

Hot Idea

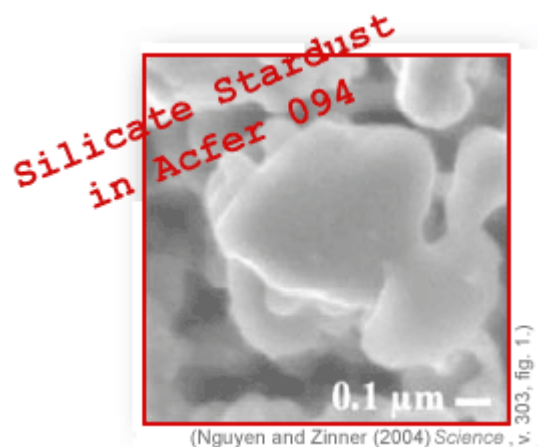
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Silicate Stardust in Meteorites

--- Silicates are the most abundant solids in disks around growing stars, but presolar silicates have not been found in even the most primitive meteorite--until now.

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One of the most exciting discoveries in cosmochemistry during the past 15 years is the presence of presolar grains in meteorites. They are identified by the unusual abundances of isotopes of oxygen, silicon, and other elements. Presolar grains, also called stardust, are exotic compounds such as diamond, graphite, aluminum oxide, and silicon carbide. Why are there no silicates? Spectroscopic observations of young stars show that silicates are abundant. This means that silicates are abundant in molecular clouds like the one in which the solar system formed. Cosmochemists wondered why do we not find silicates in the most primitive extraterrestrial materials: interplanetary dust particles (IDPs) and primitive chondrites. These materials are the least altered since they formed and if any preserved presolar silicate grains, IDPs and chondrites would. Were they all destroyed as the solar system formed? Or was it that we were looking for stardust in all the wrong places?

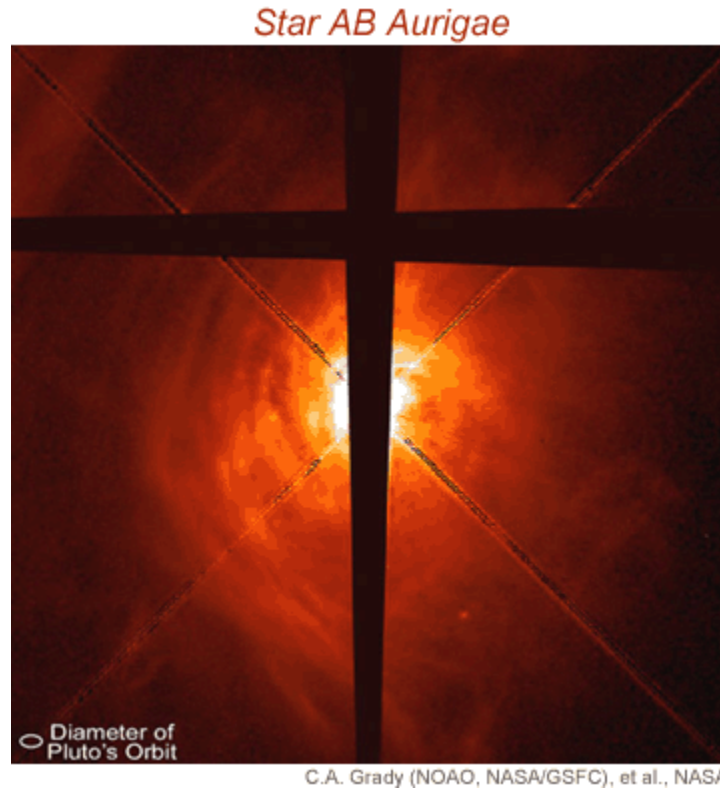
As we reported previously [see [PSRD](#) article [A New Type of Stardust](#)], Scott Messenger and colleagues have found silicates in IDPs. Now, researchers report finding presolar silicate grains in primitive chondritic meteorites. Ann Nguyen and Ernst Zinner (Washington University in St. Louis) and Kazuhide Nagashima and Hisayoshi Yurimoto (Tokyo Institute of Technology), with Alexander Krot (University of Hawai'i) used advanced instrumentation to image the isotopic compositions of small regions of the Acfer 094 carbonaceous chondrite and found several silicate grains with isotopically anomalous oxygen isotopes, a clear indicator of presolar origin. Nagashima and his colleagues also investigated the primitive CR2 carbonaceous chondrite Northwest Africa 530, finding presolar grains in it as well. The grains will shed (star)light on the histories of the stars in which they formed. The relative abundances of presolar silicates in different types of meteorites will help cosmochemists understand the processes of heating and chemical reaction that took place in the cloud of gas and dust in which the Sun and planets formed. The significance of this work is discussed in a lucid editorial by Sara Russell (Natural History Museum, London.)

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- Nguyen, A. N. and Zinner, E. (2004) Discovery of ancient silicate stardust in a meteorite. *Science*, v. 303, p. 1496-1499.
- Nagashima, K., Krot, A. N., and Yurimoto, H. (2004) Stardust silicates from primitive meteorites. *Nature*, v. 428, p. 921-924.
- Russell, S. S. (2004) Stars in stones. *Nature*, v. 428, p. 903-904.

Abundant Silicates

Telescopic observations of the disks around young stars and materials surrounding other stars indicate an abundance of both amorphous and crystalline silicates dust grains. Crystalline versions are magnesium-rich olivine and pyroxene. This is not particularly surprising. The Earth and other inner planets are composed mostly of silicates. Meteorites and the asteroids they come from are mostly silicates. The tiny grains composing interplanetary dust particles (IDPs) are mostly silicates. Comets have been called dirty snowballs--the dirt is silicate. Silicates abound.



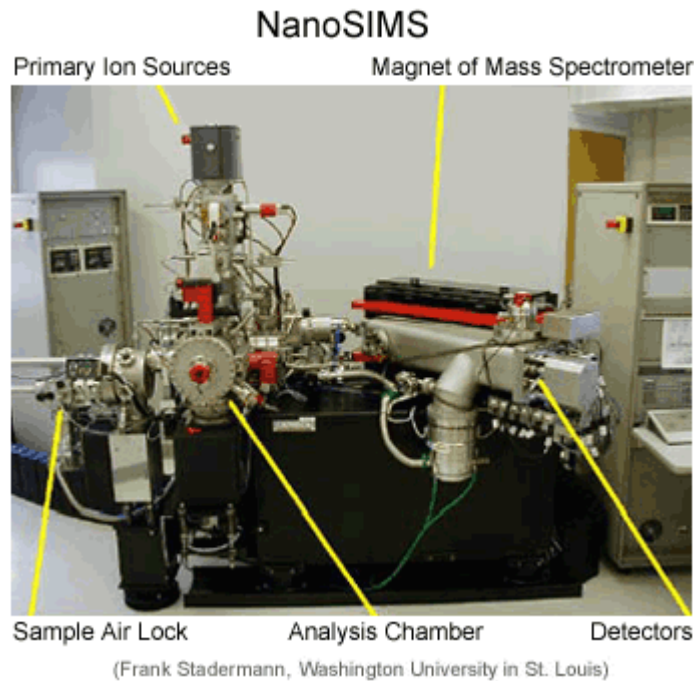
Photograph taken by the Hubble Space Telescope of a swirling disk of gas and dust surrounding the young star AB Aurigae. The black bars are part of the coronagraphic system used by Hubble. Spectroscopic observations show that silicate compounds are abundant in disks like this one. ([High resolution version](#) will open in a new window.)

If silicates are so common, why have all the presolar grains we find in meteorites been oxides, carbides, nitrides, and carbon compounds? One explanation is that until recently presolar grains were found by using strong acids to dissolve 99.9% of the meteorite, leaving a residue of acid-resistant grains. Silicates are not resistant to acids, so were lost during the process. Another reason is that silicates are abundant, but presolar silicates make up only a tiny fraction of all the silicates. In contrast, all silicon carbide grains are presolar. It would be better to simply measure the isotopic compositions of tiny grains in meteorites and IDPs until we found silicates with anomalous isotopic compositions, or concluded that there are none. But this would require measuring thousands of grains, many only a micrometer or less across, an impossible task--until technological advances made the search possible.

Technological Innovations

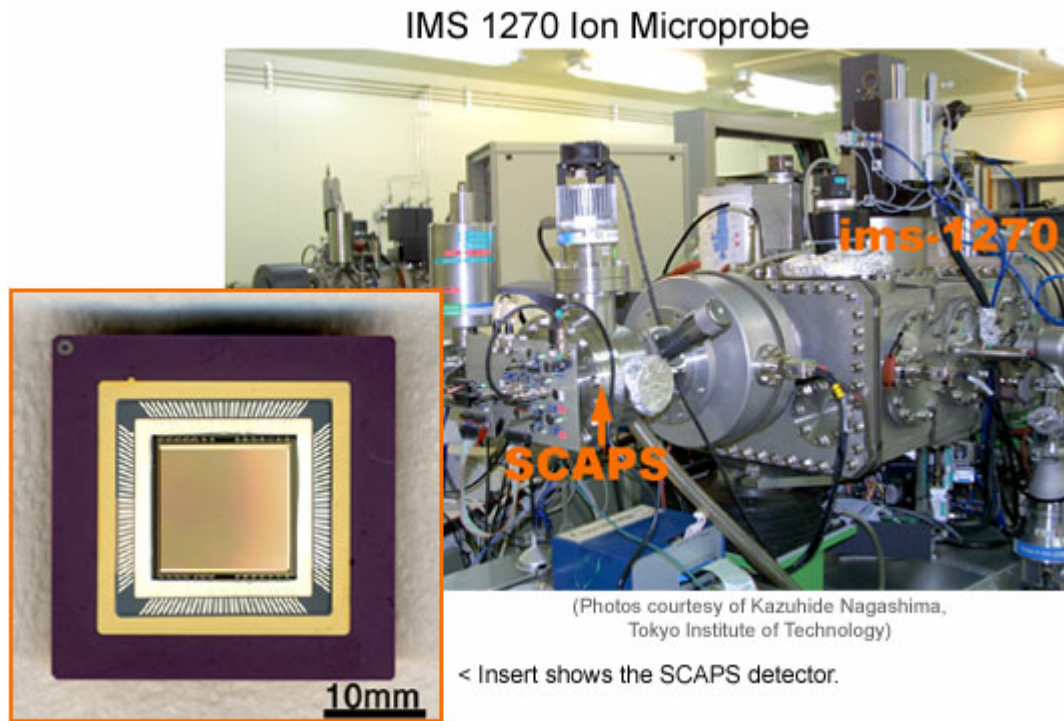
The ideal way to find small presolar survivors of solar system formation is to be able to image a sample using a special light that causes presolar grains to light up, as if they were using microscopic flares to help us locate them. That is more or less what advances in instrumentation allow us to do. Ann Nguyen and Ernst Zinner used the latest type of ion microprobe, the NanoSIMS at Washington University in St. Louis. SIMS stands for secondary ion mass spectrometry, and the "Nano" refers to the tiny size of the ion beam used to sputter atoms from a sample. The beam size can be as small as 30 nanometers in diameter, so the abundances of isotopes can be measured in individual submicron grains. The NanoSIMS is manufactured by Cameca Instruments, Inc. (Paris, France), but almost all instruments purchased by cosmochemists are modified substantially to make them even more capable.

Besides having a tiny beam size and excellent sensitivity, the NanoSIMS can measure up to five isotopes simultaneously, allowing precise measurements on the identical spot. Most important for the hunt for presolar silicates is the ability to raster the beam over a region packed with hundreds or thousands of grains, allowing automatic measurements of a large number of grains in a relatively short time. By analyzing oxygen isotopes (^{16}O , ^{17}O , and ^{18}O), the rare presolar grains will be conspicuous in a sea of grains with normal solar system oxygen isotopic composition, like supernovae in the normal starry sky.



This is a photograph of the Cameca 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 makes it possible to measure the isotopic compositions of extremely small grains in extraterrestrial materials. Ann Nguyen and Ernst Zinner used this instrument to discover presolar silicate grains in the meteorite Acfer 094.

Kazu Nagashima and Yoshi Yurimoto used a different type of ion microprobe, the Cameca IMS 1270. This instrument has great sensitivity, but it does not have the required nanometer beam size (grains must be about 10 micrometers or larger). To get around this problem, they and their colleagues at TiTech devised a whole new ion detection system, building a solid-state detector called SCAPS. Working backwards, APS refers to "active pixel sensor." The C stands for CMOS, or complementary metal oxide semiconductor; in short, a transistor. The S stands for stacked, referring to the arrangement of metal layers for ion-irradiation stacked on the APS. The device allows for sensitive measurements and no distortions in the signal across the detector, and can measure the isotopic compositions of oxygen and other elements in grains as small as about 1 micrometer, but can detect presolar grains as small as about 100 nanometers.

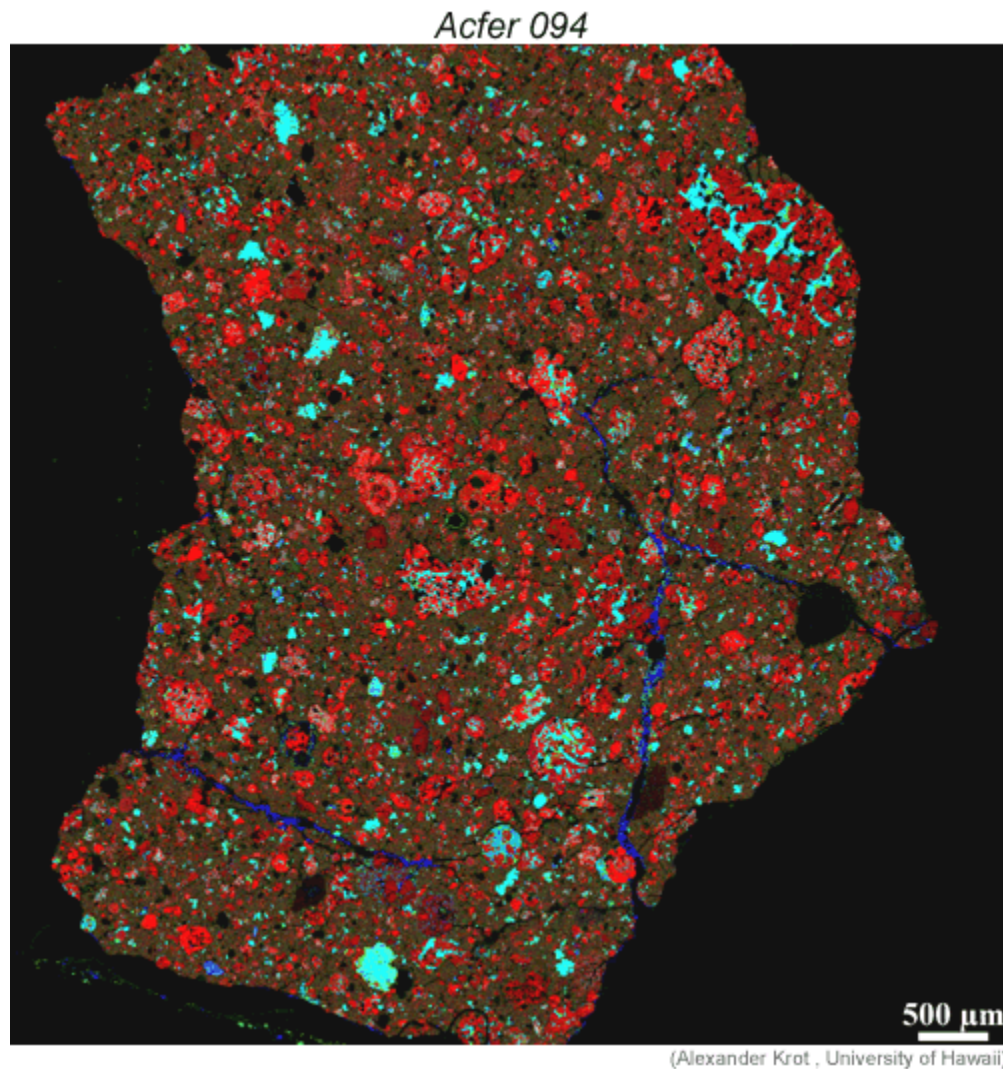


Isotope microscope system consisting of the SCAPS and IMS 1270 ion microprobe. The SCAPS detector is located on the image-focusing plane inside the vacuum of the ion microprobe.

The Right Extraterrestrial Materials

Formation of the solar system involved heating of the cloud of gas and dust surrounding the nascent Sun. This caused some silicate grains to vaporize and others to react chemically. As planetesimals formed, they heated up by decay of short-lived isotopes such as ^{26}Al or possibly by impact, causing additional chemical reactions including those driven by water. Thus, much of the record of presolar silicates has been destroyed. To find them we must search in the least altered materials we can find.

Scott Messenger and his colleagues at Washington University in St. Louis (including Ernst Zinner) searched for presolar grains in IDPs (see [PSRD article A New Type of Stardust](#)). Ann Nguyen and Zinner, and Kazu Nagashima and his colleagues obtained samples of one of the most primitive carbonaceous chondrites, Acfer 094. This meteorite was found in the Sahara desert, an excellent place for preservation since the meteorite arrived on Earth. More importantly, Ansgar Greshake (Wilhelms-Universität, Münster, Germany) showed through detailed electron microscopy that the meteorite is exceptionally primitive and has little or no aqueous alteration. Its fine-grained matrix contains a substantial amount of amorphous silicate material that contains tiny (few hundred nanometers) grains of olivine, low-Ca pyroxene, and metallic Fe-Ni. The meteorite contains the highest content of presolar SiC (obtained by the whole-rock dissolution method), leading Greshake to suggest that some of the silicates may also be presolar.



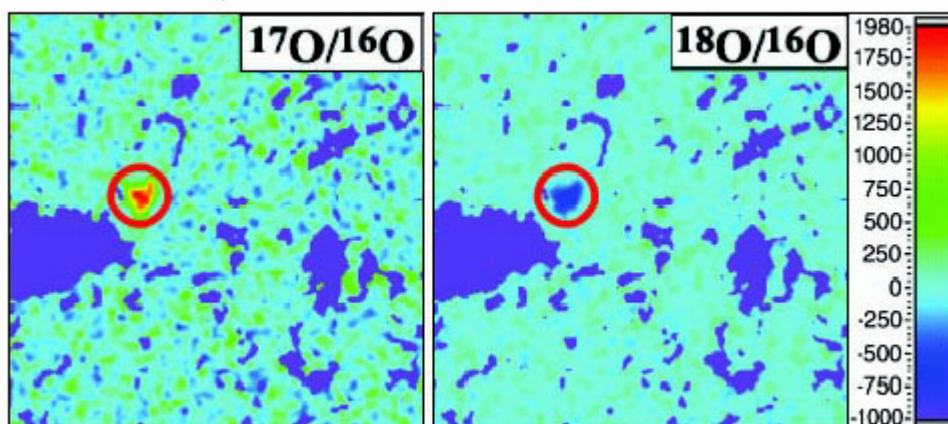
Map of Acfer 094 made from element abundances determined with an electron microprobe. The presolar grains were found in the fine-grained matrix (colored brown). Ca,Al-rich inclusions are colored blue. Chondrules and amoeboid olivine aggregates are colored red. The Acfer 094 meteorite is one of the most primitive carbonaceous chondrites known, making it a logical target for the search for presolar silicates.

Kazu Nagashima and his colleagues studied Acfer 094, too, but also searched for presolar silicates in Northwest Africa (NWA) 530. This meteorite is also a very primitive carbonaceous chondrite that experienced some very mild aqueous alteration, but no heating.

Silicate Stardust

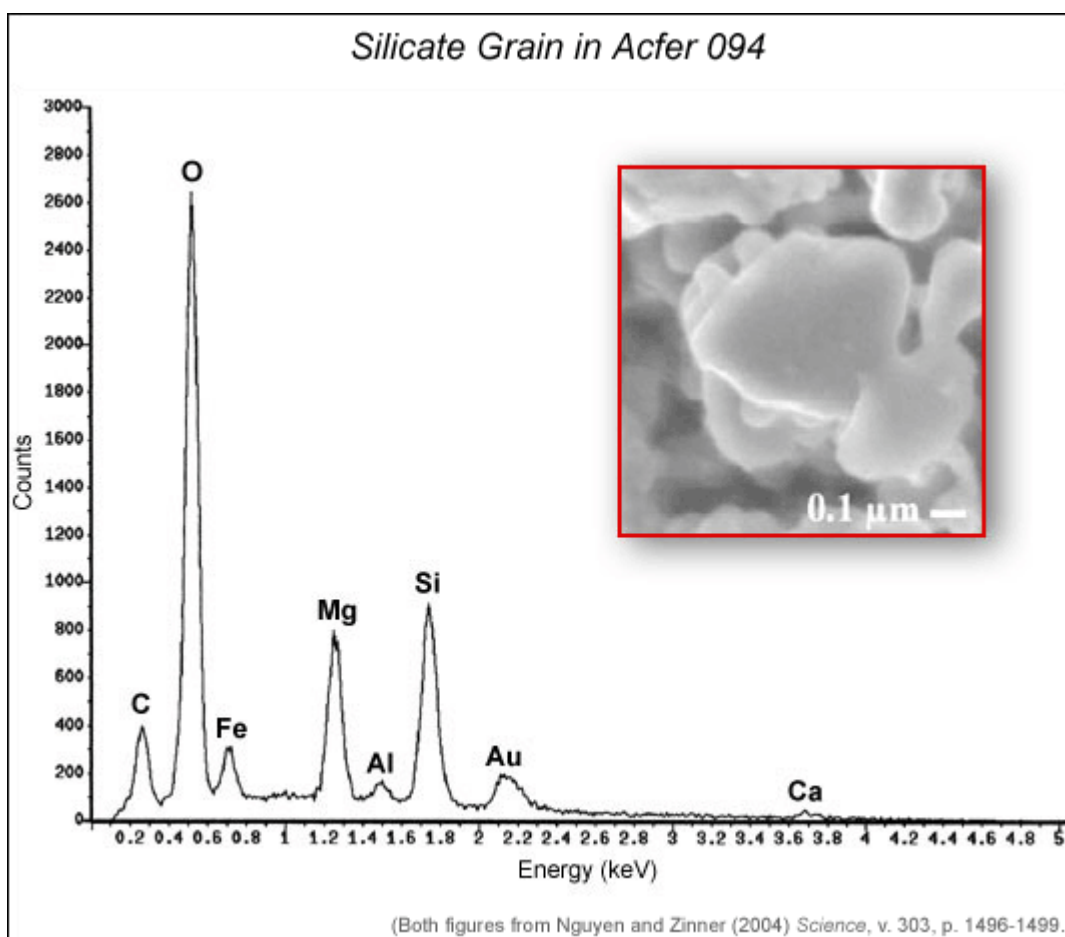
The new technologies and well-chosen primitive samples have led to the unambiguous discovery of presolar silicate grains in chondritic meteorites. They show up on images of the $^{17}\text{O}/^{16}\text{O}$ ratio and $^{18}\text{O}/^{16}\text{O}$ ratio, and other measurements prove that the grains are silicates.

O-isotopes in an Anomalous Grain in Acfer 094



(Ann Nguyen, Washington University in St. Louis)

Images of the isotopic composition of a small region (only 100 square micrometers) in Acfer 094. The scale on the right is in deviations from solar oxygen isotopic composition in parts per thousand. Most of the material has typical solar system compositions, averaging a zero deviation from solar. The grain identified with the red circle, however, stands out by being enriched in ^{17}O and depleted in ^{18}O compared to solar values; it is a presolar grain. Chemical analyses show that it is a silicate (see graph below).

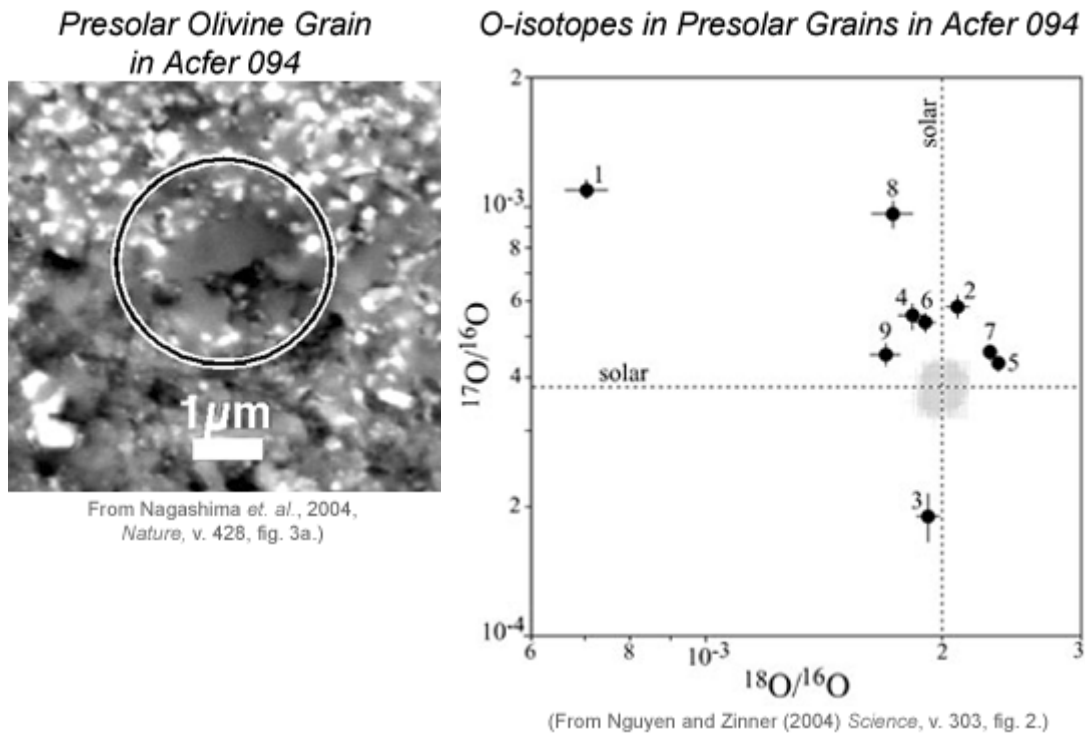


(Both figures from Nguyen and Zinner (2004) *Science*, v. 303, p. 1496-1499.)

Scanning electron microscope (SEM) image (**insert**) of the presolar grain shown above, with the spectrum of x-rays emitted from the particle due to electron bombardment in the scanning electron microscope (SEM). The tall peaks for oxygen and silicon show that it is a silicate. The presence of magnesium and calcium indicate that it is a pyroxene. Carbon is a contaminate in the SEM; gold is from the substrate the sample was placed on.

Nagashima and his colleagues surveyed a total area of 44,100 square microns in each meteorite, and Nguyen and Zinner surveyed 5750 square microns in Acfer 094. In total they found 15 grains that are clearly different from average solar material in their oxygen isotopic compositions. For Acfer, this translates into an abundance of 30 to 40 parts per

million, which is much more than the abundance of non-silicate presolar grains. Silicon carbide is the most abundant (except for nanodiamonds, whose presolar origin is somewhat disputed), at 14 parts per million. So, not only did our silicate searchers find presolar silicate grains, they found that silicates are more abundant than oxides, carbides, and nitrides.



LEFT: Backscattered electron image of a presolar olivine grain in the Acfer 094 chondrite. The SCAPS detector in the Cameca IMS 1270 allows in situ isotope imaging of such small grains. (Courtesy of Kazu Nagashima.) **RIGHT:** Oxygen isotopic compositions of nine anomalous (hence presolar) grains in Acfer 094 from Nguyen and Zinner. The large cloud of points centered at the intersection of the dashed lines is where most components in chondrites and IDPs plots--it is average solar system material. The numbered grains are significantly different in composition from ordinary solar system, and their positions on the diagram suggest origins in different types of stellar environments.

Continued searches for presolar grains in meteorites will undoubtedly lead to additional tiny samples. Their isotopic compositions will allow cosmochemists and astrophysicists to test models of star formation and evolution. Variation in abundances in different types of meteorites and subtle elemental differences among the populations of presolar grains in different meteorites will help us understand the extent of heating and chemical reaction during formation of the solar system.

None of this would be possible without the great leaps forward in analytical instrumentation. There is an essential synergism between cosmochemistry and instrument development. One drives the other. As our understanding of extraterrestrial materials improves, we ask sophisticated questions that require better analytical capabilities to answer. Cosmochemists and other scientists and engineers develop new tools, such as the SCAPS detector, allowing the questions to be addressed. Of course, this leads to other questions. It is an exciting cycle of discovery and instrument innovation, punctuated by an influx of new extraterrestrial materials--Apollo samples 25 years ago, Antarctic meteorites, recognition of meteorites from Mars, collection of IDPs in the stratosphere, return of the samples from the Stardust mission.

Additional Resources

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