GRAIN FORMATION IN SUPERNOVAE AND ISOTOPIC ANOMALIES IN THE EARLY SOLAR SYSTEM; S. W. Falk*, J. M. Lattimer**, S. H. Margolis and D. N. Schramm, Enrico Fermi Institute, University of Chicago, Chicago, IL 60637

Anomalous isotopic abundances recently discovered in the primitive carbonaceous chondrite Allende seem in most cases to fall in a pattern which can be explained simply in terms of contamination by material processed in a supernova event. Notable among these are the ^{26}Al-^{26}Mg chronology developed by Lee, et al., who showed that ^{26}Al must have been synthesized within a few million years of Allende inclusion solidification. It can be argued that the observed ^{26}Al was synthesized in a supernova rather than produced by spallation. Another important anomaly is the ^{16}O component discovered by Clayton, et al., with some material apparently showing a 5% enhancement in this isotope. Recently Lee, et al. (1978) and McCullough and Wasserburg (1978) have found one Allende inclusion to contain anomalies in almost every element examined, in particular in Ca, Ba, and Nd as well as O and Mg. Calculations by Blake et al. show that the carbon zone of a supernova can produce many, if not all of these anomalies, because during explosive carbon burning free neutrons are produced and captured, redistributing the isotopic abundances of most of the heavies already present in the zone. In addition, the carbon zone is enriched in ^{16}O relative to $^{17,18}O$.

Since the ^{26}Al seems to tie a supernova to within a few million years of the early solar system, it is interesting to inquire as to what else a supernova might do. Many people (Hoyle, Öpik, and recently Truran and Cameron, Woodward, etc.) have suggested that the nearby event may actually have caused the dynamical collapse of the presolar nebula, but this is not necessary to the SN-anomaly picture. The question of whether the contamination was via gas or grains is unresolved; a two-component gas mix seems unable to explain the Ca-Ba anomalies. Grain injection of such anomalies affords a simpler explanation in this context, and additionally anomalies carried by grains will not suffer homogenization by mixing in the nebula. Equilibrium condensation sequences for various SN zone compositions have been calculated (Lattimer et al. 1978). They show a marked sensitivity to the value of the C/O ratio. For values greater than unity, various carbides will condense at high temperatures, instead of silicates or other refractory oxides. However, these condensation sequences bear close resemblance to those which obtain for solar compositions with identical values of the C/O ratio. Thus, the minerals which condense in SN are expected to be stable against evaporation in the early solar nebula, and grains which form in the ejecta could then effectively carry and retain isotopic compositions in the nebula.

Calculations of nucleation of grains have been carried out for material flows representative of both novae and supernovae, including effects of expansion, cooling, and energy input (Lattimer and Falk 1978). The formation and growth is followed numerically through a partition of grain sizes into size groups, including monomers. Roughly, the nucleation is a balance between aggregation (here, monomer addition) and an evaporation determined by assuming an equilibrium with the evolving and supersaturated

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gas. The processed material of interest is hydrogen and helium depleted, and will cool to condensation temperatures ($T_c \sim 1000$ K) by several months to a year, depending upon the exact parameters of the event. Typical velocities for expansion of this processed material are several hundred km s^{-1}. Nucleation is rapid after this cooling, with an approach to a static size distribution occurring in times typically like 10^6 s or less, as long as the number density of condensibles exceeds about 10^6 s or so, and as long as energy input is insignificant. Type I supernovae almost certainly do not make grains (Falk et al. 1978). Monomer depletion, rather than declining density, determines the end of significant change in the size distribution. The resulting distribution is roughly flat in number fraction versus size (measured in number of constituent monomers), but shows strong peaking in mass fraction versus size. Typical sizes in this peak are 10^{2-3} monomers, or grains of order 10^{-2} microns; the tendency is for nucleation of many small grains to occur. Coagulation has not been included explicitly in the calculations; we estimate its effect to be predominantly in depleting the low-monomer-number end of the size spectrum, and to cause an increase in mass-weighted mean size by a factor less than about two. Chemical effects on molecule formation before nucleation, which may effect the dominant monomer composition, and during nucleation itself have been neglected. We expect the ejecta not to be highly mixed, and stratified layers of varying composition may persist. For the zones of interest, the C/O ratio is probably the determining factor, with a value less than unity possible for many events. Thus the refractories like ^{26}Al, Ca, etc., may naturally be available for grain formation from the carbon burning zone.

The evolution of grain material until contact with the protostellar nebula is largely unexplored, depending as it does upon the assumptions of time and distance to the nebula, since the SNR passes through distinct stages before dispersal. It seems safe to say that the only probable difficulty for grain survival comes if cosmic rays are accelerated in large numbers in this same material. In this case, electron sputtering may change the pattern of surviving grains (Scalo 1977). Numerical calculations of a plane parallel, semi-infinite encounter of ejecta with nebula have some very interesting results (Margolis 1978). Initial contact generates a shock wave which decelerates and compresses the incoming SN gas, and accelerates inward the ambient (nebular) gas. The embedded dust in these two gas phases is largely unaffected by the shocks, since viscous interaction with the gas over larger length scalesis the dominant coupling. They tend to accumulate near the interface itself, as interpenetrating distributions with smoothly varying relative abundances. In particular, the incoming SN grains penetrate the nebular gas by distances typically several 10^{14} cm before becoming momentum coupled to the gas: a natural result therefore includes the possibility of variable component additions of SN grains with the ambient nebular dust over length scales of order 10^{15} cm orso. Possible fluid instabilities at the contact discontinuity between the gas phases may lead to blobs interpenetrating and mixing the gas, though preliminary estimates suggest that the incoming SN gas in more subject to, e. g., the Rayleigh-Taylor instability (favored wavelengths are of order 10^{12} cm or so)

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on the time scales of interest here. Supported in part by NASA grant NSG-7212.

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