Sands of time: Silica stardust in meteorites

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It has become a common and poetic notion that we are the children of stars. Indeed, the atoms in our bodies were formed by nuclear reactions in the dying cores of suns. Our solar system formed about 4.55 billion years ago from the collapse of a giant cloud of gas and dust that came from dying stars predating our own sun. What resulted was a giant, rotating disc that caused mass to collect in the centre and form our sun. What could have caused the gravitational collapse that formed our solar system? A nearby supernova explosion could have done it; perhaps even the same supernova that flooded the presolar cloud with gas and dust. I have heard professed that we are "all made of stardust". However, our early solar system was a hostile place; so hostile, that half a century ago it was believed that "stardust" could not have survived. Stardust, or presolar grains as they are scientifically known, are tiny time capsules; remnants of a time before our solar system. The tiny fraction of presolar dust that did survive became trapped in primitive meteorites. Presolar grains are relics of a variety of stars including novae, supernovae and red giants. They offer the opportunity to study nucleosynthetic processes of different stars and their contributions to the presolar dust population of our solar system. A grain the size of a speck of dust can provide more detail about stellar processes than even our most powerful telescopes.

Presolar Grains in Meteorites

Presolar grains are formed from the nucleosynthetic products of stars, which survived the collapse of the presolar cloud and became trapped in primitive meteorites (Fig. 1). The first presolar grains discovered were nanodiamonds in 1987.[1] Since then, scientists have found grains of more than ten different minerals in primitive meteorites. Abundant presolar minerals include diamond, silicon carbide, graphite, corundum, spinel and silicates.

Presolar grains are of the order of nanometres to several micrometers in size. They are identified by their unusual, "alien" compositions, that differ from the material in which they are embedded. The grains are isolated from the bulk meteorite by a series of acid and oxidising reagent treatments, which dissolve ~99% of the rock's silicates and organic materials.[2] The grains of interest are then removed from the residue by colloidal or density separation. Since their discovery, several thousand presolar grains have been analysed, each contributing vital information about the stars that gave birth to our solar system.[3]

The Legacy of the Stars: Red Giants and Supernovae

Giant stars are steadily pumping dust into our solar system. Thus, it is no surprise that the majority of known presolar grains appear to have condensed from the nucleosynthetic products of giant stars.

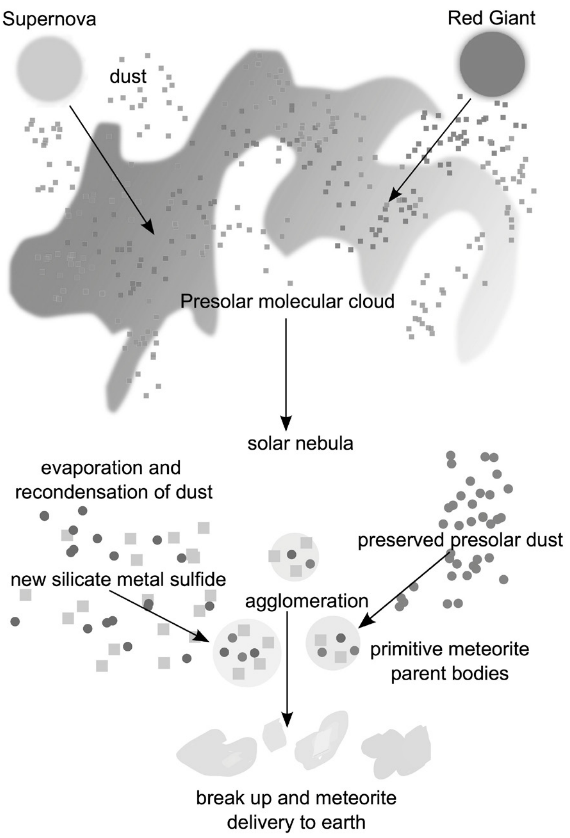

Fig. 1. Before our solar system began, dying giant stars such as red giants and supernovae produced dust grains that were ejected into the presolar cloud. A tiny amount of the original stardust survived the formation of our early solar system. This stardust became trapped, along with new silicate material, in the parent bodies of primitive meteorites. Some of these meteorites were delivered to earth where the presolar stardust may be extracted and analysed. Adapted from Lodders & Amari (reference 3).

Stars have a life cycle that can be tracked in terms of their temperature and brightness. Giant stars occur in the late stages of stellar evolution. Red giants originate from dwarf stars with masses of 1 – 8 times that of our sun. For most of its life a star will burn hydrogen (H) to helium (He) in its core. Once the H is exhausted, the He core contracts and increases in temperature, igniting H-burning in an envelope around the He-core. This causes the radius of the star to expand and the star moves on to the red giant branch (RGB) phase. During the RGB stage, He-burning and nuclear reactions in the core create carbon (C) and oxygen (O), resulting in a C- and O-rich core. Once the He is exhausted, the star enters the asymptotic giant branch (AGB) phase. Each of these giant stars produces different types of presolar grains with characteristic compositions. Presolar grains from AGB and red giant stars are the most abundant and most widely studied of all known stardust.

Massive stars, greater than eight times the mass of our sun, end their lives in spectacular stellar explosions (supernovae), spewing their nucleosynthetic products into space. After the production of carbon and oxygen, massive stars are able to sustain further nucleosynthetic reactions, forming neon, silicon and sulfur, among other elements, terminating at nickel. Before a supernova explosion, the star consists of onion-like layers of different elements that are a result of nuclear reactions at varying temperatures (Fig. 2). The temperature of the star increases toward the core, so different elements exist in zones from the core to the surface. These zones are named after the dominant element present: nickel (Ni), silicon/sulfur (Si/S), oxygen-rich zones: oxygen/silicon (O/Si), oxygen/neon (O/Ne) and oxygen/carbon (O/C), helium/carbon (He/C) and helium/neon (He/Ne) zones surrounded by an H-envelope. Within these zones, the atoms that make up different presolar minerals are formed.

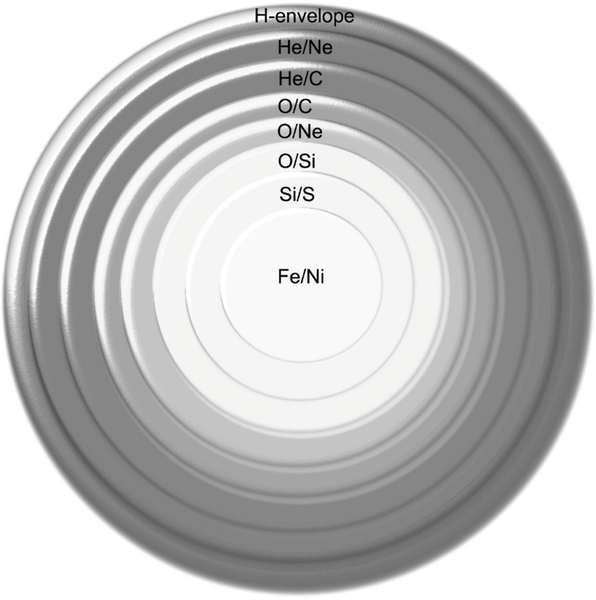

Fig. 2. Onion model depicting the layers of a supernova before its explosion. Nuclear fusion reactions result in layers of elements of increasing mass towards the core where the star is hottest. Theoretical models can be used to predict in which layers particular presolar minerals could form.

Stellar Fingerprints: the Importance of Isotopes

Presolar grains have different "fingerprints" from those formed after the birth of our solar system. These fingerprints come in the form of very tiny differences in the masses of the elements that make up the grains. Grains from ancient stars have highly unusual isotopic signatures that cannot be explained by any processes occurring in our solar system.[3] Furthermore, different stars can produce different proportions of isotopes. This means that isotopes, and the characteristic signature they impart on presolar grains, are the key to unlocking secrets of our early solar system.

Oxygen isotopes are a key identifier of presolar grains. A classification system was developed to characterise oxide-silicate grains into four groups based on their oxygen isotopic composition.[4] These four groups (Fig. 3) reflect the different stellar origins or nucleosynthetic processes that may have produced the grains.[5]

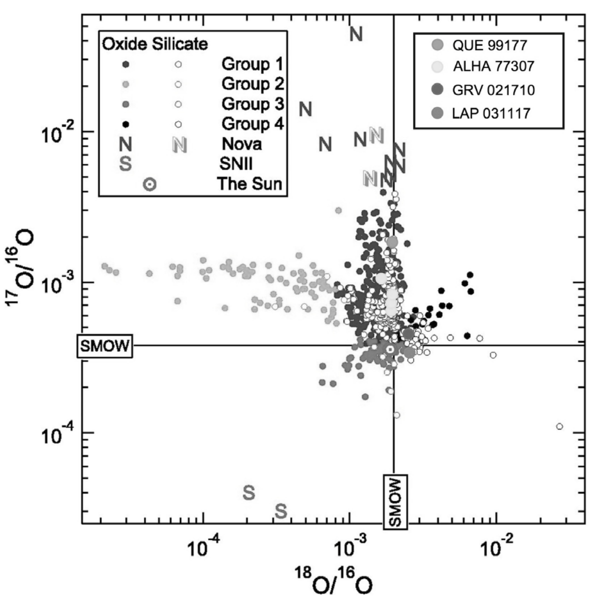

Fig. 3. A three-isotope plot displaying oxygen isotopic compositions of presolar oxide-silicate grains and their classification into four groups. SMOW (standard mean ocean water) oxygen isotopic composition is historically used to represent the solar system average. The silica grains thought to come from supernovae (GRV 021710 and LAP 031117) plot with the Group 4 oxide grains. The silica grains from QUE 99177 and ALHA 77307 are also plotted and fall amongst the group 1 grains. These grains are believed to have originated from AGB or red giant stars (adapted from Davis (ref. 5).

Presolar Sand, the Mythical Condensate

One mineral we are all familiar with is silicon dioxide (silica, SiO_2), or "sand". Initially, thermodynamic calculations predicted that silica would not condense in stellar environments. From these models, it was expected that silicon would be completely consumed by forming magnesium and iron rich silicates. In fact, presolar sand was dubbed the "mythical condensate" by researchers at the University of Washington in St Louis. Much to their surprise, presolar silica grains were discovered by researchers at the very same university. In 2009, Christine Floss and Frank Stadermann discovered the first silica grain in a primitive meteorite QUE 99177.[6] Within the next year, four more such grains were found in ALHA 77307.[7] However, all of these grains were enriched in ^{17}O relative to the solar abundance and had close to solar $^{18}O/^{16}O$ ratios (Fig. 3). This oxygen isotope fingerprint indicates that these grains probably originated from a red giant or AGB star. Not long after this discovery, graduate students in Christine Floss' group discovered two more silica grains in primitive Antarctic meteorites LaPaz 031117 and Grove Mountains 021710.[8] These grains were unusual. Their oxygen isotopic composition was different from those discovered in QUE 99177 and ALHA 77307. These grains were enriched in ^{18}O and had subsolar $^{17}O/^{16}O$, meaning they must have been formed in core-collapse supernovae (Fig. 3). In fact, the oxygen isotopic signatures of both grains were so similar that they were probably produced in the same supernova explosion; perhaps even the same supernova that was thought to trigger the collapse of the presolar cloud and form our solar system.

Calculations had suggested that the oxygen isotopic composition of many Group 4 oxide and silicate grains would result from mixing of ^{16}O-rich material from the O-rich layers with material from the He/C zone and the H envelope.[9] It was suggested that silica might originate from inner O and Si/S layers of supernovae. If silica grains do condense in the O-rich layers, the grains should exhibit large excesses in ^{16}O. However, the grains identified in LAP 031117 and Grove Mountains 021710 had excess ^{18}O. The ^{18}O enrichment in these grains could be reproduced by mixing small amounts of material from the O-rich inner zones and the ^{18}O rich He/C zones with large amounts of material from the hydrogen envelope. In fact, most presolar oxide and silicate grains from supernovae have shown excesses in ^{18}O instead of ^{16}O, much like these silica grains; the reason for the discrepancy remains unclear.

Perhaps we are not all made of stardust, but true stardust does exist — trapped within primitive meteorites: pure samples of stars. The presolar silica grains discovered at the University of Washington in St Louis are a snapshot of a supernova. Whether they are from a supernova that caused the formation of our solar system, our planet and ultimately the star children that inhabit it, we should take with a grain of sand.

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