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Introduction: Models of Type II supernovae (SN) indicate that the explosively processed ejecta are concentrically zoned in chemical and isotopic composition due to burning of successively heavier nuclides with increasing depth in the presupernova star. It is common to divide the ejecta into ~8 zones, labelled by their one or two most abundant elements by mass, although rather large gradients in composition exist within each zone. As time passes after the explosion, the gaseous ejecta expand and cool, and condensation occurs as the total pressure (P^t) falls with temperature (T). Observations of SN1987A suggest that cooling occurs on a time-scale comparable to the half-lives of some abundant nuclides (*e.g.*, 77-day ^{56}Co), so that relative atomic abundances change significantly due to radioactive decay during condensation. Thermodynamic calculations have been used to predict the identities of condensates expected in SN ejecta as an aid to interpretation of isotopic anomalies in presolar grains found in chondrites [1-5]. While the variation of P^t with T was considered in [1] and [2] and the variation in composition within a zone in [5], the time variation of abundances due to radioactive decay has never been built into such calculations. All three effects are included in the present work, as follows.

Technique: The cooling time-scale of the gas was derived from the variation of dust temperature with time after the explosion of SN1987A inferred by [6], by assuming that the gas was always 300K hotter than the dust. The variation of gas density with T was interpolated between the curves in [1], assuming a radiation-pressure-dominated regime, radiative losses and an initial atomic fraction of ^{56}Ni of 5x10^{-4}. We calculated the variation of P^t with T from the density-T variation separately for each bulk gas composition using the ideal gas law. Our condensation calculations were carried out with the program of [7], whose thermodynamic data base was augmented with gaseous and solid species that are potentially important in the unusual compositions found in SN ejecta. Nucleosynthesis calculations were used by [8] to obtain the variation of chemical and isotopic abundances with depth in SN of different masses. In particular, the compositions at the 25000 sec mark are discretized into 780 concentric layers for s21a28g, the ejecta from an initially 21-solar–mass stellar model, available online. Bulk chemical compositions of systems employed here were those of individual or linear combinations of layers.

Because P^t and T are linked to time in the condensation calculation, elemental abundances can be corrected for radioactive decay at each T step. This was done by following the decay chains of radioactive species with routines built on top of libnucnet, a library of codes for storing and managing nuclear reaction networks [9]. We calculated the equilibrium condensation sequence for the bulk composition of each of the 8 main burning zones defined in [10], and for many individual layers, including the top and bottom layer of each zone.

Results: As found in [1], condensation temperatures in SN ejecta are comparable to those in solar gas at much higher P^t due to the very low abundance of H, which acts to dilute condensable elements in the solar case. Equilibrium condensate assemblages vary gradually from one layer to the next along the composition gradients within each burning zone. In this model, T falls from 1500K at 140 days to 1000K at 360 days. In the Ni and Si/S zones, much of the condensation occurs in this interval, during which the P^t falls from ~1x10^{-9} to 3x10^{-10} bar. By the time condensation begins, these ^{44}Ti- and ^{28}Si-rich zones are composed predominantly of Fe, S and Si, although He is very abundant at the base of the Ni zone and O at the top of the Si/S zone. Typical high-T (>1000K) condensates in these zones are silicides of Ti, Ni and Fe, TiC, very Si- or Co-rich alloys and oldhamite (CaS), but perovskite (CaTiO$_3$), grossite (CaAl$_4$O$_7$) and melilite displace some of these at the top of the Si/S zone. Graphite does not form in these zones but SiC has a relatively low-T stability field throughout the Si/S zone. Corundum (Al$_2$O$_3$) is the first condensate in most of the layers of the O/Si, O/Ne and O/C zones, appearing between 1870 and 1650K at 5-8x10^{-9} bar. Condensate assemblages from these ^{16}O- and ^{28}Si-rich zones are very similar to those from solar composition in that Ca- and Al-rich oxides and silicates condense at higher T than olivine and metal. But there are significant differences as well. The maximum akermanite (Ca$_2$MgSi$_2$O$_7$) mole fraction (X_{Ak}) in the melilite reflects the atomic Mg/Al ratio of the layer in which it condenses. X_{Ak} <0.01 at the base of the O/Si zone where Mg/Al=1.4, but >0.6 everywhere else because 8<Mg/Al<75. Despite the fact that the log f_{O2} at the time of olivine condensation is very high, ~IW+2, at the top of the O/Si zone and throughout the O/Ne zone, the fayalite (Fe$_2$SiO$_4$) content of the olivine that forms in these regions is very low, X_{Fa}<0.002, due to the very small bulk atomic Fe/Mg

ratios. The base of the O/C zone has the same log f_{O2} but a higher atomic Fe/Mg ratio, so X_{Fa} reaches 0.016 in this region. The metallic phase in all these high-f_{O2} regions is a Ni-rich NiCo alloy. The top of the O/C zone has a much higher atomic Fe/Mg ratio, 0.32, but log f_{O2} is IW-2.5 so $X_{Fa}<0.002$ and the alloy is Fe-rich FeNi. In fact, without mixing of layers from different zones, it is difficult to make fayalitic olivine in any layer predicted by this SN model because olivine is not a high-T condensate in any of the zones below these, and log f_{O2} is extremely low in those layers of the He/C and He/N zones where olivine is stable. Even in the H envelope, where Fe/Mg is near-solar and the C/O ratio is lowered to ~0.29 by nuclear processing, the gas is still so reducing (log f_{O2}~IW-6) that olivine always has $X_{Fa}<10^{-3}$ at T>1000K.

The C abundance is much greater than that of O throughout the He/C zone and the basal portion of the He/N zone. Graphite is the first condensate in these regions, appearing at T>2000K throughout the He/C zone. Other high-T condensates in these zones are TiC, SiC, Fe and Ni silicides, very Si-rich NiFe alloys, AlN and CaS. In the top 25% of the He/N zone by mass, the C/O ratio is so low (<0.6) that Al_2O_3 is the first condensate, rather than graphite or TiC.

Some presolar graphite spherules found in the Murchison CM chondrite contain correlated excesses of ^{28}Si and ^{44}Ca. The latter is associated with TiC subgrains and is due to decay of short-lived ^{44}Ti. The spherules are thought to have originated in a Type II SN because ^{28}Si and ^{44}Ti are co-produced in the inner-most Ni and Si/S zones of such objects [11]. Although TiC can form in these zones [4], graphite can condense only from the layers of the He/C and He/N zones where C/O>~1, but these are much closer to the surface of the star. Lodders [5] theorized that Fe-Ni titanide grains condensed in the Ni zone, were hurled into the He/C zone where graphite condensed around them, and that they then reacted with the graphite to form metallic FeNi and TiC. While this can potentially explain the presence of ^{44}Ti-bearing TiC subgrains in graphite and the existence of metallic FeNi grains on TiC grain surfaces [12], it cannot explain the presence of excess ^{28}Si in the graphite. Travaglio et al. [13] explored mixing calculations to see if a gas composition could be produced that simultaneously has the isotopic compositions of the graphite spherules and a C/O ratio ≥1 that could possibly stabilize the graphite-TiC assemblage. Using the homogenized compositions of the inner 7 burning zones as end-member components, they were unable to find a match. In the present work, it is assumed that filaments of material from widely-spaced SN layers intermingle during the explosion, and that they mix with one another before homogenization of all

the layers of a burning zone. In the s21a28g model, the topmost layers of the Ni and the He/C zones each contain $1-2\times10^{-2}$ solar masses of material. Although a similar result can arise from selection of other layers of similar composition to these, Fig. 1 shows that, when these 2 layers are mixed together, the condensation T of graphite falls due to dilution of the C, and the condensation T of TiC increases due to the increased concentration of Ti, as the proportion of the layer from the Ni zone increases. TiC condenses at a higher T than graphite whenever there is >75% of the latter layer in the mixture, at which point virtually all the Ti, Si, Fe and Ni come from the Ni layer, ensuring a ^{28}Si- and ^{44}Ti-rich mixture, and almost all the C comes from the He/C layer. SiC is the next phase to become stable after graphite but the only metal grains that condense do so at a T well below the graphite condensation T and are Ni-poor, Fe-Si-Co alloys, whereas the metal grains found by [12] are binary NiFe alloys. Perhaps the metal grains formed by exsolution from TiC that originally had Fe and Ni in solid solution. Alternatively, they may have condensed from the top of the O/C zone or the base of the O/Si zone, the only regions interior to the He/C zone where NiFe grains can form at T>1000K.

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Fig. 1