PLANETARY SCIENCE RESEARCH PSRD Discoveries

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A New Type of Stardust

--- Interplanetary dust particles contain rare grains that formed in stars older than the Sun.

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Many meteorites contain small quantities of microscopic particles with unusual mixes of isotopes. The abundances of the isotopes, such as the relative amounts of oxygen-16, 17, and 18, indicate an origin outside the solar system. The dust particles are bits of stars, some of which no longer exist. Since their discovery in the late 1980s, only grains made of carbon (diamond and graphite), carbides, and oxides have been found. None were silicates--compounds that contain silicon, oxygen, and assorted other ions such as magnesium and calcium. This seemed peculiar to scientists because meteorites and the rocky planets are made mostly of silicate minerals. Part of the problem might have been a sampling bias introduced by the way grains of stardust were extracted, which involves dissolution of meteorites by strong acids. Silicates are more easily dissolved than carbides, oxides, or carbon compounds. However, Scott Messenger and his colleagues at Washington University in St. Louis and at the Johnson Space Center in Houston have found silicate grains in interplanetary dust particles, which are probably remnants of comets. This shows that presolar silicates exist, but it leaves open the question of why none have been found in meteorites.

Reference:

Messenger, S., Keller, L. P., Stadermann, F. J., Walker, R. M., and Zinner, E. (2003) Samples of stars beyond the solar system: silicate grains in interplanetary dust. *Science,* vol. 300, p. 105-108.

Stardust in Meteorites

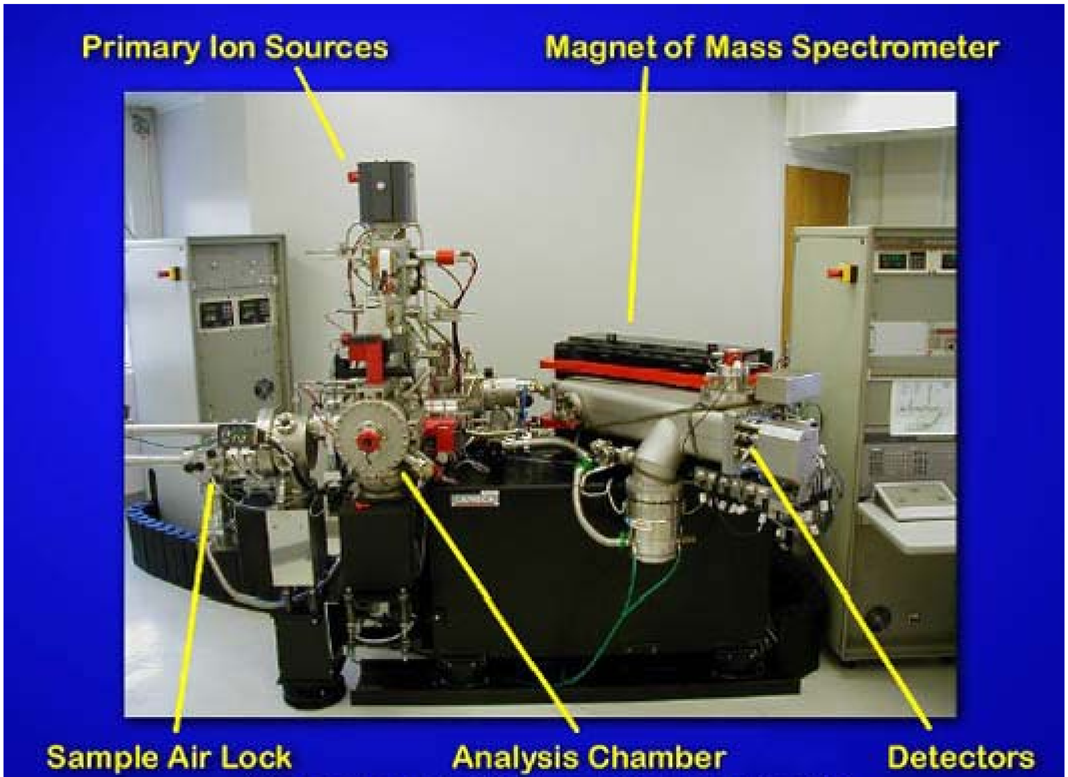
Astronomical observations and astrophysical theory tell us that the solar system formed by the collapse of a vast molecular cloud. A portion of the cloud collapsed into the primitive Sun surrounded by a disk of gas and dust. Planets, asteroids, and comets formed in this disk. One of the most exciting discoveries made by meteoriticists in NASA's Cosmochemistry Program is that meteorites contain tiny grains that once inhabited the interstellar cloud. These grains, called presolar grains or stardust, are typically only a few micrometers in diameter. They survived cloud collapse and heating in the accretion disk surrounding the nascent Sun. These relicts from stars give us a close-up look at the grains that inhabit interstellar space and offer a highly informative complement to astronomical observations of stars and interstellar clouds. They are minuscule bits of stars available for close study.

This mosaic of images taken by the Hubble Space Telescope shows a portion 2.5 light years wide of the Orion nebula, a huge star factory. It reveals at least 153 glowing protoplanetary disks in which stars and perhaps planets are forming. Regions like this are natural laboratories for studying how stars form, so astronomers view them in as many ways as possible to determine what chemical compounds make up the vast clouds. Studies of presolar grains in meteorites allow scientists to examine interstellar dust grains up close in the laboratory. Meteoriticists do astronomy with microscopes instead of telescopes.

Evidence that the grains are presolar comes from the relative abundances of the isotopes of common elements, such as silicon, oxygen, and carbon. The abundances of the isotopes differ from all samples of typical solar system material as found on the planets, asteroids (as sampled by meteorites), and comets. The aberrant isotopic compositions are caused by nuclear reactions in dying and exploding stars. All the isotopes of elements other than hydrogen and helium are synthesized by nuclear reactions in the interiors of stars. The isotopes are expelled into interstellar space by stellar winds or monumental explosions. Many condense into dust grains. These products of the life and death of stars mixed into the cloud from which the Sun developed, forming the raw materials for the solar system. Thus, the solar system is a mixture of materials from countless stars. During the formation of the solar system, most of the material was homogenized, giving the normal solar system isotopic compositions for the elements. A small percentage of grains escaped homogenization, giving us a window into the nature of stellar evolution and interstellar clouds.

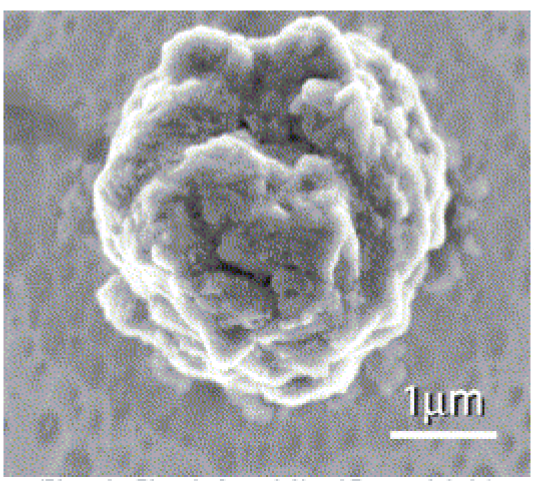
The Presolar Dust Grain Menagerie

As far back as the 1960s, there were hints that meteorites might house presolar grains. The clues came from analyses of bulk meteorites, but since the dust grains are only microns across, bulk analyses were too blunt a tool. It required development of high-tech instruments capable of analyzing the abundances of isotopes in micrometer-sized grains. The star analytical tool is secondary ion mass spectrometry, nicknamed "SIMS" or "ion microprobe". In SIMS analysis, a primary beam of high-energy ions is aimed at a small area of a sample, such as a mineral grain. The ion beam sputters atoms and molecules from the sample, creating charged ions (called secondary ions). The secondary ions are extracted with a strong electrostatic field and sorted by mass with a large magnet. A series of ion detectors counts the ions in different mass categories, giving the abundance in the original sample. (The raw data is corrected for assorted effects and normalized to well-analyzed standards.) The technique allows measurement of both elements and isotopes. A recent advance in instrumentation is the development of the NanoSIMS, which allows analyses of astonishingly small grains--only a few tens of nanometers (billionths of a meter) in diameter.



This is a photograph of the NanoSIMS at Washington University in St. Louis, the first such instrument in the world. The major parts are labeled. This state-of-the-art instrument enabled the work by Scott Messenger and his colleagues, and opens the door to numerous other discoveries in cosmochemistry. Photo courtesy of Frank Stadermann, Washington University.

The standard way of finding presolar grains is to dissolve away everything else in a meteorite. Stardust seekers crush chips of meteorites to a powder and pour various acid concoctions onto the powdered rock. Fortunately, some minerals that condense in stars are resistant to the strong solutions and remain in an undissolved residue. Of course, this might bias our sampling of presolar grains. Perhaps some of the easily dissolved grains are also stardust. Nevertheless, many of the residue grains are presolar. In other words, you burn down the haystack to find needles the size of pinpoints and analyze them with state-of-the-art analytical equipment.



(Photo by Rhonda Stroud, Naval Research Lab.)

A presolar (stardust) grain of silicon carbide, SiC. The grain is only 3 micrometers across. Photo by Rhonda Stroud, Naval Research Laboratory, and displayed in Nittler (2003).

Larry Nittler (Carnegie Institution of Washington) summarizes recent advances in research on stardust. The table below, from Nittler's paper, shows the types of presolar grains that have been discovered, their abundances, and sizes. There is some question about the amazingly small nanodiamonds being presolar, as they are too small to analyze individually, even with our advanced tools. A quick look at the table reveals that something is missing. There are no silicate minerals. Only carbides, silicides, nitrides, and oxides are in the certified list. This is surprising because silicon and oxygen, the key ingredients in silicates, are abundant elements in the solar system. Pick up a rock from the Earth, another planet, or an asteroid and you are almost certain to be hefting a bunch of silicate minerals.

Types of presolar grains extracted from meteorites by acid dissolution (from Nittler, 2003)

Type	Abundance (parts per million)	Size
Nanodiamond (C)	1400	2 nanometers
Silicon carbide (SiC)	14	0.1-20 micrometers
Graphite (C)	10	1-20 micrometers
Carbides of titanium, zirconium, molybdenum, ruthenium, and iron, and iron-nickel metal	Small grains inside presolar graphite	5-220 nanometers
Silicon nitride (Si_3N_4)	>0.002	About 1 micrometer
Corundum (Al_2O_3)	About 0.05	0.5-3 micrometers
Spinel ($MgAl_2O_4$)	<0.05	0.1-3 micrometers
Hibonite ($CaAl_{12}O_{19}$)	0.002	2 micrometers
Titanium dioxide (TiO_2)	One grain	About 1 micrometer

One reason for the absence of silicates in our collection of presolar grains in meteorites may be that we destroy them during the extraction process. Perhaps there are presolar silicates in meteorites, but they are dissolved away during the dissolution process. This is one of the reasons why Scott Messenger and his colleagues decided to search for presolar silicates in interplanetary dust particles.

Collecting Interplanetary Dust

An important source of information about the early solar system comes from the tiniest meteorites of all--interplanetary dust particles. As small, fast moving particles enter the atmosphere, they are gradually slowed down by atmospheric drag. Depending on their velocity and angle of entry, particles will be heated to greater or lesser extent. Some burn up entirely. Nevertheless, countless particles survive atmospheric entry and slowly drift around at high altitudes.

A NASA program collects the particles in the stratosphere using a high-flying ER-2 reconnaissance plane (basically the same as the U-2 spy plane). During each collecting flight, the plane carries circular collectors that are free of contaminants and smeared with silicone oil. The collectors remain flat against a wing until the plane reaches its cruising altitude of about 20 kilometers (about 65,000 feet). Once at cruising altitude, the collectors are deployed and gently-drifting particles hit the collectors, like bugs on a windshield. Most of the particles are extraterrestrial (bits of comets and asteroids), but some are volcanic dust particles, exhaust from solid rocket motors, and other types of earthly aerosols. The terrestrial dust particles are of great interest to atmospheric scientists because they cause chemical reactions in the atmosphere and reflect sunlight back into space.

ER-2 airplane in flight. Ultra-clean dust collectors are mounted under the wings (not shown in this view).

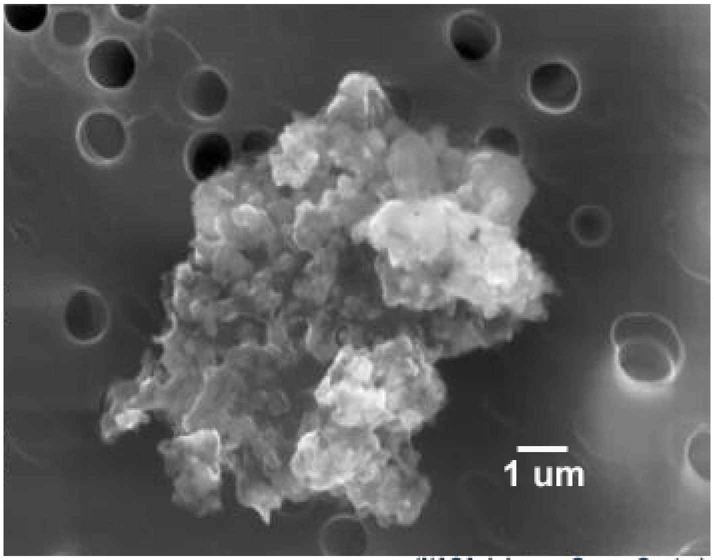
The particles are typically only 5 to 50 micrometers in diameter. Because a lot of terrestrial dust is in that size range, the samples are handled and stored in a special clean room at the Johnson Space Center. The room, dubbed the Cosmic Dust Laboratory, contains no more than 100 particles larger than 0.5 microns in any given cubic foot of air. Laboratory scientists wear special lint-free garments and use micromanipulators to handle the particles.

(NASA Johnson Space Center)

The cosmic dust laboratory at the Johnson Space Center. Laboratory scientists wear special garments, affectionately known as "bunny suits," to prevent contamination. Laboratory air is filtered so that each cubic foot of air contains no more than 100 particles larger than 0.5 micrometers.

Silicate Grain in Interplanetary Dust Particles

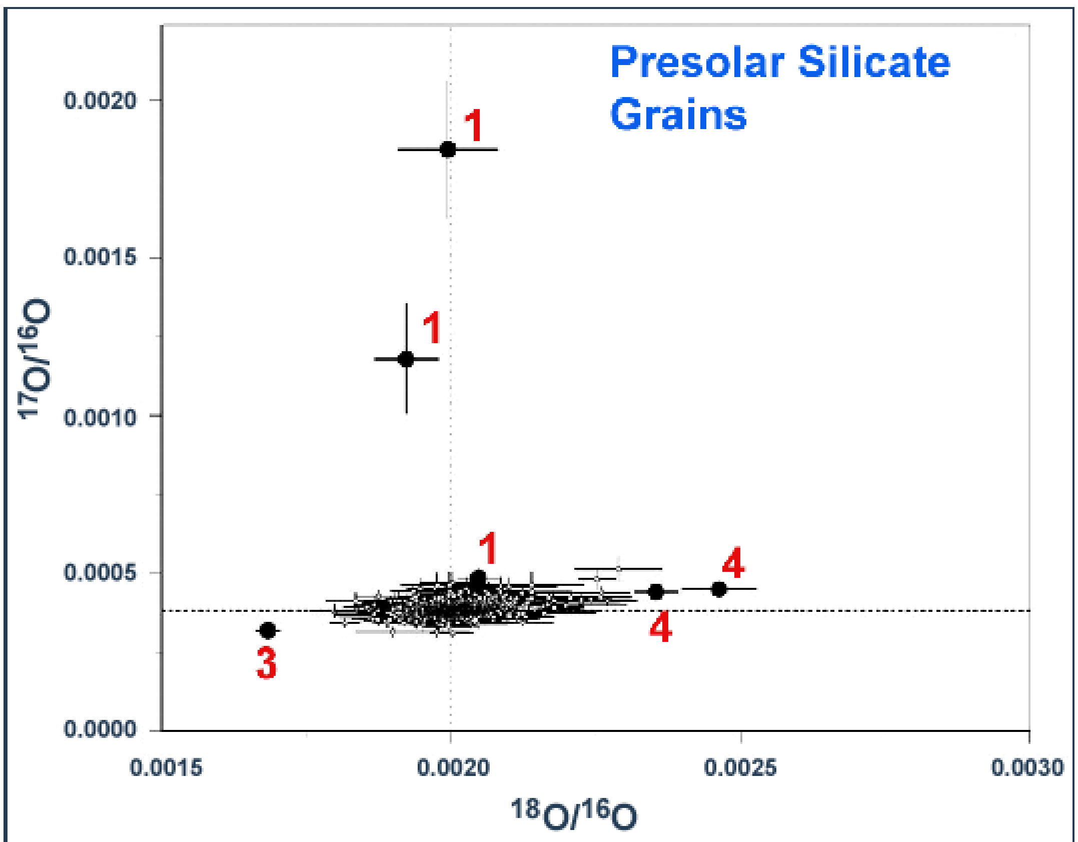
The development of the NanoSIMS makes it possible to search individual particles of interplanetary dust for presolar grains. Conventional SIMS instruments cannot analyze grains smaller than a few micrometers, but the grains making up a typical interplanetary dust particle (IDP) are much smaller. The higher spatial resolution of the NanoSIMS allows individual grains to be analyzed.



(NASA Johnson Space Center)

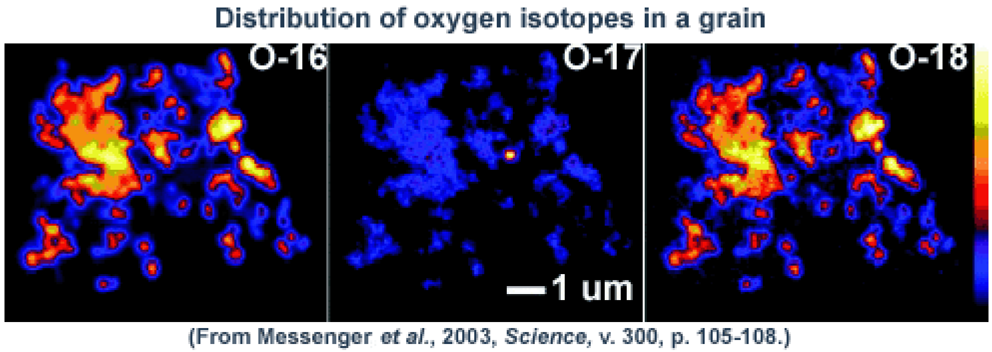
Typical cosmic dust particle. Note that the particle is composed of numerous small grains. Using the NanoSIMS at Washington University in St. Louis, Scott Messenger was able to determine the oxygen isotopic composition of individual grains in particles like this one.

Messenger measured the abundances of the three oxygen isotopes in 1031 grains in several interplanetary dust particles. Lindsay Keller of NASA Johnson Space Center determined the mineralogy of 113 grains using a transmission electron microscope. The electron microscope studies show that there is an assortment of silicate grains present, including both mineral grains and GEMS (glass with embedded metal and sulfide). All but six of the 1031 grains had oxygen isotopic compositions like typical solar system stuff. Those six special grains are presumed to be presolar because of the distinctive compositions of their oxygen isotopes. This does not mean that some of the other 1025 grains are not also presolar. They might have been modified in the solar nebula, erasing the evidence of their origin as stardust.



(From Messenger *et al.*, 2003, *Science*, v. 300, p. 105-108.)

Ratios of oxygen-17 and oxygen-18 to oxygen-16 allow us to distinguish presolar grains from typical solar system materials. The grains labeled are the six grains analyzed by Scott Messenger (out of 1031) that have oxygen compositions clearly different from the solar system, hence are presolar. The red numbers refer to groups of presolar grains identified from analyses of oxides separated from meteorites. Group 1 grains form in red giant or asymptotic giant branch (AGB) stars, and group 3 in metal-rich AGB stars. The stellar origins of group 4 stars are not known with certainty; they might be formed in type II supernovae.



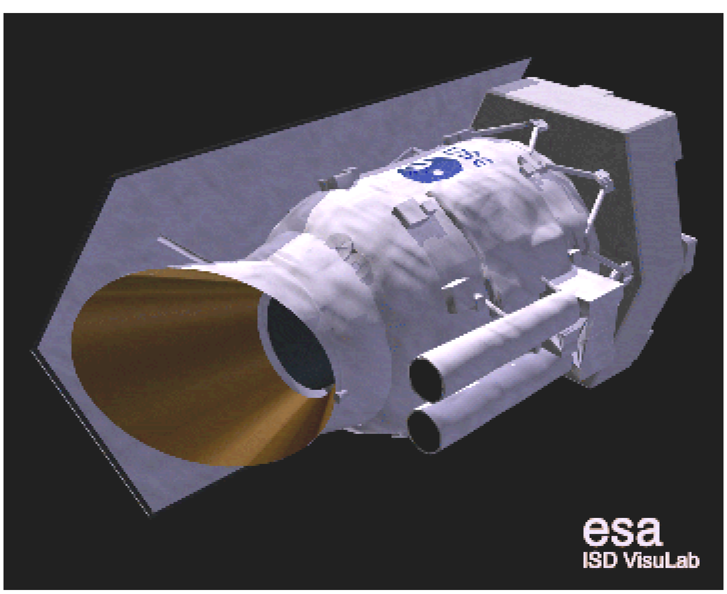
The NanoSIMS at Washington University allows investigators to make maps of the distribution of the oxygen isotopes in tiny particles. In this image, taken from the paper by Messenger and his colleagues, one of the grains in an interplanetary dust particle is clearly richer in oxygen-17. Its anomalous nature marks it as a candidate for being a presolar grain.

Using astrophysical theory and previous results on presolar oxide grains found in meteorites, Messenger and colleagues conclude that the six confirmed presolar grains formed in three different stellar environments (labeled in the diagram above). The groups reflect differences in the masses, ages, and chemical compositions of the stars in which they formed. Group 1 are rich in oxygen 17. They are thought to form in either red giant stars or stars known as asymptotic giant branch (AGB) stars. Red giants form when a star has used up its hydrogen by converting it to helium by nuclear fusion. The star cools and expands, becoming a red giant. This phase is followed by nuclear fusion of helium, forming heavier isotopes and elements. Once the helium is used up, pressures and temperatures inside stars smaller than 8 Suns are too low to allow further fusion to take place, so the star becomes just a hot ball of gas. Its outer portions expand, however, and it becomes a red giant again, known as an AGB star.

There was one group 3 grain, characterized by high amounts of oxygen-16, pushing it towards the left in the diagram above. These are thought to have formed in red giant and AGB stars particularly rich in what astronomers call "metals," which is any element heavier than helium. The two group 4 grains are low in oxygen-16, so plot on the right of the diagram. The environment in which they formed is unknown. Some scientists have speculated that they might form during supernova explosions. These happen in stars more massive than about 8 Suns. Instead of fizzling out as do smaller stars, fusion continues to occur in the deep interior, eventually producing heavy elements such as iron. Once iron is produced fusion halts and the core of the star collapses. When it rebounds, it sends out a strong shock wave that spews most of the star into interstellar space in an explosion known as a type II supernova.

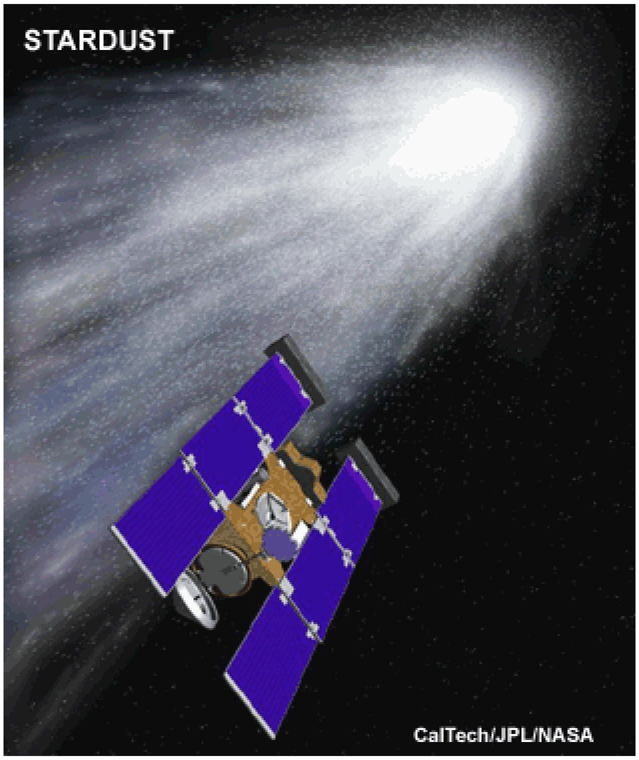
Checking with Telescopes

If the presolar grains found in interplanetary dust particles come mostly from red giants or AGB stars, is there evidence that grains of silicates and GEMS, the glassy objects that contain tiny grains of metallic iron and sulfide, are present in such stars? Astronomers have used the European Space Agency's Space Infrared Observatory [http://www.iso.vilspa.esa.es/] to make spectroscopic observations of red giants and AGB stars. They find spectral evidence for the presence of amorphous silicate (the glassy part of GEMS) and silicates such as enstatite and forsterite. Thus, Messenger's identification of presolar forsterite and GEMS is consistent with the astronomical observations.



The European Space Agency's Infrared Space Observatory was operational between November 1995 and May 1998. It allowed scientists to study distant stars, interstellar clouds, disks around stars, and galaxies at wavelengths between 2.5 and 240 micrometers, observations difficult or impossible to do from the ground because of the Earth's atmosphere.

Future studies of interplanetary dust using the NanoSIMS will allow for other isotopic measurements of other elements, a broader survey of the abundances of certifiable presolar grains, and detailed tests of astrophysical theories of how stars evolve and how grains are modified in interstellar space. The distinction between cosmochemistry and astronomy is blurring. They are complementary ways of looking at our origins, and both reach for the stars and back in time. And there's more to come. Besides continuing studies of interplanetary dust particles and meteorites, in 2006, the Stardust mission will return samples of interstellar dust and comet Wild 2, which should provide a treasure of bits of stars beyond the solar system.



Artist's rendering of the STARDUST spacecraft flying past comet Wild-2. The mission will also collect particles of interstellar dust.

Additional Resources

Infrared Space Observatory, a European Space Agency mission.

Messenger, S., Keller, L. P., Stadermann, F. J., Walker, R. M., and Zinner, E. (2003) Samples of stars beyond the solar system: silicate grains in interplanetary dust. Science vol. 300, p. 105-108.

Nittler, L. R. (2003) Presolar stardust in meteorites: recent advances and scientific frontiers. Earth and Planetary Science Letters, vol. 209, p. 259-273.

Stardust, NASA's comet sample return mission.

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