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Hot Idea

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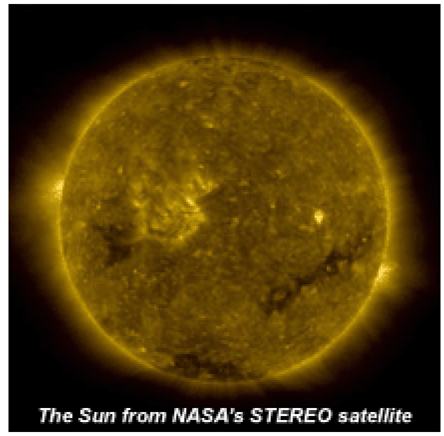

The Sun from NASA's STEREO satellite

The Sun's Crowded Delivery Room

--- Isotopes in meteorites suggest that the Sun formed in a dense cluster of stars.

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Astronomic observations with the latest and greatest telescopes are leading astronomers to embrace the idea that stars usually form in clusters, even if they end up, like our Sun, isolated from other stars. Cosmochemists using optical microscopes, electron microscopes, and mass spectrometers are finding evidence supporting the idea, along with important details about the star-forming regions and about the earliest history of the Solar System. The latest breakthrough is reported by Martin Bizzarro and his colleagues at the Geological Institute and Geological Museum in Denmark, at the University of Texas, and at Clemson University in South Carolina. They made high-precision measurements of iron and nickel isotopes. The results show that the oldest planetesimals to form in the solar system did not contain any iron-60 (^{60}Fe), which decays to nickel-60 (^{60}Ni) with a half-life of only 1.5 million years, yet somewhat younger materials did contain it. In contrast, aluminum-26 (^{26}Al), with a half-life of 740,000 years, was relatively uniformly distributed.

This suggests to Bizzarro and his colleagues that ^{60}Fe was added to the cloud of gas and dust surrounding the primitive Sun (the protoplanetary disk) about 1 million years after the Solar System formed. This could happen if the Sun's nursery contained massive stars (perhaps 30 times the mass of the Sun). Such stars last only about 4 million years. They are extremely active, blowing away their outer layers in the last million years of existence. The dispersed material would have included ^{26}Al and might have caused collapse of interstellar gas and dust to cause formation of the Sun and its protoplanetary disk. A million years later the massive star exploded, ejecting ^{60}Fe from its interior. Bizzarro and colleagues argue that this huge event of destruction and creation is recorded in the meteorites.

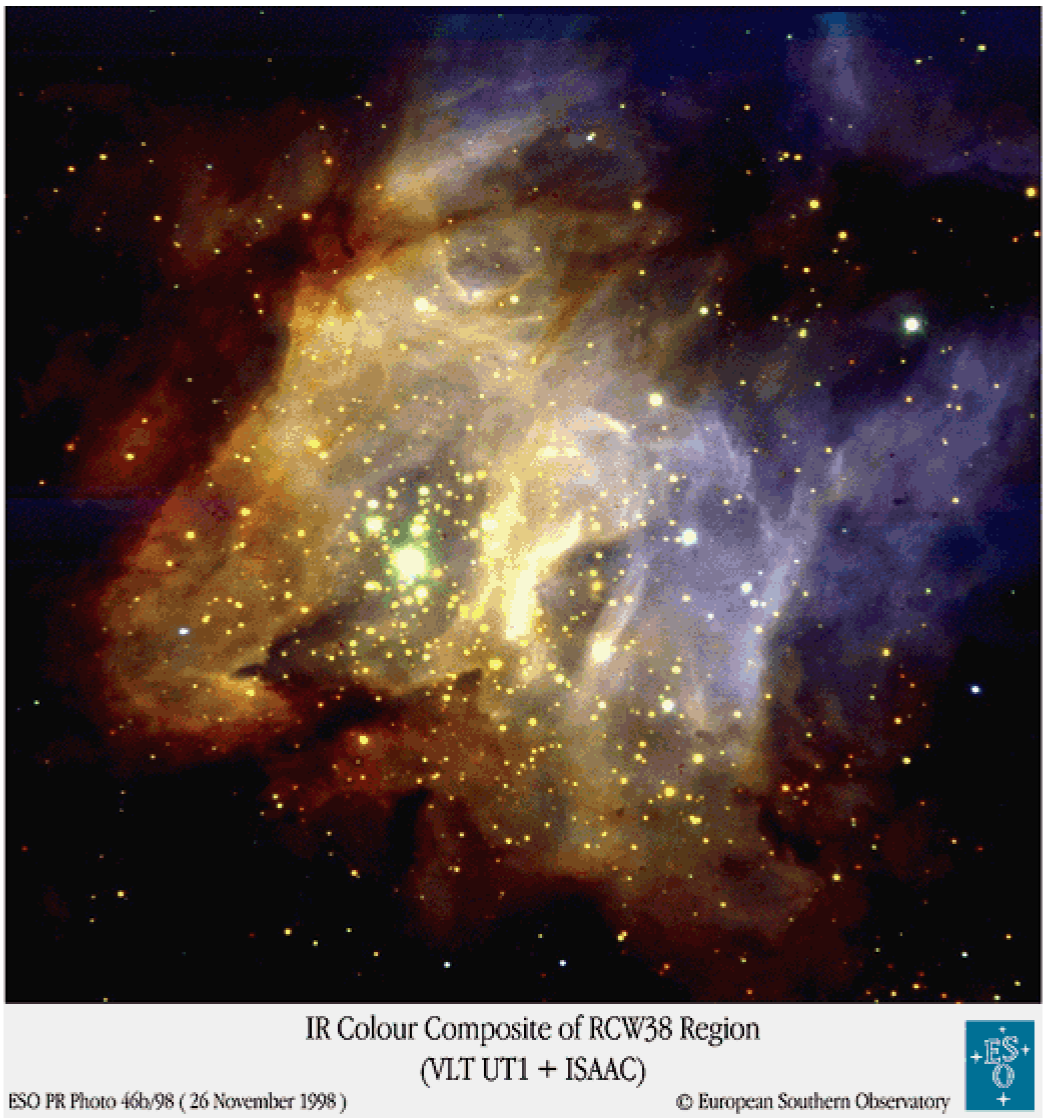
Reference:

- Bizzarro, M., Ulfbeck, D., Trinquier, A., Thrane, K., Connelly, J. N., and Meyer, B. S. (2007) Evidence for a later supernova injection of ^{60}Fe into the protoplanetary disk. *Science,* v. 316, p. 1178-1181.

PSRDpresents: The Sun's Crowded Delivery Room --Short Slide Summary (with accompanying notes).

Crowded Star-Forming Regions

There are a lot of stars, including the Sun, sitting by themselves in the cosmos. Astronomers used to think that stars formed as isolated objects in vast molecular clouds, but new observations lead many to now believe that most stars form in clusters containing numerous companions, large and small. Isolated stars like the Sun may all be derived from multiple systems. Because massive stars form in such dense clusters, burn hydrogen and then explode before the cluster has finished producing new stars, the early lives of stars may be profoundly affected by nearby siblings. The evidence for the presence of short-lived isotopes like aluminum-26 (^{26}Al) and iron-60 (^{60}Fe) in meteorites provides strong evidence that the Sun probably formed in such a neighborhood and was peppered with stardust from an exploding star. Cosmochemists like Martin Bizzarro and his coworkers want to understand the details of events associated with formation of our Sun. Meteorites contain that record.



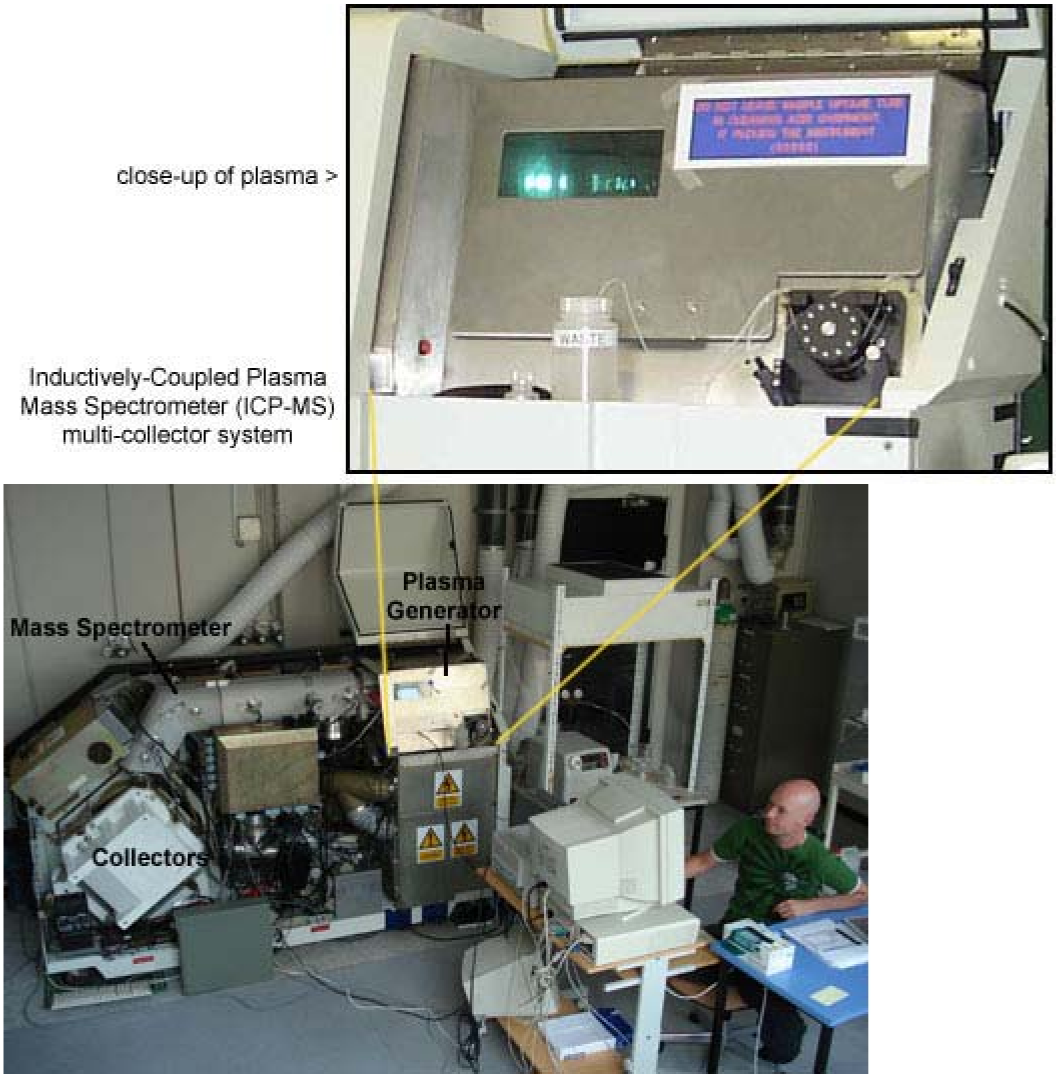
Infrared color image of RCW38, an extremely dusty region of young star formation in the constellation of Vela. Use of infrared allows astronomers to see into this very dusty region to observe the numerous stars making up a cluster. The photograph was taken with the Infrared Spectrometer and Array Camera on the 8.2-meter Very Large Telescope (VLT) on the top of Cerro Paranal mountain in the Atacama Desert of northern Chile.

Measuring Short-Lived Isotopes

Short-lived isotopes no longer actually exist in meteorites, except for a few produced by cosmic ray interactions. They formed in other stars (and perhaps close to the Sun in our Solar System), were incorporated into solids such as meteorite parent bodies and the planetesimals that accreted to form the planets, and decayed away with half lives ranging from 0.1 to 100 million years. Fortunately, their decay products remain behind, including ^{60}Ni from decay of ^{60}Fe and ^{26}Mg from decay of ^{26}Al.

A real trick is to measure the abundances of the isotopes accurately and precisely enough to determine the ratio of a decay product (for example, ^{60}Ni) to a common nickel isotope (for example, ^{58}Ni). This is where laboratory chemistry and high-tech gear come into play. Bizzarro and his colleagues used acids and ion exchange columns to separate nickel from other elements from metallic iron minerals and from silicate (rocky) minerals. The metallic samples were dissolved in hydrochloric acid, and then sent through an ion exchange column. Ion exchange is a technique used to separate ions from a solution. A common use is to purify water in a water-softening system, where calcium and magnesium are removed by passing water through a column filled with granules (usually of a resin) that latch on to certain ions. Bizzarro and his lab mates ran the meteoritic iron through two separate types of columns to get rid of all elements except nickel. They followed a similar procedure for extracting nickel from silicate minerals. They also ran "blanks," a common chemical procedure in which all the procedures are followed, but no sample is used. This tells the chemist how much contamination there is in the chemical system and how good their separation techniques are. They found insignificant levels of nickel in their blanks.

Once Bazzarro had a solution containing nickel only, he and his colleagues analyzed them in an inductively-coupled plasma mass spectrometer. This technique uses a hot flame coupled to a radio frequency generator to create a plasma from the solution. A plasma is a gas in which many of its atoms and molecules are ionized (that is, charged). The ions in the plasma are sent through a mass spectrometer and the abundance of each nickel isotope is measured. The system is equipped with multiple detectors, which allow the investigators to measure all nickel isotopes at once. This produces a more accurate analysis than older techniques that required each ion mass to be selected by varying the magnetic field strength in the mass spectrometer, which introduces errors largely because of small variations in the plasma with time.

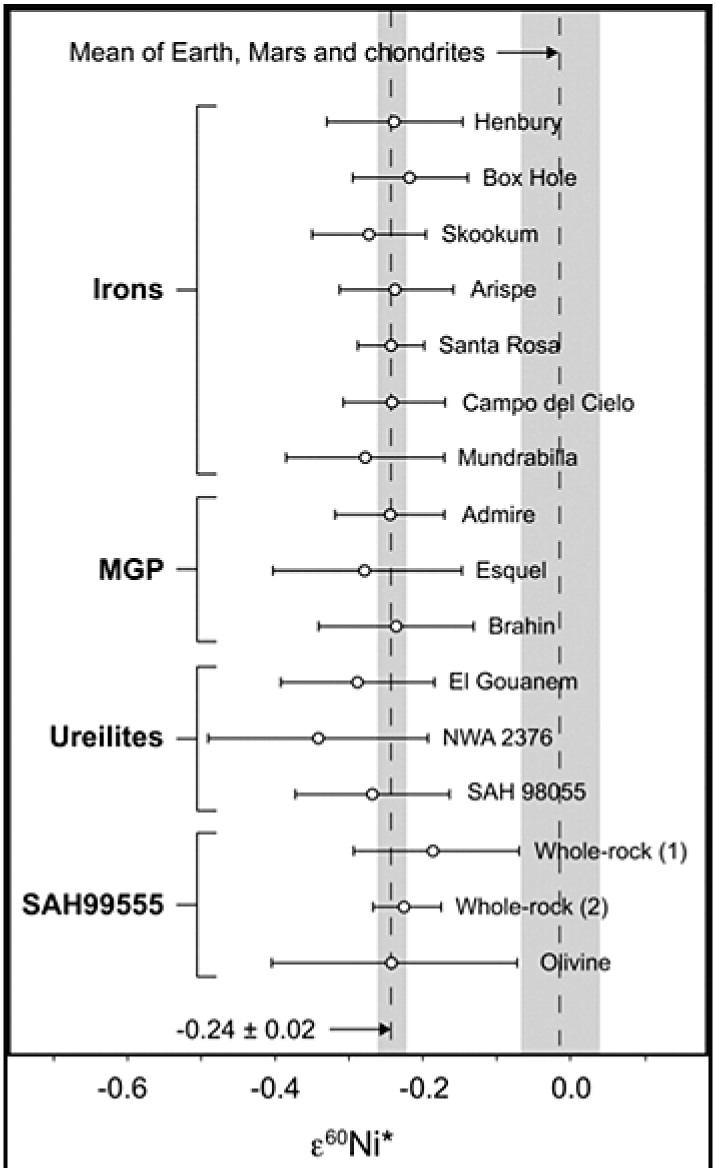


The photo above shows the Inductively-Coupled Plasma Mass Spectrometer (ICP-MS) multi-collector system used in the Geological Institute in Copenhagen. The glowing area is where the plasma is produced (see close-up insert). At the far left is a set of collectors to count the number of ions of a specific mass traveling through the mass spectrometer (central area). Courtesy of Martin Bazzarro.

Planets and Chondrites

Bazzarro and his team studied terrestrial samples, meteorites from Mars, chondritic meteorites, and differentiated meteorites (hence from asteroids that melted early in their histories). Other studies have shown that the formation ages of the meteorites studied range from the start of the Solar System to about 3 million years later. The beginning of the Solar System is defined by the ages of calcium-aluminum-rich inclusions, CAIs, 4.5672 billion years ago [see PSRD article: Dating the Earliest Solids in the Solar System].

Eight samples from Earth, a Martian meteorite, and chondritic meteorites have essentially the same abundance of ^{60}Ni (see diagram below). This gives them a value of epsilon-^{60}Ni of 0.0 on the diagram. (The epsilon notation (ε) is simply the deviation from the terrestrial value in parts per 10,000.) This uniformity indicates that inner Solar System objects that formed after ^{60}Fe had decayed away (Earth and Mars) or have solar iron/nickel ratios (chondrites) must have formed from materials in which ^{60}Fe had been uniformly distributed. In contrast, differentiated meteorites have no evidence for ^{60}Fe (low epsilon-^{60}Ni); see figure and discussion below.



(From Bizzarro *et al.*, 2007, *Science*, v. 316, p.1178-1181.)

$\varepsilon^{60}Ni$ values for differentiated meteorites (irons, pallasites, ureilites, and one angrite, SAH9955, are systematically lower than the values for the inner planets (Earth and Mars) and chondritic meteorites. This indicates that when the differentiated meteorites formed, they did not contain ^{60}Fe. That was added about a million years later, mixing with the raw materials for chondrites and subsequently the planets. Because differentiated meteorites and chondrites both contain evidence for the presence of now-extinct ^{26}Al, it appears that the ^{60}Fe addition to the Solar System was decoupled from that of ^{26}Al.

Melted Planetesimals

The differentiated meteorites formed in asteroids that melted. Some are cores (irons), others seems to represent the boundary between a core and rocky mantle (pallasites), still others are residues left behind when magma formed inside and migrated to the surface (ureilites), and yet others are lava flows (angrites). It used to be thought that differentiated meteorites were somewhat younger than chondrites, but recent age dating shows that in fact, they are 1-2 million years older than most chondritic components. CAIs are the oldest, about 1 million years older than differentiated meteorites. [See PSRD article: Cosmochemistry from Nanometers to Light Years.]

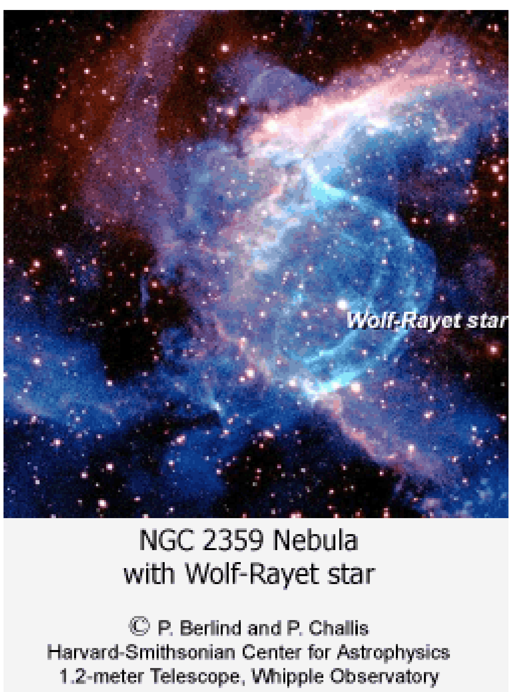
All the differentiated meteorites analyzed by Bizzarro and his colleagues have significantly lower epsilon-60Ni values. This indicates that they did not contain measurable ^{60}Fe when they formed and melted. Thus, because the younger objects (chondrites and the inner planets) did contain it, ^{60}Fe must have been added after the differentiated planetesimals formed. On the other hand, ^{26}Al was present in the differentiated meteorites. The

^{60}Fe must have come in later. Bizzarro and colleagues estimate that ^{60}Fe was added about 1 million years after Solar System formation began.

Bizzarro and coworkers think they have an explanation for the difference in arrival times of ^{26}Al and ^{60}Fe. Formation of the Sun might have involved the formation and rapid life span (only 4 million years) of a massive star, 30 times more massive than the Sun. Astronomical observations indicate that such stars pass through a stage in which they lose mass--up to an Earth mass per day!-- rapidly by blowing it into space at a couple of thousand kilometers per hour. These stellar winds contain ^{26}Al, but ^{60}Fe is still ensconced in the interior. At some point the star blows up, sending the products of nuclear fusion into interstellar space, including ^{60}Fe. Note the sequence here: ^{26}Al leaves with the strong stellar winds, which possibly triggered the collapse of a cloud of gas and dust to form a new star, our Sun. There is good evidence that ^{26}Al was uniformly distributed throughout the Solar System [see **PSRD** article: Using Aluminum-26 as a Clock for Early Solar System Events]. The ^{60}Fe comes about a million years later when the star explodes, but also after many planetesimals differentiated. They did not contain any ^{60}Fe, but had their full complement of ^{26}Al. In fact, they had enough ^{26}Al to heat up internally and melt.

The ^{60}Fe cannot have come from a source too far from the infant Sun. If too far away it would decay before arriving or be so diluted that we could not measure it. The exploding star had to be in the Sun's general vicinity. It was a cluster mate of the Sun.

One type of massive star is called a Wolf-Rayet star (named after the discoverers). In these large objects, elements formed inside by nuclear fusion, such as oxygen and aluminum, migrate toward the surface. This concentration of material begins to adsorb light from inside, eventually resulting in strong winds blowing off the surface and into interstellar space. The winds are shown in the image, below, taken in the infrared. Astronomers believe that most massive stars (those >20 times the mass of the Sun) go through a Wolf-Rayet phase, which ends when they explode as supernova.



Stellar winds blowing from a massive Wolf-Rayet star (brightest star near center). Courtesy of P. Berlind & P. Challis, Harvard-Smithsonian Center for Astrophysics.

Testing the Observations

Cosmochemists welcome the results reported by Martin Bizzarro and his colleagues. It is going to start a new round of meteorite analyses to test the measurements. Scientists spend a lot of time testing each other's results, and these results are so important that it is essential that they be tested. In fact, previous results have not observed the deficiency in ^{60}Fe that Bizzarro reports. Besides replicating the measurements, there are other tests to perform, such as searching for ^{60}Fe in a greater range of meteorites and in specific components in meteorites (for example, individual chondrules). This research is just beginning.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- **PSRDpresents:** The Sun's Crowded Delivery Room --Short Slide Summary (with accompanying notes).
- Bizzarro, M., Ulfbeck, D., Trinquier, A., Thrane, K., Connelly, J. N., and Meyer, B. S. (2007) Evidence for a later supernova injection of ^{60}Fe into the protoplanetary disk. *Science,* v. 316, p. 1178-1181.
- Taylor, G. J. (January, 2006) Cosmochemistry from Nanometers to Light Years. *Planetary Science Research Discoveries.* http://www.psrd.hawaii.edu/Jan06/protoplanetary.html
- Taylor, G. J. (May, 2003) Triggering the Formation of the Solar System. *Planetary Science Research Discoveries.* http://www.psrd.hawaii.edu/May03/SolarSystemTrigger.html
- Taylor, G. J. (September, 2002) Using Aluminum-26 as a Clock for Early Solar System Events. *Planetary Science Research Discoveries.* http://www.psrd.hawaii.edu/Sept02/Al26clock.html
- Taylor, G. J. (September, 2002) Dating the Earliest Solids in our Solar System. *Planetary Science Research Discoveries.* http://www.psrd.hawaii.edu/Sept02/isotopicAges.html

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