas and J. N. Goswami (Physical Research Laboratory, Ahmedabad, India), and A. M. Davis (University of Chicago) found clear evidence in meteorites that beryllium-10 (^{10}Be), the one isotope that everybody agrees can be produced by solar radiation, is not accompanied by other short-lived isotopes as it would be if they were all produced by radiation flowing from the young Sun. (^{10}Be can also be made by galactic cosmic rays in the interstellar molecular cloud from which the solar system formed.) Two other research groups reported at the Lunar and Planetary Science Conference (March, 2003) that unmetamorphosed ordinary chondrites contained iron-60 (^{60}Fe), an extinct isotope with a half-life of 1.5 million years. ^{60}Fe cannot be produced by intense, energetic solar radiation, so it must have been made before the Solar System began to form. The best bet is that much of it was made during the supernova explosion that triggered the formation of the Solar System.

References:

Zinner, Ernst (2003) An isotopic view of the early solar system. *Science,* v. 300, p. 265-267.

Marhas, K. K., Goswami, J. M., and Davis, A. M. (2002) Short-lived nuclides in hibonite grains from Murchison: Evidence for solar system evolution. *Science,* v. 298, p. 2182-2185.

Mostefaoui, S., Lugmair, G. W., Hoppe, P., and El Goresy, A. (2003) Evidence for live Iron-60 in Semarkona dn Chervony Kut: A nanosims study. *Lunar and Planetary Science XXXIV,* abstract #1585.

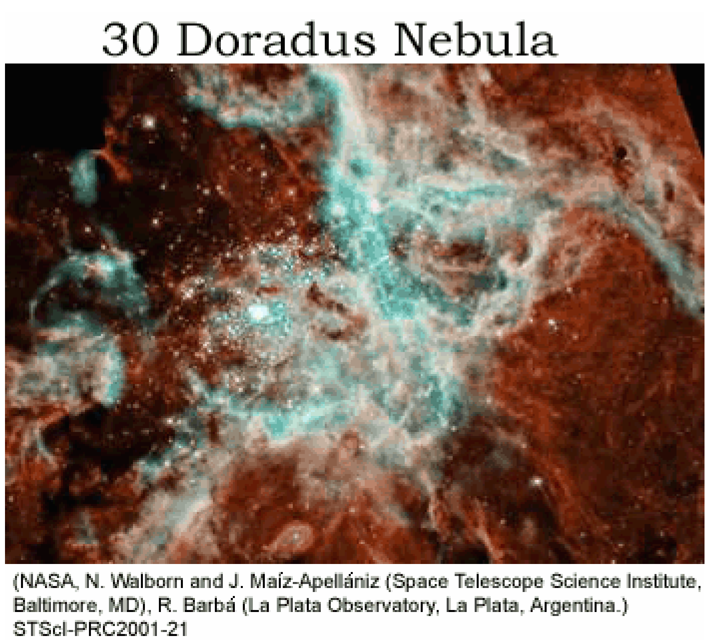
Tachibana, S. and Huss, G. R. (2003) Iron-60 in troilites from an unequilibrated ordinary chondrite and the initial Fe-60/Fe-56 in the early solar system. *Lunar and Planetary Science XXXIV,* abstract # 1737.

Short-Lived Isotopes: Gone Yet Useful

Some scientists analyze meteorites to determine the abundances of things that no longer exist in the Solar System. Analyzing nothing might seem to be impossible. Or perhaps it's a quixotic job taken on only by delusional people. Neither is true. (Actually, I suppose it's possible that some of those people are delusional, but not because they study things that are not there.) Like all radioactive isotopes, short-lived ones decay to another isotope. It is the distinctive nature of the daughter isotopes that record the presence of the short-lived, extinct isotope. For example, ^{26}Al decays into magnesium-26, ^{26}Mg. If present in a mineral grain that contains a small amount of magnesium (most of which is in the form of non-radioactive ^{24}Mg), its decay leads to an anomalously high ratio of ^{26}Mg to ^{24}Mg. (In cases where there is a lot of magnesium, the presence of ^{26}Al cannot be determined.) All short-lived isotopes are referenced to an appropriate stable isotope. ^{26}Al, for example, is referenced to ^{27}Al, the only stable (not radioactive) isotope of aluminum. Its initial abundance is given by the ratio of ^{26}Al to ^{27}Al, which was 5×10^{-5} in the oldest meteoritic materials. A certified list of short-lived isotopes is given in the table below.

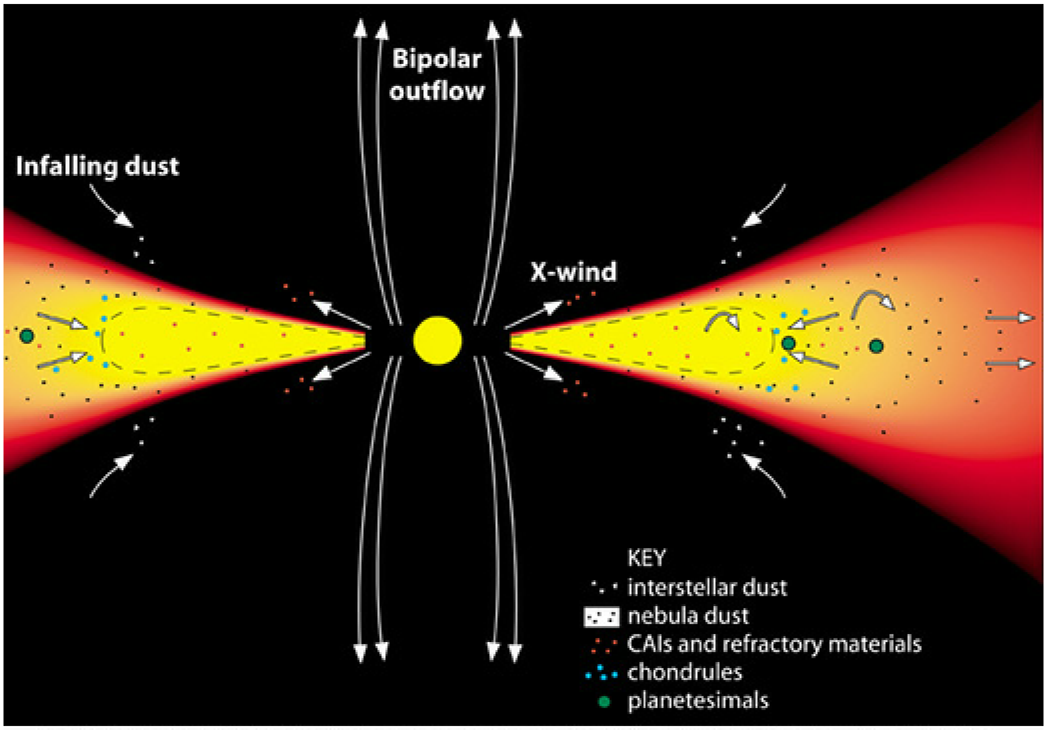
Short lived, now extinct isotopes proven to have been present in meteorites				
Radioisotope	**Half-life (million years)**	**Daughter isotope**	**Reference isotope**	**Initial ratio**
^{41}Ca	0.10	^{41}K	^{40}Ca	1.5×10^{-8}
^{26}Al	0.74	^{26}Mg	^{27}Al	5×10^{-5}
^{10}Be	1.5	^{10}B	^{9}Be	$\sim 5 \times 10^{-4}$
^{60}Fe	1.5	^{60}Ni	^{56}Fe	$\sim 10^{-6}$
^{53}Mn	3.7	^{53}Cr	^{55}Mn	$\sim 10^{-5}$
^{107}Pd	6.5	^{107}Ag	^{108}Pd	4.5×10^{-5}
^{182}Hf	9	^{182}W	^{180}Hf	10^{-4}
^{129}I	16	^{129}Xe	^{127}I	10^{-4}
^{244}Pu	81	Fission Xe	^{238}U	$(4 - 7) \times 10^{-3}$
^{146}Sm	103	^{142}Nd	^{144}Sm	$(5 - 15) \times 10^{-3}$
From Zinner (2003) *Science,* v. 300, p.265-267.				

These extinct isotopes are incredibly informative. For a long time astrophysicists and meteorite experts agreed that the isotopes were produced before collapse of the huge interstellar cloud of gas and dust in which the Sun and perhaps other stars formed. Supernova explosions in the galaxy could continuously produce the longer-lived ones, such as plutonium-244 (^{244}Pu) and iodine-129 (^{129}I). They would decay, but supernovae would continuously make fresh batches. On the other hand, the short-lived isotopes are around for too short a time to be replenished by supernova explosions or other stellar element-forming processes, leading to lower abundances than we observe in meteorites. Their presence in our solar system indicates that cloud collapse began within a few tens of thousand of years of isotope formation. This led to the idea that a supernova explosion triggered the collapse of the interstellar cloud, thereby causing formation of the Sun and planets.



This Hubble Space Telescope mosaic gives us a beautiful view of the fertile star-forming region "30 Doradus Nebula." High-energy ultraviolet radiation and intense pressures of stellar winds produced by stars in the cluster (the large blue blob left of center) trigger the collapse of parts of the gas and dust clouds, producing a new generation of stars. Supernova explosions might also trigger the collapse of interstellar clouds.[Click the image to open a new browser window with higher resolution options.]

One of the characteristics of science is that someone always comes along to challenge conventional wisdom. In this case, Frank Shu (University of California, Berkeley, now President at the National Tsinghua University in Hsinchu, Taiwan) and his coworkers suggested the renegade but imaginative idea that short-lived isotopes were made near the Sun while it was exhibiting a youthful exuberance by emitting vast amounts of radiation. Shu's idea is that the short-lived isotopes ^{26}Al, ^{41}Ca, and ^{53}Mn were made by intense radiation by the "X-wind," a flow of material and radiation from a region near the nascent Sun. The idea was shored up by the discovery by Kevin McKeegan (UCLA) and his coworkers of beryllium-10, which everybody agrees can be produced only by irradiation by energetic particles and was not made in stars. Others liked the idea and calculated that the right amounts of short-lived isotopes can be produced, though it requires a unique combination of the compositions of the grains being irradiated and the energy spectrum of the radiation (that is, the intensity of the radiation has to vary with wavelength in a unique way).

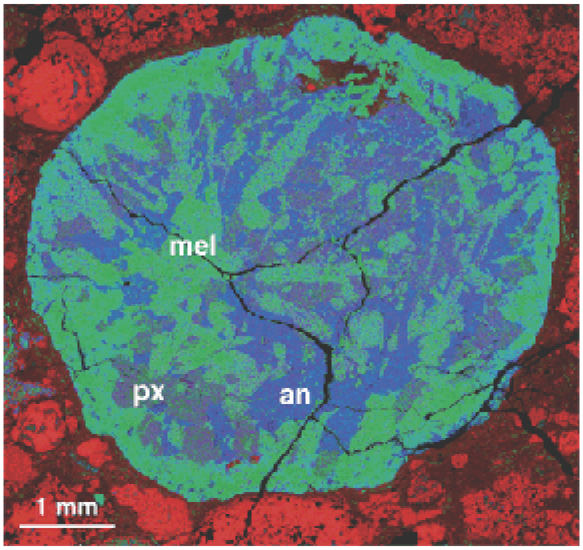


(PSRD graphic by Nancy Hulbirt, based on a conceptual drawing by Edward Scott, Univ. of Hawaii.)

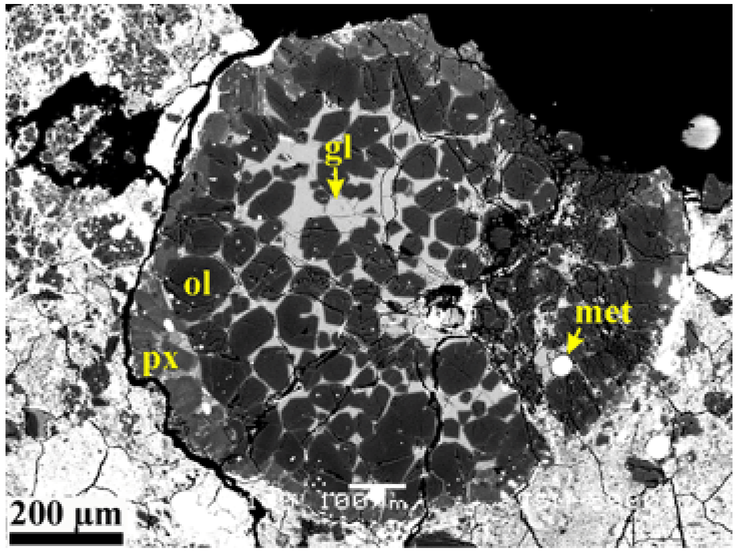
This drawing depicts some of the processes that might have operated in the nebular disk surrounding the young Sun. It shows the jet flow model of the formation of calcium-aluminum-rich inclusions (CAIs) and chondrules. The yellow region near the Sun is very hot, which vaporizes all the dust falling into 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. One hypothesis depicts CAIs forming closer the the Sun than chondrules, giving them higher initial abundances of short-lived isotopes like ^{26}Al than chondrules, making them appear to have older ages. The competing hypothesis suggests that short-lived isotopes were distributed uniformly throughout the solar nebula. The higher ^{26}Al in CAIs would then indicate that CAIs are older than chondrules.

Age or Distance?

These two views affect whether we can use short-lived, extinct isotopes as chronometers to distinguish events that took place 4.5 billion years ago. For example, suppose ^{26}Al was distributed uniformly throughout the solar system. This implies that it formed in a supernova and that the supernova debris was mixed uniformly in the material from which the solar system formed. Now suppose that an isotopic expert measures its abundance in two ancient objects from a meteorite and finds that the ratio of ^{26}Al to ^{27}Al differs by a factor of two. That can be explained by one object being one half-life (740,000 years) younger than the other. The difference in ^{26}Al/^{27}Al ratio between calcium-aluminum-rich inclusions (CAIs) and chondrules in chondritic meteorites indicates an age difference of about 2 million years. Or does it? Not if Frank Shu is right. If the ^{26}Al was made near the Sun while it was spewing radiation, CAIs might have been closer to the Sun than chondrules. So, instead of being 2 million years older than chondrules, CAIs simply formed closer to the Sun. Which is it, age or distance? Somebody had to figure out where the extinct isotopes were made.



(Courtesy of A. Krot, University of Hawaii.)

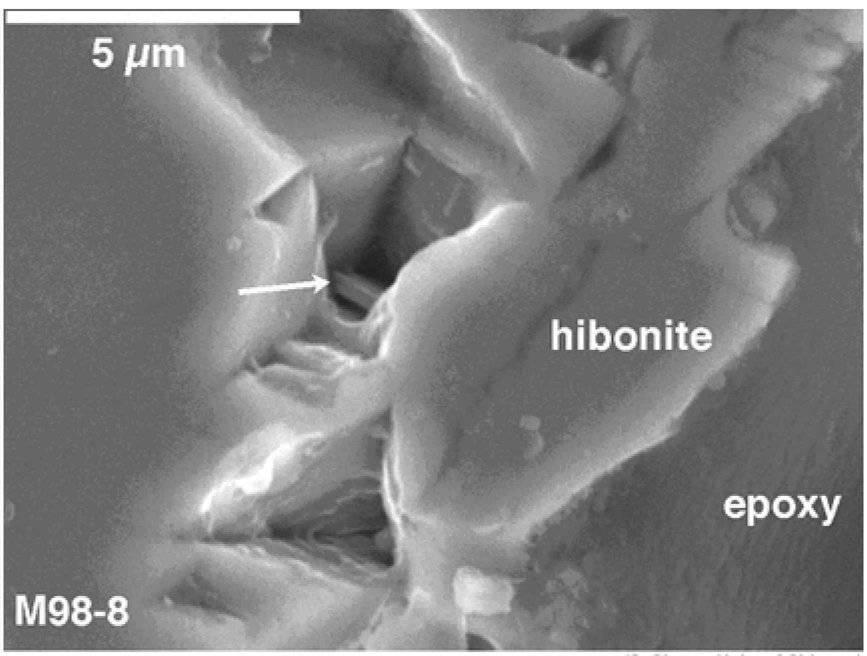


(Courtesy of A. Krot, University of Hawaii.)

LEFT: A calcium-aluminum-rich inclusion (CAI) in the carbonacious chondrite Efremovka with anorthite (an), melilite (mel), and pyroxene (px). RIGHT: A type I chondrule with olivine (ol), glass (gl), metallic rion (met), and pyroxene (px). Ages determined by short-lived isotopes suggest that CAIs either formed about 2 million years before chondrules or formed closer to the Sun than did chondrules.

Where Were Short-Lived Isotopes Made?

If the X-wind made short-lived isotopes, then ^{10}Be, ^{26}Al, and ^{41}Ca should all be present in the same object in a meteorite. Making this test requires finding the right material--one that has low concentrations of the daughter products of all three short-lived isotopes. The mineral hibonite, $CaAl_{12}O_{19}$ (though it can also contain magnesium and titanium), fills the bill. It is low in beryllium and potassium, and does not contain too much magnesium to determine if ^{26}Al was present. Hibonite occurs in only a few special CAIs, the ones that formed at the highest temperature in the solar nebula. [See PSRD article: The First Rock in the Solar System.]



(S. Simon, Univ. of Chicago)

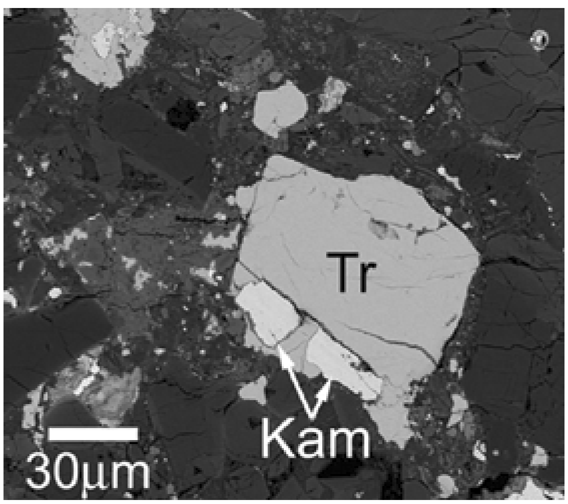
A secondary electron image of a CAI, named M98-8, from the Murchison chondrite meteorite. Plates of hibonite, a crystal habit typical of this mineral, can be seen in the gap at the center of the photo (shown by the arrow).

K. Marhas and colleagues used an ion microprobe at the Physical Research Laboratory in India to analyze several hibonite-bearing CAIs. They found clear evidence for the presence (long ago) of ^{10}Be, but not for ^{26}Al or ^{41}Ca. Whatever process made the beryllium-10 did not make the other isotopes. Since ^{10}Be can be made by solar irradiation but not by stellar processes, this discovery favors the idea that is short-lived aluminum and calcium isotopes were made in exploding stars. So, the answer to the question "age or distance?" is age--the short-lived isotopes were made in exploding stars and incorporated into the materials from which the Sun and planets formed.

The case for a pre-solar source for short-lived isotopes (except for beryllium) is also supported by the agreement between the ^{26}Al clock and other dating techniques. See, for examples, the PSRD articles Dating the Earliest Solids in our Solar System and Using Aluminum-26 as a Clock for Early Solar System Events. These age techniques do not depend on short-lived isotopes, so the agreement provides strong evidence for the veracity of the aluminum chronometer and for the production of most short-lived isotopes in other stars.

The Trigger

The relatively high abundance of ^{60}Fe isotopes in primitive meteorites points to a supernova as the source for most short-lived isotopes and as the trigger for solar system formation. Measurements suggested that the $^{60}Fe/^{56}Fe$ ratio was quite low and could be explained by continuous production of ^{60}Fe throughout the region where the solar system formed. However, recent measurements reported at the Lunar and Planetary Science Conference indicate that troilite (FeS) in primitive, unheated chondrites (nicknamed unequilibrated ordinary chondrites) has a relatively high ratio of ^{60}Fe to ^{56}Fe. Teams at Arizona State University (S. Tachibana and G. Huss) and at the Max-Planck Institute for Chemistry in Mainz, Germany (S. Mostefaoui, G. Lugmair, P. Hoppe, and A. El Goresy) made the measurements using secondary-ion mass spectrometry. The indicated amount of ^{60}Fe is much too high to record continuous production and decay. A large amount of it must have been manufactured right before the solar system formed. This points to a supernova explosion forming the ^{60}Fe (and other short-lived isotopes) and also triggering the collapse of the interstellar cloud. Other stellar sources do not seem to be capable of making enough ^{60}Fe, so a supernova seems to be the best bet. The problem is not quite solved, however. Astrophysicists need to improve models of element formation in stars before we can confidently conclude that the source of short-lived isotopes and the triggering mechanism for formation of our solar system was a supernova. For example, some scientists argue that ^{60}Fe can be produced by stars that have left the main branch and have arrived at the asymptotic giant branch (AGB). Most stars do this after their main hydrogen fusion phase has ended, becoming cool, luminous, and pulsating red giant stars. Such stars, if the right size, might spew enough ^{60}Fe to produce the high ratio of $^{60}Fe/^{56}Fe$ observed in the unequilibrated chondrites. Clearly, more research is needed before we can decide if supernova explosions are needed or if AGB stars can produce enough ^{60}Fe.



(Courtesy of S. Tachibana and G. Huss, Arizona State Univ.)

Polished piece of the meteorite Bishunpur, as viewed in reflected light. Kamacite, labeled Kam, is metallic iron-nickel. Tr denotes troilite (FeS). Dark gray areas are silicates. Troilite contains only tiny amounts of nickel, making it ideal for detecting the presence of ^{60}Fe which decays to ^{60}Ni.

This research is a good example of how meteorite studies overlap with astronomical and astrophysical studies. Studies of pre-solar grains also provide this link. Meteoriticists use microscopes, electron microscopes, ion microprobes, and other high-tech gizmos to study bits of stardust and the isotopic remains of catastrophic explosions. Astronomers use telescopes, spectrographs, and nuclear physics. Both address the same basic questions: How do stars form? How did the solar system form?

Additional Resources

Hubble Space Telescope

Marhas, K. K., Goswami, J. M., and Davis, A. M. (2002) Short-lived nuclides in hibonite grains from Murchison: Evidence for solar system evolution. *Science,* v. 298, p. 2182-2185.

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