MULTI-DIMENSIONAL MIXING IN SUPERNOVAE AND IMPLICATIONS FOR DUST FORMATION

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Introduction: The isotopic signatures from presolar meteoritic graphite grains from supernovae are puzzling. They contain excesses in ^{28}Si and ^{44}Ca (from decay of ^{44}Ti), e.g., [1]. These are both indicators of material from the inner regions of the exploding star. On the other hand, the carbon isotopic abundance and high $^{26}Al/^{27}Al$ ratio in the grains seems to require a significant degree of material from the outer He-rich layers of the star [1,2]. If one requires C/O > 1 in the condensing matter, that matter must also contain outer He-rich material. The C/O > 1 requirement has been challenged [3], but, even if this requirement is relaxed, the isotopic evidence is strong for mixing between the inner supernova matter specifically with the He-rich zones of the ejecta [2].

Multi-dimensional mixing in supernovae: It is curious that supernova graphite grains should result from mixtures of core material with the He-rich zones when a large, oxygen-rich layer lies between them. Nevertheless, multi-dimensional supernova models [4,5] may be providing the clue for how this happens. After core collapse and bounce, a shock wave is generated that travels through the overlying mantle of the massive star. Once it reaches the He/H interface, the shock slows down. The slowing shock causes material behind it to slow down and pile up. This forms a helium "wall". Meanwhile, instabilities at shell interfaces in the inner part of the star lead to formation of clumps of matter that eventually decouple and travel out ballistically through the star. In the 2-d models [4], the clumps typically slow down and get stuck in the He wall. From this point on, they comove with the He-rich layers. All this occurs within the first day of the explosion, so subsequent mixing could provide an appropriate initial composition for the supernova graphite grains. In the more recent 3-d models, the fastest clumps are able to pierce the He wall and reach into the H envelope. Nevertheless, we might still expect some "implantation" of inner core matter into the dense, He-rich zones.

Drag forces at the boundary between the fast moving, nickel-rich clumps and the He-rich matter might favor the necessary mixing for initial composition for the graphite grains. The oxygen-rich fingers found in the 3-d models [5] tend to expand more slowly than the nickel-rich clumps. This fact might help explain how it is possible to mix inner core material with the outer He-rich zones despite the large oxygen-rich region lying between them.

References: [1] Nittler L. et al. 1996, *Astrophys. J.* 462:L31-L34. [2] Travaglio C. et al. 1999. *Astrophys. J.* 510: 325-354. [3] Clayton D. D. et al. 1999. *Science* 283:1290-1292. [4] Kifinodis K. et al. 2003. *Astron. Astrophys.* 408:621-649. [5] Hammer N. J. et al. 2010. *Astrophys. J.* 714:1371-1385.