GROWTH OF LARGE CARBONACEOUS GRAINS IN OXYGEN-RICH SUPERNOVA MATTER.

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Introduction: In previous work, we have developed a model for the condensation of carbonaceous dust in the oxygen-rich inner layers of the ejecta from an exploded massive star [1-4]. In the model, ^{56}Co produced in the supernova explosion is present in the grain-growth regions. The fast electrons that result from Compton upscattering of the gamma rays emitted by ^{56}Co decay break up carbon monoxide (CO). This permits free C to be present, even in environments in which the abundance of O is greater than that of C. Free carbon atoms can interact with each other to form n-carbon chains, denoted C_n. Interactions with photons and free oxygen atoms break up the carbon chains. In the model, carbon captures on C_n to build up larger chains until the C_8 chain isomerizes to become a ring. The ring is stable against further oxidation and thus serves as a seed for grain growth.

In this work, we compute the first detailed grain-size spectrum from this model and illustrate quantitatively how break up of CO by fast electrons allows growth of large grains in oxygen-dominated matter.

Calculations: We consider an oxygen-rich layer in the expanding supernova ejecta with three times as many oxygen as carbon atoms (O/C = 3). Such oxygen-rich matter is a natural outcome of core He burning in massive stars, and O/C = 3 is fairly characteristic of the output of models of these stellar sites. We consider that the material has a temperature T = 6000 K and a mass density $\rho = 10^{-11}$ g/cc at a time 5.5 x 10^6 seconds after the explosion. We take T to decline with time t as τ/t, with $\tau = 5.5 \times 10^6$ seconds, which is appropriate for homologous expansion of a radiation-dominated environment such as the supernova ejecta. We consider $\rho \propto T^3$, again as appropriate for radiation-dominated matter.

To follow the evolution of chemical species, we use the chemical network we have previously developed [4] and incorporate rates from [5,6]. We estimated the rate for the CO break up reaction by fast electrons, from energy deposition arguments (see also [2,3,7]).

To follow grain growth, we consider a co-moving volume with a fixed number of total atoms. Once the total abundance of C_8 in the co-moving volume becomes sufficiently large, we create a grain seed and correspondingly decrease the network abundance of C_8. Henceforth in the calculation, we couple C atom captures on that seed molecule in the network; thus, when that seed molecule captures free C, the C abundance decreases. We keep track of all grains that form, their formation time, and their grain size (the number of C atoms in the grain).

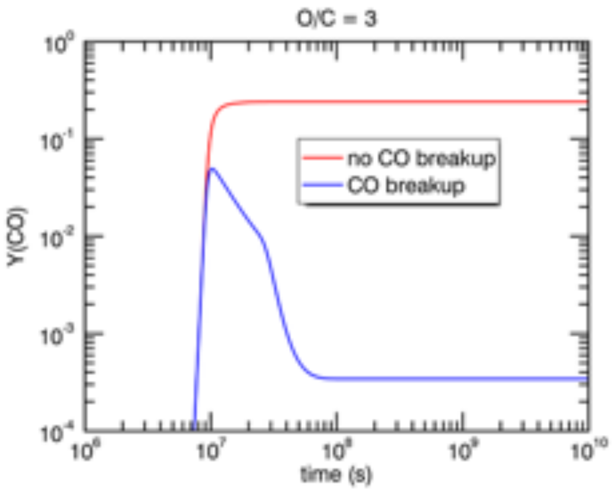

Fig. 1: The abundance per atom of CO in the absence and presence of the CO break up by Compton-upscattered electrons from ^{56}Co decay.

The abundance of CO when we include and do not include CO break up in the calculation is shown in Fig. 1. Without break up of CO by fast electrons, the abundance of CO per atom, Y(CO), rises ~10^7 s (about 5 months) after the explosion and locks up nearly all C. With the inclusion of CO break up, the CO first rises but, around ~10^7 s after the explosion, falls. The reason is CO is produced by the radiative-capture reaction $C + O \rightarrow CO + \gamma$. It is destroyed by the photo-disintegration reaction $\gamma + CO \rightarrow C + O$ and by the break up reactions by fast, Compton-upscattered electrons such as $e + CO \rightarrow C + O + e'$. At high temperature, the radiative-capture and photo-disintegration reactions dominate, and the CO achieves an equilibrium abundance. This abundance rises as the temperature falls and the disintegration reaction rate plummets. The capture reaction rate also declines with declining density. Eventually, the fast-electron reactions come to dominate both the capture and disintegration reactions, which causes the CO abundance to decline. The CO abundance freezes out at an abundance well below that in the absence of the break up reactions. This result is expected from astronomical observations which showed that the CO abundance of SN 1987A is considerably below what it would have been in the absence of radioactivity (see [7] and references therein).

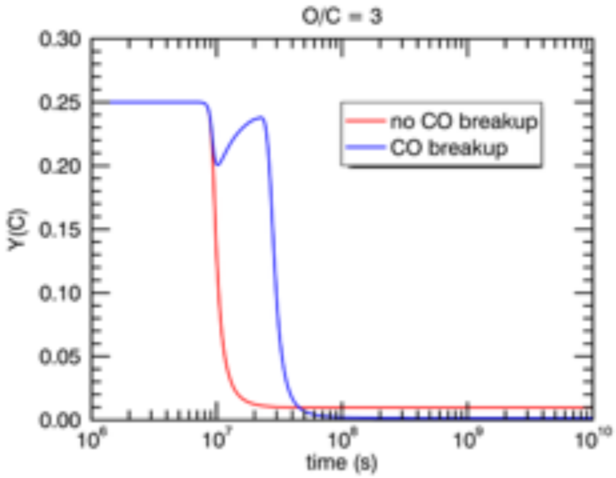

Fig. 2: The abundance per atom of free C in the absence and presence of the CO break up by Compton-upscattered electrons from ^{56}Co decay.

CO break up plays a key role in the abundance of free C in the calculations. As is evident, the CO break up leads to an abundance of free C ~25x greater than in the absence of radioactivity at ~2 x 10^7 seconds after the supernova explosion.

In the calculation with no CO break up, the free C abundance drops at ~10^7 seconds because the C locks up into CO. In the calculation with CO break up, the free C abundance first drops as C is incorporated into CO (cf. Fig. 1) but then rises again as break up of CO restores much of the free C. After ~2 x 10^7 seconds, the free C abundance then drops. This depletion is due to capture of C onto the growing dust grains.

Fig. 3 shows the grain-size spectrum in the two calculations. As is evident, only large grains (up to 10^{16} atoms in each grain) grow even though the matter has three times as much oxygen as carbon if we include CO break up by fast electrons. The grains grow rapidly from ~2 x 10^7 when the first grain seeds form until ~4 x 10^7 seconds when all carbon is locked into grains. Assuming closely packed carbon atoms, each with size 70 pm, our largest grains are ~15 µm in size. This growth mechanism therefore could account for at least some of the low-density presolar graphite grains of supernova origin [8].

By contrast, only small grains grow without CO break up. In this latter case, the abundance of free C and, therefore, C_8 is too low to create seed grains until late in the expansion (later than ~3 years) by which time the grains that do form do not have time to capture many C atoms. Moreover, the abundance of C is low throughout the grain growth epoch because most C is locked in CO, which also hinders production of large grains. The fraction of total C locked into grains is much less than 1%.

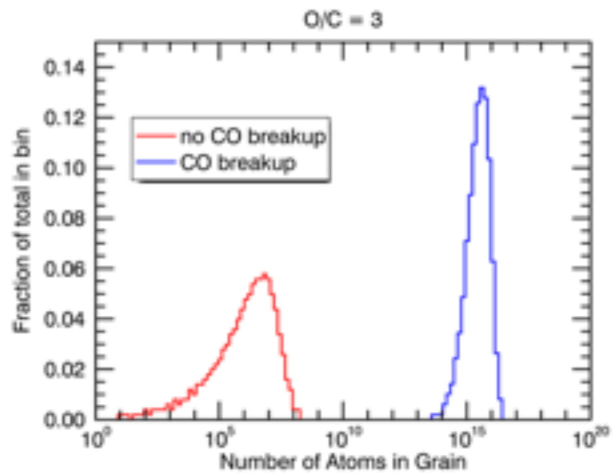

Fig. 3: The grain-size spectrum in our calculations with and without CO break up by fast electrons.

Conclusion: Roughly 80% of the carbon ejected in a core-collapse supernova is from the inner, oxygen-rich layers of the star (O/C > 2). Herschel [9] and ALMA [10] observations strongly suggest that nearly all carbon in 1987A condensed into dust; therefore, we expect there is a mechanism to produce carbonaceous dust in oxygen-rich supernova matter. Our model shows that fast-electron break up of CO allows for production of large carbon dust grains in such oxygen-rich layers.

References: [1] Clayton D. et al. (1999) *Science,* 283, 1290-1292. [2] Clayton D. et al. (2001) *Astrophys. J.,* 562, 480-493. [3] Deneault E. A. N. et al. (2006) *Astrophys. J.,* 638, 234-240. [4] Yu. T. et al. (2013) *Astrophys. J.,* 769, 38. [5] Cherchneff I. and Dwek E. (2009) *Astrophys. J.,* 703, 642-661. [6] Cherchneff I. and Dwek E. (2010) *Astrophys. J.,* 713, 1-24. [7] Liu W. and Dalgarno A. (1995) 454-499. [8] Jadhav M. et al. (2006) *New Astron. Rev.,* 50, 591-595. [9] Matsuura M. et al. (2011) *Science,* 333, 1258-1261. [10] Indebetouw R. et al. (2014) *Astrophys. J. Lett.,* 782, L2.