Hot Idea

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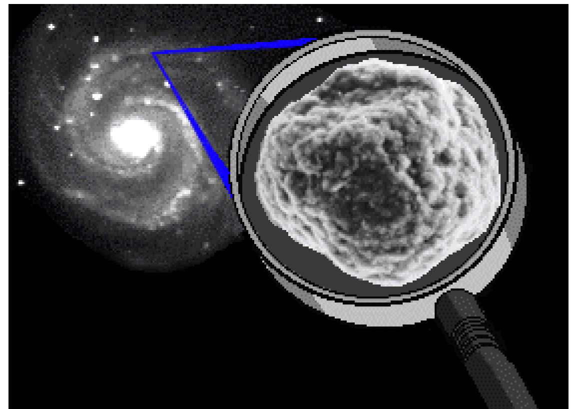
Moving Stars and Shifting Sands of Presolar History



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Many surprising things have been revealed by the presolar grains that scientists extract from meteorites. They are small (micrometer sized) mineral grains that existed in space, as part of clouds of interstellar dust, prior to the formation of our Sun and Solar System. What an astonishing discovery! These castoffs from ancient stars have been preserved within some types of meteorites making them available for close scrutiny in our laboratories. Analyses of these grains have led to better understanding of element formation, motions inside stars, and the migration of stars in the Milky Way Galaxy. This article describes a new view of the astronomical events in the Milky Way. It builds on a decade of detailed research by meteorite specialists, as summarized in a 1993 article by Edward Anders and Ernst Zinner.

References:

Clayton, Donald D., 1997, Placing the Sun and mainstream SiC particles in galactic chemodynamic evolution. *Astrophysical Journal*, vol. 484, p. L67- L70.

Timmes, F. X. and D. D. Clayton, 1996, Galactic evolution of silicon isotopes: application to presolar SiC from meteorites. *Astrophysical Journal*, vol. 472, p. 723-741.

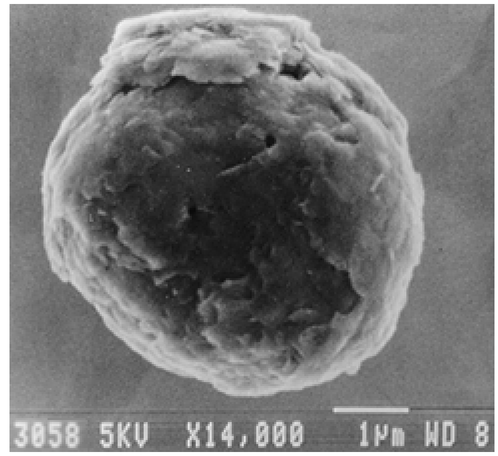
Anders, E. and E. Zinner, 1993, Interstellar grains in primitive meteorites: diamond, silicon carbide, and graphite. *Meteoritics*, vol. 128, p. 490-514.

When the Solar System formed by the collapse of a molecular cloud into the Sun and a dusty disk around it, small mineral grains were included. These dust grains and gases were mixed and mildly heated, and then were accreted onto growing asteroids that became the parent bodies for the pieces of rock that later were to fall to Earth as meteorites. Throughout this well known story, certain types of those presolar dust grains went along for the ride and are found today in the meteorites, extracted, and subjected to study. The presolar nature of the dust grains is revealed in the relative abundances of the isotopes of the common elements. The isotopic abundances differ from those known in **all** Solar System material--almost certainly the result of nuclear reactions in dying stars and exploding stars.

Hands-on Astronomy

Study of presolar grains has become an interdisciplinary field, creating a kind of hands-on astronomy that involves meteorite researchers, astronomers, astrophysicists, chemists, and mineralogists. The field blossomed in 1987 when John Wacker and Tang Ming, working in the laboratory of Edward Anders at the University of Chicago, discovered minuscule diamonds, only a few nanometers across, from a type of meteorite called carbonaceous chondrites. To do so, 99.9% of the meteorite specimen must be dissolved, leaving behind a resistant residue. (Anders has noted that the process is like burning down a haystack to find the needle!)

SEM micrograph of presolar graphite grain, 5 micrometers in diameter, from the Murchison meteorite. Its surface texture resembles an onion. Photo courtesy of S. Amari, Washington University, St. Louis.



(Scale bar is 1μm.) Photo courtesy of S. Amari.

Since then, several types of presolar grains have been found, all of which have distinctive isotopic compositions of oxygen, carbon, nitrogen, magnesium, silicon, titanium, noble gases, and other elements. As an example of the dramatic deviation of isotopic composition, grains of silicon carbide (SiC) have $^{12}C/^{13}C$ ratios that range from 2 to 7000, compared to the range in earth materials of 88-90. These discoveries could not have been made without the techniques to isolate different types of presolar grains. These painstaking separation techniques were developed by S. Amari (Washington University, St. Louis), and R. S. Lewis and E. Anders (Univeristy of Chicago). Significant advances in instrumentation were also needed. The most important one was the ion microprobe which allows precise measurements of isotopic compositions of tiny, micron-sized grains. The ion microprobe techniques were refined by E. Zinner, T. Ireland, S. Amari (Washington University, St. Louis), P. Hoppe (Switzerland), and R. S. Lewis.

Types and characteristics of presolar grains found in meteorites.

Type	Size	Concentration in Meteorites	Sources
Diamond (C)	1-5 nanometers	1000 parts per million	Supernovae
Silicon carbide (SiC)	0.1-10 micrometers	10 parts per million	Carbon-rich giant stars, or supernovae
Graphite (C)	1-10 micrometers	2 parts per million	Supernovae and carbon-rich giant stars
Aluminum oxide (Al_2O_3)	1-5 micrometers	0.1 parts per million	oxygen-rich giant stars
Spinel ($MgAl_2O_4$)	1 micrometer	2 parts per billion	oxygen-rich giant stars
Silicon nitride (Si_3N_4)	1 micrometer	2 parts per billion	Supernovae

Table adapted from a 1993 *Meteoritics* review by Edward Anders and Ernst Zinner, and Conel Alexander's *Carnegie Institution Yearbook 95*, report "Stardust in the Laboratory."

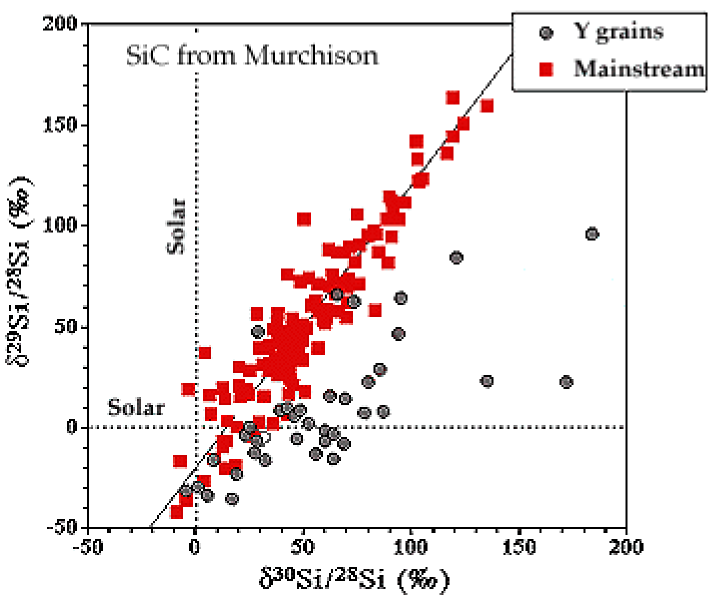
The Special Case of Silicon Carbide

Scale bar is 1 µm. (Photo courtesy of S. Amari.)

Scanning electron microscope (SEM) micrograph of a 4 micrometer presolar SiC crystal from the Murchison meteorite.

One class of presolar grains, made of silicon and carbon, is the well known hard mineral silicon carbide, or SiC. Its hardiness allows it survival, not only in presolar space, but also during the severe chemical treatment to which the meteorites are subjected in the effort to extract those particles. About 90% of these SiC particles are related by a common pattern of silicon isotopes. They are enriched in the two heavier isotopes of silicon, ^{29}Si and ^{30}Si. The third Si isotope, its most abundant one, ^{28}Si, forms the comparison standard. The results are, stated prosaically, that for equal numbers of ^{28}Si atoms, the presolar Si has more ^{29}Si and ^{30}Si atoms than does common Solar System silicon. This discovery, primarily by researchers at Chicago, Caltech, Washington University (St. Louis) and Bern University in Switzerland, astonished and delighted scientists for the past decade because they recognized that the isotope enrichments must be due to the nuclear processes operating inside stars.

As these data mounted, however, a great puzzle emerged. The number of excess ^{29}Si atoms varies from grain to grain, but it is always 2.2 times greater than the number of excess ^{30}Si atoms in the same grain (in comparison with normal silicon). When plotted on a graph of excess ^{29}Si atoms versus excess ^{30}Si atoms, each grain is a single point; but those points line up in almost a straight line. Moreover, most of the presolar particles defining that line have more ^{29}Si and ^{30}Si than has the Solar System. Both facts are puzzling. That line has been called "the mainstream" of SiC particles by the meteorite researchers that first defined it by their experimental measurements.



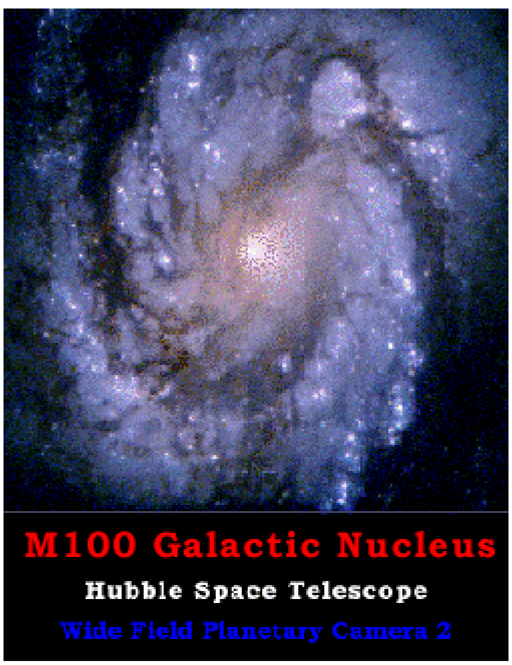
Ratios of silicon isotopes in presolar grains from the Murchison carbonaceous chondrite. Mainstream particles are the most abundant SiC grains. Y grains are a rare (1%) subgroup, but are not important to the story told here. (Courtesy of Ernst Zinner, in whose laboratory the data were obtained.) Silicon isotopic data can also be imaged in an ion microprobe.

In 1988 I published an *Astrophysical Journal* paper in which I offered a possible explanation of the alignment of these data points. Using the theory that explains the growth of the heavy element abundances in the Milky Way Galaxy with time (observed by astronomers) as being a consequence of nucleosynthesis (element formation) in the stars, I argued that the interstellar abundance of silicon should increase in such a way that the number of ^{29}Si and ^{30}Si atoms should grow more rapidly than the number of more abundant ^{28}Si atoms and that, furthermore, the excesses would align along a slope very similar to that observed. This idea helped to establish a theory for the formation of these particles; namely, that they were created within the streams of matter leaving the surfaces of red giant stars called "carbon stars" by astronomers. Their dust grains inherited the initial interstellar Si isotopes from which the stars were born. That idea was also suggested by the discoverers of those particles. These heavy elements have had their isotopes changed by the star in a predictable way that is well understood. The excess heavy element isotopes are called " s process isotopes" by nuclear astrophysicists.

So far so good. For almost a decade this picture has grown in assurance. It faced, however, a growing problem and concern. How can presolar stars have more ^{29}Si and ^{30}Si than the Sun when they have, by definition, formed and lived their lives prior to the birth of the Sun? The theory led one to expect that presolar stars should have *less* ^{29}Si and ^{30}Si than the Sun, not more. This problem resisted all attempts at solution, and threatened to destroy the otherwise successful theory.

Stars on the Move

My new work offers a solution that couples my earlier ideas to growing astronomical evidence that the orbits of stars in the Milky Way are altered over the life time of the Galaxy. Because the element abundances are higher in more central regions of the Galaxy, I suggest that the carbon stars were born there, rather than at the location of the Sun's birth. Being richer in elements heavier than carbon, they will also be rich in ^{29}Si and ^{30}Si, and samples from them would lie along the correlation line described earlier. During their approximately 2 billion year lifetimes, the orbits of these stars evolved to larger orbits, farther from the center of the Galaxy. Many would have ended their lives near the cloud from which the Solar System formed and, therefore, deposited their dust there.



Stars do not have fixed locations in a galaxy. Not only do they orbit around the galactic center but they spiral outwards as well. This striking photo is of a galaxy similar to our Milky Way. (M100 Galactic Nucleus, Hubble Space Telescope, Wide Field Planetary Camera 2.)

Astronomers have studied the effects of moving stellar orbits in two different cases. First, studies of Globular Clusters in the Galaxy (spherical assemblages of 100,000 stars held together in orbits about their own center of mass) show that the central regions shrink over time and outer regions move out to compensate. These movements result from gravity collisions that cause small stars to diffuse outward and large ones to sink inward. It is described in the famous book **Galactic Dynamics** by Binney and Tremaine. In the Milky Way Galaxy, which is similar to the photograph of M100 shown above, the small carbon stars diffuse outward in a similar fashion.

In the second case, Roland Wielen and his colleagues in Heidelberg, Germany published an exciting interpretation of the Sun's own excess of heavy-element abundances. They argued in terms of stellar diffusion theory that the Sun has also diffused outward from its birthplace 6600 pc from the galactic center to its present location at 8500 pc from that center. When I read their arguments I was very excited, for not only had they offered a solution to the old problem of the Sun having more heavy elements than the gas in the solar neighborhood, but they also triggered my own solution for the presolar carbon stars. They diffused outward not to the Sun's present location, but to the cloud at 6600 pc where the Sun was born.

Gravity Assist

Why would the carbon stars move to larger orbits? I think that the stars are scattered by molecular clouds in the inner regions of the Galaxy. Because of their great masses, about 100,000 times that of the Sun's mass, these clouds provide a strong gravitational force. When the carbon stars approach them, they are accelerated by the gravity field to higher velocity, placing them on orbits that reach further out. This same mechanism is used by mankind when sending spacecraft to the outer Solar System. For example, the Voyager spacecraft was allowed to approach Jupiter's strong gravity as it flew past the giant planet and its moons . Voyager picked up speed and was scattered past Jupiter to a new orbit farther out, allowing it to pass Saturn and the other outer planets. Such gravity assists have been used frequently by NASA. I suggest that gravity assists were also used by our own Milky Way Galaxy.

Astronomers are also excited by this possibility. There exist few ways to learn of stars that existed before the Sun in the more central portions of our Galaxy, but their STARDUST carries the message. By carefully learning the relative abundances of these particles, astronomers will be able to map the dynamic history of our Milky Way. By noting that the molecular clouds are known to be concentrated in the inner Galaxy, the numbers that scattered outward to meet the forming Sun will exceed the number that scattered inward by the factor ten that meteorite specialists have documented with their meticulous cataloguing of the isotope ratios within those particles. What an astronomical story to be read within a stone!

Editor's note: One of the leading scientists in the study of presolar grains is Dr. Ernst Zinner of Washington University in St. Louis. To honor his contributions to this and other fields of meteoritics, Ernst is the winner of the 1997 Leonard Medal of the Meteoritical Society, which will be awarded at the annual meeting of the society, July 21-25, 1997, in Wailea, Maui.

Additional Resources

Alexander, Conel ,1996, Stardust in the Laboratory. *Carnegie Institution Yearbook 95*, p. 57-64.

Amari, S., R. S. Lewis, and E. Anders, 1994, Interstellar grains in meteorites: I. Isolation of SiC, graphite and diamond. *Geochim. Cosmochim. Acta*, v. 58, p. 459-470.

Anders, E. and E. Zinner, 1993, Interstellar grains in primitive meteorites: diamond, silicon carbide, and graphite. *Meteoritics*, vol. 128, p. 490-514.

Binney, James and Scott Tremaine, 1987, **Galactic Dynamics**, Princeton University Press, Chapter 8, p. 520-532.

Clayton, Donald D., 1997, Placing the Sun and mainstream SiC particles in galactic chemodynamic evolution. *Astrophysical Journal*, vol. 484, p. L67- L70.

Clayton, Donald D., 1988, Isotopic anomalies: chemical memory of galactic evolution. *Astrophysical Journal*, vol. 334, p. 191-195.

Glanz, James, 1996, Dust Grains Bring Long-Lost Stars into the Laboratory. *Science*, vol. 274, p. 1078-1079.

Hoppe, P., S. Amari, E. Zinner, T. Ireland and R. S. Lewis, 1994, C, N, Mg, Si and Ti isotopic composition of single interstellar silicon carbide grains from the Murchison carbonaceous chondrite. *Astrophysical Journal*, v. 430, p. 870-890.

Meech, Karen J., "1997 Apparition of Comet Hale-Bopp: The Scientific Importance of Comets." *PSR Discoveries*. Feb. 1997. <http://www.psrd.hawaii.edu/Feb97/Science.html>. This reference provides additional information about solar system formation.

Timmes, F. X. and D. D. Clayton, 1996, Galactic evolution of silicon isotopes: application to presolar SiC from meteorites. *Astrophysical Journal*, vol. 472, p. 723-741.

Wielen, R., B. Fuchs and C. Dettbarn,1996, On the birthplace of the Sun and the places of formation of other nearby stars, *Astron. & Astrophys*, v. 314, p. 438-447.

Title photo credits:
Scanning Electron Microscope (SEM) micrograph of presolar 10-micrometer graphite grain courtesy of Sachiko Amari, Washington University, St. Louis.

Whirlpool Galaxy (M51) photo taken with the 1.1 meter Hall Telescope, Lowell Observatory courtesy of Bill Keel, University of Alabama.

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