CONDENSATION IN EJECTA FROM DENSE THERMONUCLEAR SUPERNOVAE. T. Yu[1], B. S. Meyer[1], A. V. Fedkin[2], and L. Grossman[2,3], [1]Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-0978, USA (tyu@clemson.edu, mbradle@clemson.edu), [2]Department of the Geophysical Sciences, The University of Chicago, Chicago, IL 60637, USA, [3]Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637, USA.

Introduction: Roughly correlated isotopic anomalies in neutron-rich iron-group isotopes such as ^{48}Ca and ^{50}Ti exist in FUN CAIs and hibonite grains (e.g., [1] and references therein). The correlation of these neutron-rich iron-group species makes sense from a nucleosynthesis point of view because they are abundantly co-produced in freezeouts from quasi-statistical equilibrium of low-entropy, neutron-rich matter [2]. Possible sites for such freezeouts are rare, dense thermonuclear (Type Ia) supernovae [2,3] or electron-capture supernovae [4].

The crucial question for preserving the correlated nucleosynthesis signatures, of course, is the nature of the carriers of these isotopes into the Solar System. In an effort to shed light on this question, we here present equilibrium calculations of the condensation of chemical species in a thermodynamic trajectory drawn from a simple Type Ia supernova model [5].

Simple Thermonuclear Supernova Model: Thermonuclear (Type Ia) supernovae are explosions of white dwarf stars. Our model solves the equations of fluid dynamics, but makes the simplification that there is only one zone. We thus replace all radial gradients with the difference of the central and surface values for the quantity divided by the radius of the star.

While the fluid dynamics of the model is greatly simplified, the microphysics is complete. We include a full nuclear reaction network and a fully relativistic, fully degenerate equation of state for the electrons, nucleons, and photons present in the system. We also include neutrino energy loss from weak decays and schematic radiative loss.

The models begin at time t = 0 with a mixture of 50% ^{12}C and 50% ^{16}O by mass (atomic C/O=1.33), a reasonable guess for the composition of most white dwarf stars, though it is possible to have a composition with atomic C/O <1. As carbon burning and then oxygen burning proceed under degenerate conditions, a thermonuclear runaway occurs, which leads to the explosion of the star. We follow the subsequent expansion out to a time t > 3 x 10^7 seconds, that is, t > 1 year.

Figure 1 shows the temperature in the model with an initial density of 8 x 10^9 g/cc as a function of time. By t = 10 seconds, the temperature had dropped to less than 10^8 K from a temperature as high as 10^{10}K. The temperature continued to drop rapidly until radioactive decay from species such as ^{66}Ni heated the matter and lessened the temperature decline rate. The temperature passed through 2000 K at about 70 days and through 1000 K at about 100 days.

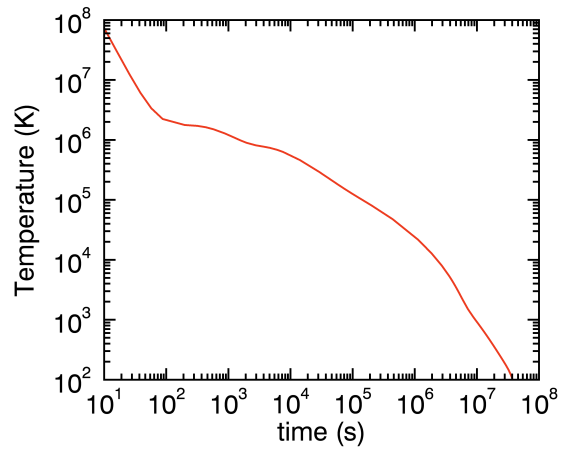

Fig. 1. Temperature as a function of time in the 8 x 10^9 g/cc simple Type Ia supernova model.

Nucleosynthesis: The high density of the stellar model allowed electron captures to occur during the explosion and drive the matter neutron rich. The electron-to-nucleon ratio (by charge neutrality, the fraction of nucleons that are protons) dropped from its initial value of Y_e=0.5 to Y_e=0.44. For such neutron-rich matter, there is abundant production of the neutron-rich iron-group isotopes. At time t = 10 seconds, after all nuclear reactions except final weak decays have ceased, the species with the largest mass fractions are ^{54}Cr (0.281979), ^{50}Ti (0.247235), ^{60}Fe (0.147771), ^{64}Ni (0.133037), ^{58}Fe (0.0749205), ^{66}Ni (0.0557688), ^{48}Ca (0.0145219), and ^{56}Mn (0.00967454).

Pressure-Temperature Profile: Figure 2 shows the temperature-pressure profile for the trajectory from the initially 8x10^9 g/cc model. The profile is initially roughly linear on the log-log plot. At a few times 10^6 seconds, however, the pressure falls for roughly constant temperature. Here the matter is expanding and the density is dropping, which tends to cause the pressure to fall, but radioactive heating helps maintain the high temperature. Once the radioactive species have decayed, the heating ceases and the pressure again falls roughly linearly with the temperature. It is worth not-

ing that the pressure in the temperature range T = 2000K - 1000K is similar to that in core-collapse supernova models (e.g., see Fig. 1 of [6]). The Type Ia model starts at much higher density than zones in the core-collapse model. However, the strong radioactive heating delays cooling to 2000K until the pressure is in the range of several times 10^{-8} bars.

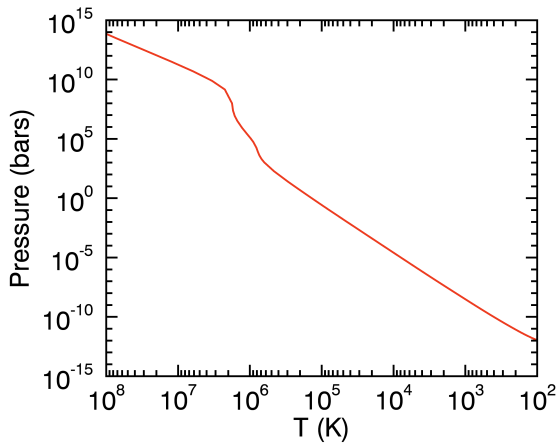

Fig. 2. Pressure-temperature profile for the initially 8×10^9 g/cc simple Type Ia supernova model.

Condensation Calculations: We computed the chemical equilibrium of species in the pressure-temperature profile of Fig. 2 with the equilibrium code described in ref. [6]. We note that this code includes radioactive decay, so the initial ^{56}Mn will have decayed to ^{56}Fe and ^{66}Ni will have decayed to ^{66}Zn by the time the temperature has dropped to ~2000K at around 70 days.

For this trajectory, the abundant solids that condense are Ti solid (appears at 1570K and disappears at 1435K), $NiTi_2$ (appears at 1560K and disappears at 1375K), FeTi (appears at 1440K), NiTi (appears at 1405K), and Ni_3Ti (appears at 1315K). The abundant solids existing at T=1000K are thus FeTi, NiTi, and Ni_3Ti, and these solids lock up all Ti, Fe, and Ni. Calcium does not condense in this trajectory but rather stays in the gas phase, at least for temperatures above 700K. From these calculations, there is no obvious condensate that would carry ^{48}Ca and ^{50}Ti together.

Thermonuclear supernovae are in fact complex, multi-dimensional events, and unburned C and O might mix with the processed layers in the outflow. To study the consequences of such mixing, we repeated the above condensation calculation but added 8% ^{12}C and 8% ^{16}O by mass for an atomic C/O ratio of 1.33.

Fig. 3 shows the fraction of Ti in various phases during condensation. Perovskite ($CaTiO_3$) appears in this calculation at 1280K by a reaction of gaseous Ca with pre-existing solid TiO. It is worth noting that such a gas-solid reaction may be kinetically hindered in such a rapidly cooling environment. The sudden drop in TiC at 800K is due to graphite condensation which takes its C from TiC. The only other abundant solid at 1000K is Fe_3C, which appears at 1235K.

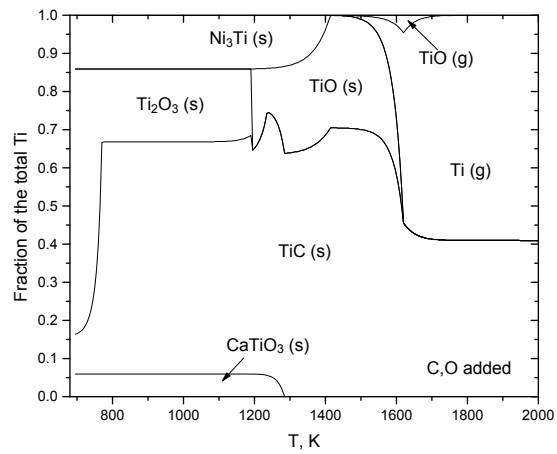

Fig. 3 Ti distribution in the condensation calculation for the trajectory in Fig. 2 with added C and O.

Discussion: Perovskite has been proposed as the carrier of the ^{48}Ca and ^{50}Ti that gives rise to the roughly correlated anomalies in FUN CAIs and hibonites and in bulk samples [7]. Our calculations show that chemical equilibrium favors condensation of perovskite in the outflows from dense thermonuclear supernovae if there is mixing with unburned O. In the trajectory we studied, this perovskite locked up all Ca and is composed of nearly pure ^{48}Ca and ^{50}Ti. It could be a good candidate for the carrier of correlated ^{48}Ca and ^{50}Ti.

If rare and dense thermonuclear supernovae condense perovskite grains, and if these grains are the carriers of correlated ^{48}Ca and ^{50}Ti into the Solar System, it is clear that there must be mixing of the densest matter in the exploding white dwarf star with unburned O. It must also be the case that the small grains that form be able to survive shocks in the supernova ejecta and in the interstellar medium.

References: [1] Meyer B. S. and Zinner E. in Meteorites and the Early Solar System II (Tucson: University of Arizona Press), p.69-108. [2] Meyer B. S. et al. 1996. *Astrophys. J.* 462:825-838. [3] Woosley S. E. 1997. *Astrophys. J.* 476:801-810. [4] Wanajo S. et al. (2013) *Astrophys. J.* 767:L26. [5] Yu T. and Meyer B. S. (2013) *LPS XXXXIV,* Abstract #1998. [6] Fedkin A. V. et al. (2010) *GCA* 74:3642-3658. [7] Dauphas N. et al. (2014) preprint.