SILICON CARBIDE DUST? THE ANSWER IS BLOWIN' IN THE WIND

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Silicon carbide (SiC) minerals, which were argued to condense in stellar winds, were first isolated and imaged in 1987 (Bernatowicz et al. 1987). However, their existence in meteorites had been speculated from extensive noble gas studies. These studies suggested that SiC minerals are the carrier phases of the exotic ^{128,130}Xe and ^{22}Ne isotopic anomalies that can be found in primitive meteorites (e.g., Anders and Zinner 1993). In fact, SiC stardust does carry large isotopic anomalies, up to 4 orders of magnitude, both in light mass elements (e.g., carbon, nitrogen) and in medium mass elements (e.g., magnesium, iron, titanium). These anomalies can only be produced in stars through nuclear reactions occurring at extreme temperatures, by which the structure of the atomic nucleus is altered. The extreme isotopic anomalies in the SiC dust grains were not completely homogenized during the first 10 million years of planet formation and Solar System evolution, so they have kept their compositions intact until today. The dust grains carrying these enormous anomalies can be identified in extraterrestrial rocks that fall to Earth.

Not all meteorites contain stellar dust grains. They are only present in the fine-grained matrix in primitive chondrite meteorites, which are rich in carbon and other organic materials. This is why samples from carbonaceous type (C-type) asteroids Bennu and Ryugu, subjects of ongoing missions, are such an exciting prospect. The abundance of stardust in meteorites is a function of the temperature and fluid–rock reactions in the bulk of the meteoritic rock, and the best samples for stardust searches are the least-altered carbonaceous meteorites. Furthermore, SiC stardust grains can be identified in meteorites through a chemical isolation technique that has been applied to only a few meteorites (e.g., Murchison, Murray, and Tieschitz). As a result, most stardust grains that have been studied in detail through multi-isotope characterization are derived from one of these meteorites.

Detailed isotopic characterization of the rare and refractory SiC minerals found in meteorites are performed in various laboratories around the globe (e.g., Zinner 2014; Nittler and Ciesla 2017, and references therein). Such studies have greatly enhanced our understanding of the stellar environment around our proto-Sun, the input from different kinds of stars, nucleosynthesis in stars, kinetic processes in the interiors of stars, alteration in the interstellar medium, and aqueous and thermal processes on asteroid bodies. One such stellar source of dust grains is Type II core-collapse supernova explosions that occur when a >8 solar-mass star explodes after having already formed oxygen, magnesium, silicon, sulfur, argon, and calcium in the neon- and oxygen-burning zones of the star's interior. Once the star fuses silicon to form an iron core, energy production halts because iron has the largest nuclear binding energy per nucleon. Because the pressure from the overlying gas is no longer balanced by fusion in the core, implosion of the central core occurs and raises the core temperature to 5 billion Kelvin. Photons emitted from the core dissociate the iron atoms, which break apart into helium nuclei and allows for the compression and formation of a nucleon gas and the formation of a proto-neutron star that can resist the gravitational collapse. As the proto-neutron star halts the core collapse, it recoils. This release of gravitational potential energy generates a shockwave that ejects the remaining stellar material and leaves behind a neutron star. When the shock wave collides with the inner layers, it ejects matter outwards at ~10,000 kilometers per second. This is known as the core bounce. This shock wave is quickly stalled because energy is lost, but it gets reheated by the capture of energetic neutrinos near the proto-neutron star. Ejection of these neutrinos rapidly drains energy from the core. Once core bounce has occurred, further neutrino emission takes place in the proto-neutron star, and it is this neutrino-heating mechanism that revives the stalled shock front. The core-emitted neutrinos contain ~10^{46} J of energy. About 1% of these neutrinos are captured by material within the stalled shock wave. The shock heats material as it travels outward, resulting in explosive nuclear burning that produces abundant amounts of ^{13}C, ^{15}N, ^{26}Al, and ^{44,47,49}Ti isotope species (Fig. 1). The seed nuclei can be heated to temperatures of several 10^9 K within the hearts of core-collapse supernova explosions, also leading to exotic iron-group elements.

It is from the resulting ejecta of a core-collapse supernova that a fraction of the stellar dust—now present in the Solar System—condensed. These dust grains show extremely large enrichments in the isotopes ^{13}C, ^{15}N, ^{26}Al, and ^{30}Si, the origins of which have long been proposed to be classical novae (Amari et al. 2001). Less energetic classical nova outbursts occur in close binary systems containing a carbon–oxygen or oxygen–neon white dwarf and a Sun-like companion. Bose and Starrfield (2019) had discussed this possibility by imposing different mixing conditions on novel carbon–oxygen nova models and comparing their isotope yields to SiC stardust. They showed that the best solutions were achieved when there was a mixing of material after thermonuclear runaway had occurred. However, the compositions of the dust in classical nova

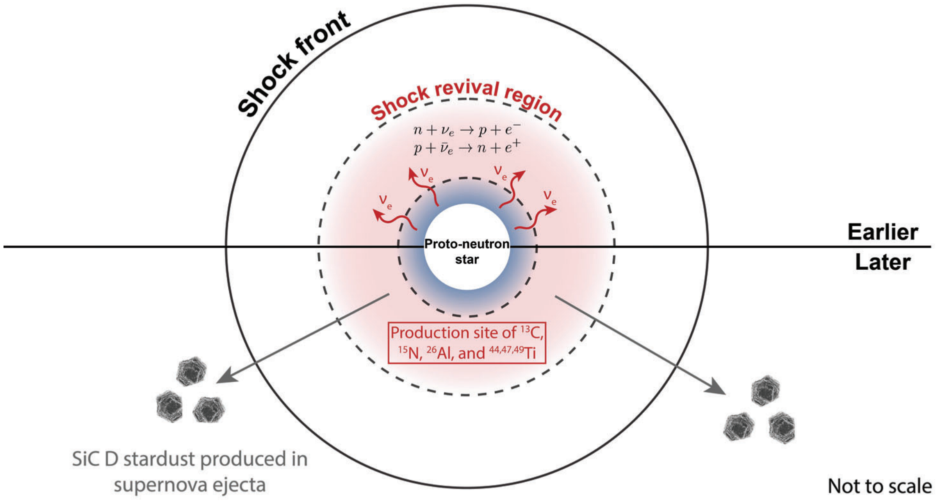

Figure 1 The formation and location of a revived shock wave due to enhanced neutrino production in a supernova explosion results in abundant ^{13}C, ^{15}N, ^{26}Al and several Ti isotope species. The red region is heated while the blue region is cooled by neutrino production and transport. The SiC D grains form in winds consisting of the innermost ejecta in a 15 solar-mass core-collapse supernova. The SiC grain secondary electron image is from Zinner (2014).

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outbursts are more extreme than those observed in stardust grains (FIG. 2). Possible origins for selected grains in core collapse supernovae was discussed because of the existence of both proton- and neutron-capture isotopic signatures in 1-D models, indicating heterogeneous hydrogen ingestion into the He shell in pre-supernova stars (Liu et al. 2016). Schulte et al. (2021) compared the isotopic compositions of these rare stardust grains to new 3-D core-collapse supernova simulations created by Patrick Young of Arizona State University (FIG. 2). They found that the abundant isotopes ($^{12}C/^{13}C < 20$ and $^{14}N/^{15}N < 60$) in these rare stardust grains, which they have renamed "SiC D grains", are produced deep within the core-collapse supernova and, thus, that SiC D grains could form from winds consisting of the innermost ejecta from a 15 solar-mass core-collapse supernova (FIG. 3). Furthermore, they found that the source material for SiC D grains is enriched in the important short-lived radionuclides ^{26}Al and ^{44}Ti, the progenitors of ^{26}Mg and ^{44}Ca, which have been carefully studied in the fields of astronomy and planetary science. This SiC stardust will form in the ejecta shortly after being accelerated by the shock wave and subsequently injected into the protosolar nebula. These grains can then survive in the primitive carbonaceous chondrite parent bodies that form early in the Solar System's history, some of which find themselves captured by Earth to become meteorites.

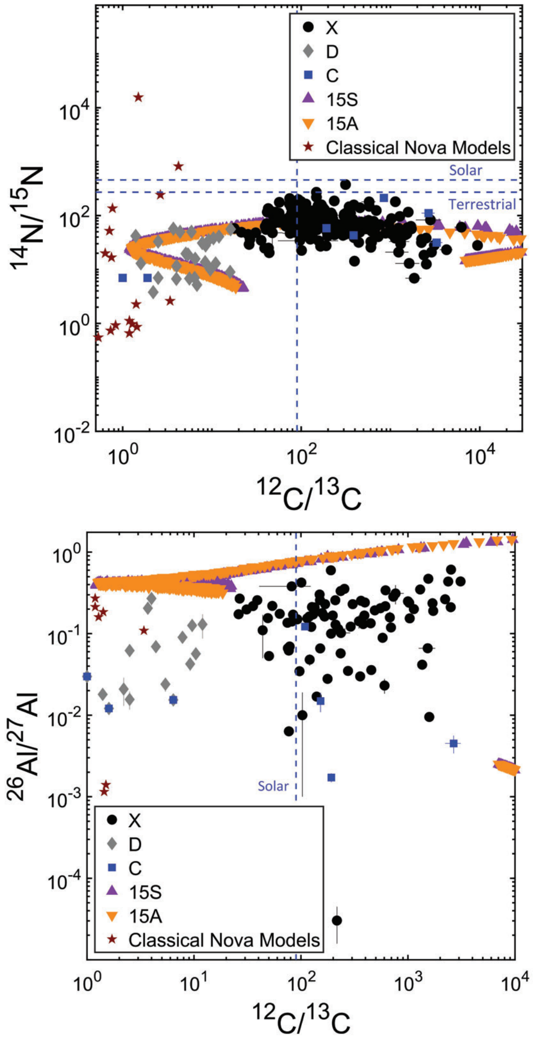

FIGURE 2 Carbon, nitrogen, and aluminum isotopic composition of SiC dust. Models of 15 solar-mass core-collapse supernovae (15S and 15A) suggest that such supernovae are capable of producing dust across the entire range of $^{12}C/^{13}C$ ratios observed in SiC grains, including the SiC D grains, which show low $^{12}C/^{13}C$ and $^{14}N/^{15}N$ ratios (Schulte et al. 2021). The same models can simultaneously match compositions of several other isotopic systems, particularly, the high $^{26}Al/^{27}Al$ ratios measured in SiC D grains. Most nova simulations predict much more extreme carbon and nitrogen isotopic ratios compared to those observed in SiC stardust (X, D, C). CLASSICAL NOVA MODEL DATA IS FROM STARRFIELD ET AL. (2020).

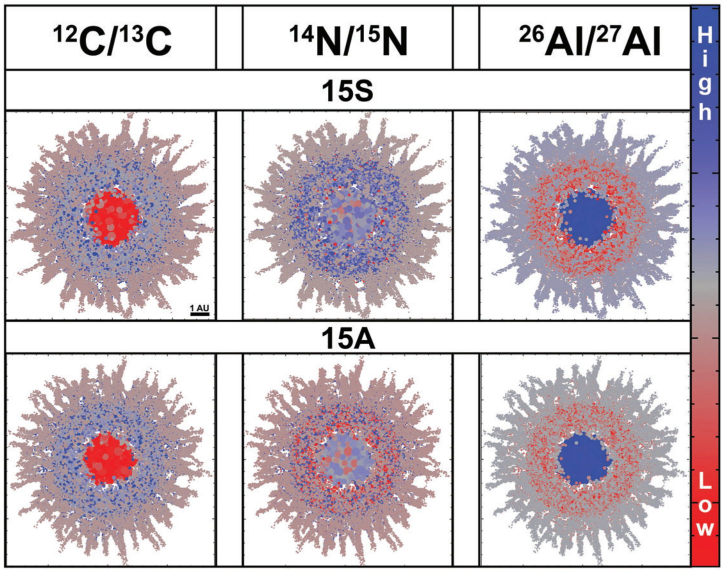

FIGURE 3 Modeled distributions of C, N, and Al found in a core-collapse supernova explosion 43 hours after core bounce. The SiC D grains with low $^{12}C/^{13}C$, low $^{14}N/^{15}N$, and high $^{26}Al/^{27}Al$ ratios are produced in the innermost regions of a core-collapse supernova. The SiC D grains, therefore, can be used to constrain nucleosynthetic and kinetic processes very close to the protoneutron star.

REFERENCES

Amari S and 6 coauthors (2001) Presolar grains from novae. Astrophysical Journal 551: 1065-1072, doi: 10.1086/320235

Anders E, Zinner E (1993) Interstellar grains in primitive meteorites: diamond, silicon carbide, and graphite. Meteoritics 28: 490-514, doi: 10.1111/j.1945-5100.1993.tb00274.x

Bernatowicz T and 6 coauthors (1987) Evidence for interstellar SiC in the Murray carbonaceous meteorite. Nature 330: 728-730, doi: 10.1038/330728a0

Bose M, Starrfield S (2019) Condensation of SiC stardust in CO nova outbursts. Astrophysical Journal 873: 14-25, doi: 10.3847/1538-4357/aafc2f

Liu N and 6 coauthors (2016) Stellar origins of extremely ^{13}C- and ^{15}N-enriched presolar SiC grains: novae or supernovae? Astrophysical Journal 820: 140-154, doi: 10.3847/0004-637X/820/2/140

Nittler LR, Ciesla F (2016) Astrophysics with extraterrestrial materials. Annual Review of Astronomy and Astrophysics 54: 53-93, doi: 10.1146/annurev-astro-082214-122505

Schulte J, Bose M, Young PA, Vance GS (2021) Three-dimensional supernova models provide new insights into the origins of stardust. Astrophysical Journal 908: 38-48, doi: 10.3847/1538-4357/abcd41

Starrfield S, Bose M, Iliadis C, Hix WR, Woodward CE, Wagner RM (2020) Carbon–oxygen classical novae are galactic ^7Li producers as well as potential supernova Ia progenitors. Astrophysical Journal 895: 70-94, doi: 10.3847/1538-4357/ab8d23

Zinner E (2014) Presolar grains. In: Davis AM (ed) Meteorites and Cosmochemical Processes. Treatise on Geochemistry, v1, 2nd edition. Oxford: Elsevier-Pergamon, pp. 181-213, doi: 10.1016/B978-0-08-095975-7.00101-7