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PSRD-supernova-nanoparticles.pdf

Headline Article
November 30, 2010

Supernova Confetti in Meteorites

--- Pre-solar grains carrying anomalous chromium-54 show evidence for formation in a supernova.

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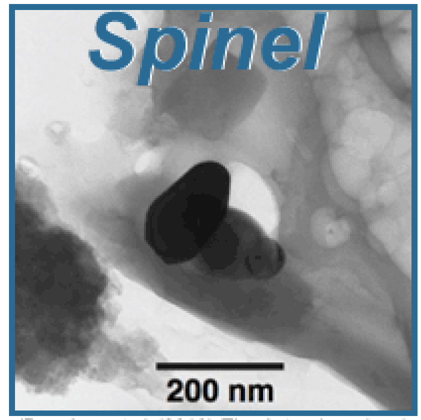


(Dauphas *et al.* (2010) *The Astrophys. Jour.*)

Chromium has four isotopes, ^{50}Cr, ^{52}Cr, ^{53}Cr, and ^{54}Cr. In terrestrial rocks the isotopes behave in predictable ways, with their variations in relative abundance governed by geochemical processes. In contrast, some meteorites have deviant abundances of the heaviest (hence the one with the most neutrons) Cr isotope, ^{54}Cr. These anomalies in isotopic composition are almost certainly caused by nuclear reactions in stars that existed before our Sun was formed. However, the mineralogical carrier of the special ^{54}Cr was not known until Nicolas Dauphas (University of Chicago) and eight colleagues there and at the California Institute of Technology, the Muséum National d'Histoire Naturelle in Paris, the Jet Propulsion Laboratory, and the Université de Lille (France) made detailed analyses of chemical and physical separates from the Orgueil and Murchison carbonaceous chondrites. They found that the carrier of the isotopically-anomalous Cr is spinel, Cr-bearing oxide grains generally smaller than 100 nanometers. Only supernovae can produce the ^{54}Cr anomalies, although which specific type of supernova is not clear. An intriguing possibility is that the ^{54}Cr-rich nano-oxide particles were produced in the same supernova that made two other short-lived isotopes, ^{60}Fe and ^{26}Al, which also existed in the Solar System when it formed. This suggests that formation of the Solar System was triggered by a supernova explosion.

Reference:

- Dauphas, N., Remusat, L., Chen, J. H., Roskosz, M, Papanastassiou, D. A., Stodolna, J., Guan, Y., Ma, C., and Eiler, J. M. (2010) Neutron-rich Chromium Isotope Anomalies in Supernova Nanoparticles. *The Astrophysical Journal*, v. 720, p. 1557-1591, doi:10.1088/0004-637X/720/2/1577.
- **PSRDpresents:** Supernova Confetti in Meteorites --**Short Slide Summary** (with accompanying notes).

Unusual Chromium and Exploding Stars

Chromium has four isotopes, with atomic weights of 50, 52, 53, and 54. Previous measurements, such as those done by Liping Qin of the Carnegie Institution of Washington and her colleagues, show that the $^{54}Cr/^{52}Cr$

ratio in terrestrial rocks is uniform, within experimental uncertainty. Meteorites are another story. Several groups of cosmochemists have shown that calcium-aluminum-rich inclusions (**CAIs**), the first solids to form in the Solar System, have $^{54}Cr/^{52}Cr$ ratios distinctly different from the terrestrial value. Similarly, leaching of chondrites reveals that these meteorites contain highly soluble materials that are deficient in ^{54}Cr and insoluble materials enriched in ^{54}Cr. Different groups of chondrites appear to have distinct $^{54}Cr/^{52}Cr$ ratios and Martian meteorites differ from terrestrial rocks.

Cosmochemists and astrophysicists conclude that these differences in $^{54}Cr/^{52}Cr$ ratio reflect heterogeneous distribution of chromium isotopes that derive from distinct pre-solar stellar sources. Details of the sources and why the carriers of the distinctive $^{54}Cr/^{52}Cr$ ratio are not distributed uniformly remain elusive, in large part because we do not know what minerals carry the isotopically-anomalous chromium. Nicolas Dauphas and his colleagues did an elaborate set of measurements to identify the carrier of this unusual, but informative, chromium.

The search is important because it seems likely that the chromium isotopes record significant, element-forming events in the stellar nursery where the Sun was born. Astrophysicists calculate element and isotope formation in different kinds of stars, including in the colossal explosions called supernovae. The production of extra ^{54}Cr appears to require either a type Ia or type II supernova (more about them later).

SN 1006 Supernova Remnant

NASA, ESA, Zolt Levay (STScI)

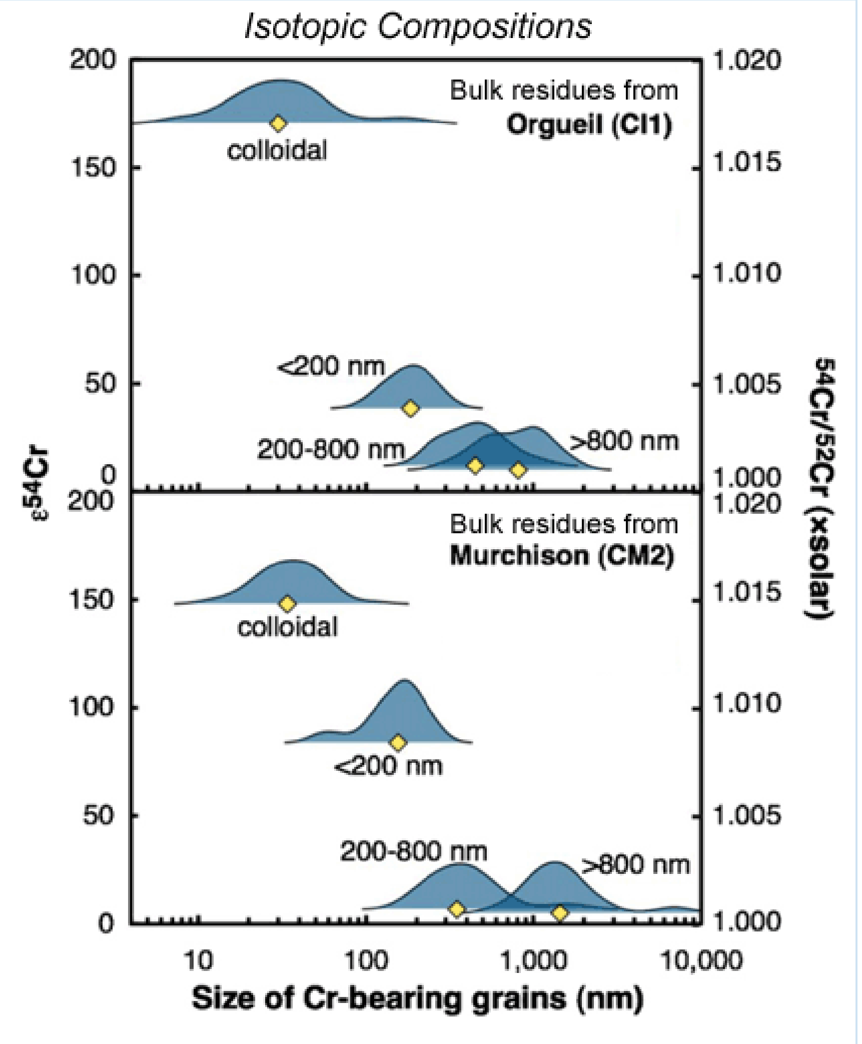
E0102 Supernova Remnant

X-ray NASA / CXC / MIT / D.Dewey *et al.*, NASA / C)
SAO / J.DePasquale; Optical NASA / STS

LEFT: This image of an expanding debris cloud, located in the constellation Lupus, is about 60 light years across and located 7,000 lig years away. The image was taken in three wavelengths: X-rays (blue), optical (yellowish hues), and radio (red). Known as SN 1006, it the remnant of a huge explosion that lit up the Earth's sky in 1006 AD. A new star appeared suddenly, brighter and larger in the sky tha Venus. Astronomers believe that this supernova remnant formed when a white dwarf star captured material from a companion star in a binary system. This process makes type Ia supernovae. RIGHT: This is a composite image made by combining X-ray and optical image from the Chandra and Hubble telescopes of the supernova remnant named E0102 (round object in the center). The remnant is an expanding debris cloud from the explosion of a massive star, a type II supernova. It is actually located in another galaxy, the Small Magellanic Cloud, about 190,000 lights years away from us. The entire field of view is about 150 light years. Click on the images for more information.

Intricate Experiments

Dauphas and coworkers used a complicated chemical procedure to try to concentrate the carrier of the ^{54}Cr anomalies. This procedure was based on previous experiments done by others dating back to 1992, demonstrating the tenacity of cosmochemists when they tackle an important problem. Dauphas obtained samples of the primitive carbonaceous chondrites Orgueil [**Data link** from the Meteoritical Bulletin] and Murchison [**Data link** from the Meteoritical Bulletin]. The samples were disaggregated by freezing and thawing repeatedly, and then leached in a series of acids, then bases, water, more acids, with separation of magnetic and size fractions of the undissolved residues along the way. Samples of each of four size fractions were analyzed for chromium isotopes by thermal ionization mass spectrometer at the Jet Propulsion Laboratory. All size fractions show distinct enrichments in ^{54}Cr/^{52}Cr ratio compared to a terrestrial standard (see diagram below), but Dauphas and his colleagues wanted to determine which specific mineral has a high ^{54}Cr/^{52}Cr ratio.



Chromium isotopic compositions from size fractions of the residues from chemically treated Orgueil (top) and Murchison (bottom) carbonaceous chondrites all have elevated ^{54}Cr/^{52}Cr ratios. These measurements were made using thermal ionization mass spectrometry of bulk samples of the size fractions. Dauphas and coworkers used a NanoSIMS (ion microprobe) to search for individual grains with elevated ^{54}Cr/^{52}Cr ratios. The diagram has two equivalent vertical axes. The left one shows the deviation of the ^{54}Cr/^{52}Cr ratio from the terrestrial value in parts per thousand; the right hand scale shows this ratio compared to the average of materials in the Solar System. These data show conclusively that the separates contain materials that carry the ^{54}Cr, Dauphas wanted to determine which mineral (or minerals) in the separates carry the high ^{54}Cr/^{52}Cr signature.

To identify the grains with an anomalous $^{54}Cr/^{52}Cr$ ratio, Dauphas and colleagues then looked at the residues with a NanoSIMS at Caltech. SIMS stands for secondary ion mass spectrometry (see **PSRD** article: **Ion Microprobe**). Typical SIMS instruments have spatial resolutions of about 1 micrometer, but as the name implies, NanoSIMS instruments can measure isotopic compositions in spots as small as about 50 nanometers. At the conditions used to ensure adequate measurement of the $^{54}Cr/^{52}Cr$ ratio, the primary oxygen beam needed a spot size of about 600 nanometers. Tiny areas of the separate smaller than 200 nanometers in size were isotopically imaged in areas measuring only 20 x 20 or 40 x 40 micrometers on a side. This allowed the team to find grains with anomalous $^{54}Cr/^{52}Cr$ ratio, such as the one shown in the diagram below.

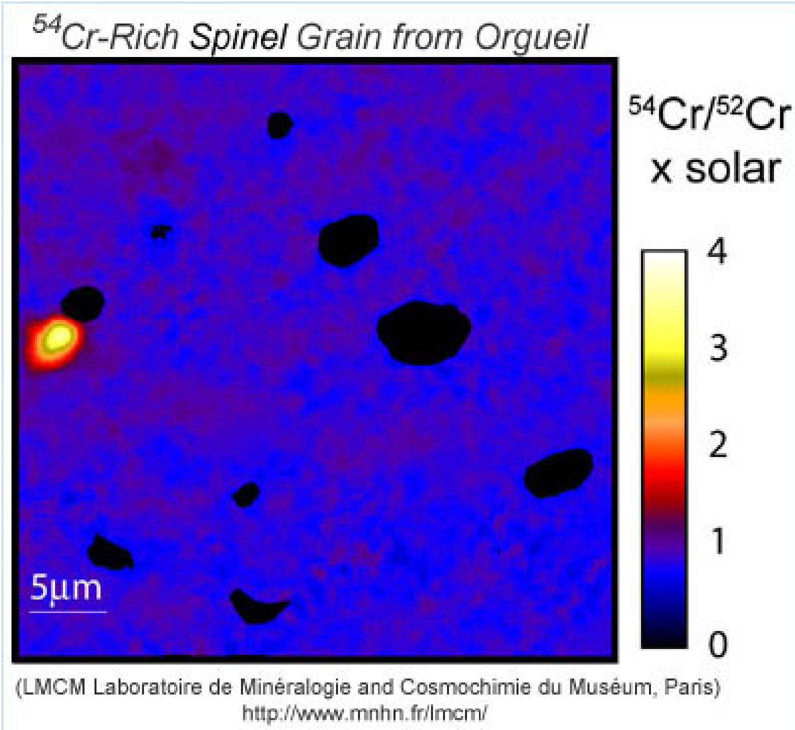


Image of the $^{54}Cr/^{52}Cr$ ratio of the < 200 nanometer size fraction of residues separated from the Orgueil carbonaceous chondrite. One grain (designated np 1 by the investigators) is significantly enriched compared to the countless others in the image. Analysis of the residues by transmission electron microscopy shows that grains like this are oxide minerals called spinel, which contain magnesium, aluminum, chromium, and oxygen. Such chromium-bearing oxides are probably the carriers of the anomalous $^{54}Cr/^{52}Cr$ ratio. The grains grew in a supernova explosion that injected them into the interstellar cloud in which the Solar System formed.

Finding a grain with an enriched $^{54}Cr/^{52}Cr$ ratio is only part of the story. It was essential to figure out the grain's mineralogy. To do this, portions of the colloidal residues were examined in a transmission electron microscope at the Université of Lille. The high $^{54}Cr/^{52}Cr$ ratios in the colloidal residue samples were highest among the fractions, making them good targets to search for Cr-bearing minerals. This detailed search led the team to discover that the most abundant minerals are tiny spinels, an oxide mineral group containing magnesium, aluminum, chromium and oxygen. Dauphas and colleagues conclude that chromium-bearing spinels are the most likely carrier of the distinctively high $^{54}Cr/^{52}Cr$ ratios, but isotopic imaging indicates that most spinels are not enriched in ^{54}Cr and have normal Solar System isotopic compositions. These results are consistent with results about to be published by Liping Qin and her colleagues at the Carnegie Institution of Washington and Washington University in St. Louis, MO.

The spinels with elevated $^{54}Cr/^{52}Cr$ reside in a matrix containing numerous nanospinels with normal $^{54}Cr/^{52}Cr$ ratio. All the grains are smaller than the spatial resolution of even the NanoSIMS, so the maximum value measured in a grain designated np 1 (see image above), 3.6 times the solar value, is likely to be a minimum because the chromium isotopic signal of an anomalous grain is averaged with that of normal grains surrounding it.

Supernova *Signature*

Some presolar grains found in meteorites have isotopic compositions of silicon, carbon, and other elements predicted for formation in material flowing from asymptotic giant branch starts, nicknamed **AGB** stars. Stars with masses not too much different from the Sun reach this stage after using up all their hydrogen via nuclear fusion. Astrophysicists calculate that the nuclear environment in AGB stars would produce a $^{54}Cr/^{52}Cr$ ratio of about 1.1, substantially smaller than the 3.6 observed by Dauphas and coworkers for the anomalous spinel grains in Orgueil. Thus, AGB stars cannot be the source of the grains with a high $^{54}Cr/^{52}Cr$ ratio. This led Dauphas to investigate the likelihood that supernovae were the source.

Dauphas and colleagues focus on two types of supernovae, called type Ia and II. Type Ia involves evolution of roughly solar mass stars in a binary system. One mechanism calls on one of the stars evolving to become a white dwarf (via a red giant stage). When the companion star becomes a red giant the additional mass added to the white dwarf causes sudden carbon fusion, resulting in a catastrophic explosion. The explosion is strong enough to produce heavy isotopes, including those like ^{54}Cr that are enriched in neutrons. Formation of type II supernovae involves the collapse of stars heavier than about 9 solar masses. As the core collapses, it uses up hydrogen, then helium, then carbon and so on, producing progressively heavier elements. The core collapse finally culminates in formation of a neutron core. Star material falling towards the core stops suddenly, causing a rapid release of energy and an explosion.

So, which one, type Ia or II? Because type Ia supernovae do not have much oxygen around, Dauphas and his coworkers argue that this favors formation in a type II supernova, where formation of magnesium-aluminum oxides is favored. They also point out that the presence of short-lived isotopes such as aluminum-26 and iron-60 in primitive meteorites supports the idea that material from a type II supernova was added to the molecular cloud in which the Solar System formed, as these isotopes are produced only in core-collapse supernovae. Dauphas raises the intriguing idea that the same event that delivered ^{26}Al and ^{60}Fe into the Solar System also transported grains rich in ^{54}Cr.

Can this idea be tested? Dauphas and colleagues suggest one way. If we assume that ^{60}Fe and ^{54}Cr were produced in the same supernova, the $^{54}Cr/^{52}Cr$ ratio ought to correlate with the initial $^{60}Fe/^{56}Fe$ ratio. Dauphas calculates that for the observed small variation in $^{54}Cr/^{52}Cr$ ratio between igneous meteorites and primitive carbonaceous chondrites, the initial $^{60}Fe/^{56}Fe$ ratio ought to vary by about 10-20%. The uncertainties in $^{60}Fe/^{56}Fe$ ratio measurements exceed this at present, so the test cannot be carried out. Yet. Given the improvement in analytical techniques and the tenacity of cosmochemists when pursuing an important answer, it is only a matter of time before they can test the idea that a supernova injected dust with high $^{54}Cr/^{52}Cr$ ratio along with ^{26}Al and ^{60}Fe into the pre-solar interstellar cloud, perhaps triggering formation of our Solar System.

On the other hand, the complexities of the processes that gave each element in the Solar System its isotopic composition make the problem surprisingly complicated. The Solar System formed from a vast molecular cloud that was receiving supernova debris and input from other stellar processes. At some point a portion of the cloud began to collapse, resulting in formation of the Sun, planets, and eventually us. If the cloud was relatively uniform, the initial isotopic compositions of the elements would have been uniform. Alternatively, a recent input from a single supernova might not have uniformly mixed the cloud, possibly causing isotopic heterogeneities in the nebular cloud of gas and dust surrounding the infant Sun. But even if the cloud was isotopically uniform, processes in the disk could have separated elements based on the ease with which they are vaporized, which can affect isotopic compositions.

Recent results by an international collaboration led by Kirstin Larsen at the Centre for Star and Planet Formation at the University of Copenhagen, Denmark suggest that the distribution of ^{26}Al was quite heterogeneous in the solar nebula, yet ^{26}Al correlates with ^{54}Cr. The correlation between these two isotopes may reflect that they have a similar origin and are carried in similar minerals, so are not easily separated when the solar nebula was heated. A heterogeneous distribution of ^{26}Al, if confirmed, severely compromises its utility as a time keeper for early events in the Solar System, so cosmochemists will be checking these results carefully.

Additional Resources

Links open in a new window.

- **PSRDpresents:** Supernova Confetti in Meteorites --**Short Slide Summary** (with accompanying notes).

- Dauphas, N., Remusat, L., Chen, J. H., Roskosz, M, Papanastassiou, D. A., Stodolna, J., Guan, Y., Ma, C., and Eiler, J. M. (2010) Neutron-rich Chromium Isotope Anomalies in Supernova Nanoparticles. *The Astrophysical Journal*, v. 720, p. 1557-1591, doi:10.1088/0004-637X/720/2/1577.
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