THE ISOTOPIC COMPOSITION OF INTERSTELLAR GRAPHITE FROM THE MURCHISON METEORITE: EVIDENCE FOR SUPERNOVA MIXING; E. Zinner and S. Amari, McDonnell Center for the Space Sciences and the Physics Department, Washington University, St. Louis, MO 63130, USA. C. Travaglio and R. Gallino, Istituto di Fisica Generale dell'Università, Via P. Giuria 1, 10125 Torino, Italy. M. Busso, Osservatorio Astronomico di Torino, 10025 Torino, Italy. S. Woosley, Board of Studies in Astronomy and Astrophysics, UCO/Lick Observatory, University of California at Santa Cruz, Santa Cruz, CA 95064, USA.

A simple mixing model of layers in a 15M☉ supernova can reproduce the C-, N-, O-, Al- and Si-isotopic ratios of Murchison low-density graphite grains remarkably well, indicating that type II SNe are the most likely source of these grains and that extensive mixing takes place during SN explosions.

Single grains from the low density (1.6-2.1 g/cm³) Murchison graphite fraction KE3 show large variations in their C-, N-, O- and Si-isotopic compositions and large inferred 26Al/27Al ratios [1-3]. (See Figs. 1-4). The most diagnostic isotopic signature for a massive stellar origin of these grains is large 18O excesses (18O/16O ratios range up to 100x solar) and large excesses and deficits in 29Si and 30Si relative to 28Si (Fig. 4). 18O is produced at the very beginning of He-burning by α-capture on the abundant 14N synthesized during the preceding CNO-cycle. In low and intermediate mass (<~8M☉) stars 18O is further transformed by α-capture into 22Ne during recurrent He-shell instabilities before it can be mixed into the outer envelope where grains condense. In massive stars, on the other hand, a considerable fraction of 18O survives in the partially He-burned zones. In Wolf-Rayet (WR) stars, the 18O-rich zone is exposed at the star's surface during the WN-WC transition [4]. Such stars have indeed been proposed as a source for 18O-rich graphite grains although major problems remain [5]. Alternatively, 18O-rich zones are ejected during supernova explosions.

In order to explore this possibility in more detail, we compared the isotopic compositions of KE3 graphite grains to theoretical compositions predicted for supernovae of 13M☉, 15M☉, 20M☉ and 25M☉ [6]. We first looked at He-rich stellar zones having C/O>1. The isotopic ratios of C, N, O, Al, and Si of these zones are plotted in Figures 1-4 together with the grain data. Two neighboring SN regions dominate these plots: the outer zone with low 12C/13C ratios, resulting from CNO cycle equilibrium, and the partial He-burning zone with high 12C/13C ratios. The first has very high 14N/15N, 16O/18O and 26Al/27Al, the second much lower values of these ratios. The 15N enrichments of the inner zone result mainly from neutrino interactions during explosive nucleosynthesis [6]. It is apparent that the grain data are intermediate between the compositions of these two SN zones. The question is whether they can possibly be reproduced by some kind of mixing between different SN layers taking place during the explosion. We note that observations of SN1987A and of other recent SNe cannot be explained without invoking macroscopic mixing during the explosion [see discussion in 7, 8]. In particular, infrared observations of dust in the ejecta of SN 1987A indicate the presence of optically thick clumps [9]. Extensive mixing due to the development of Rayleigh-Taylor instabilities driven by shock waves propagating through the H/He and He/C-O interface regions is found in postexplosion hydrodynamic models [10-15]. In these models lumps and fingers of metal-rich zones can penetrate deeply into outer layers. However, this does not result in the complete homogenization of the pre-SN chemical composition of the He-rich region with the outer H-rich envelope. Instead, different clumps of H-, He-, O- and metal-rich material will be interspersed with one another. Actually, partial microscopic mixing of various C-rich clumps, as apparently reflected in the graphite data, would require a much higher spatial resolution than can be achieved with present hydrodynamical codes. Observations of SN light curves and other spectral features indicate that also part of the innermost Ni-rich matter is mixed with the outer regions, although a theoretical explanation of this effect does not yet exist. The wide range of Si-isotopic compositions in graphite grains also indicates deep mixing. Neutron capture in the He-burning zone is expected to result only in 29Si and 30Si excesses relative to 28Si (see Fig. 4); the apparent depletion of these two Si isotopes in many grains requires the admixture of pure 28Si from the inner O- and Ne-burning regions. A similar constraint arises from the presence of essentially pure 22Ne from 22Na decay (the Ne-E(L) component) in several KE3 graphite grains [16]; in SNe the unstable 22Na is produced only in the inner metal-rich zone. Mixing of O-burning matter with C-rich outer layers is also demonstrated by the presence of 44Ti in selected graphite grains [17].

A crude ad hoc model involving mixing in a 15M☉ SN all the way down to the O-burning zone in an attempt to explain the observations of graphite grains with both 29Si and 30Si excesses and depletions and different C-, N-, O-, and Al-isotopic compositions is shown in Figure 5. Mixing profiles are compared with the original compositional profiles. The isotopic ratios resulting from this
mixing in the region with C/O>1 are plotted in Figs. 1-4 as plus symbols. We note that the anticorrelations between $^{14}\text{N}/^{15}\text{N}$ and $^{12}\text{C}/^{13}\text{C}$ and between $^{16}\text{O}/^{18}\text{O}$ and $^{12}\text{C}/^{13}\text{C}$ shown by the graphite data are successfully reproduced as is the range in the Si-isotopic data. We want to stress that the process of microscopic mixing in different clumps of C-rich matter is far more complex than the unidimensional model sketched here and it is obvious that there are some problems (e.g., grains with low $^{26}\text{Al}/^{27}\text{Al}$ ratios – see Fig. 3). However, in spite of the reservations that can be raised against such a simplistic preliminary model, the surprisingly good agreement between the graphite data and the results of our $^{15}\text{Mo}$ mixing model not only demonstrates that SNe are the most likely sources of low density graphite grains but that their isotopic composition gives evidence for extensive microscopic mixing of the ejecta during the explosion.