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# Dust in Population III Supernovae: the elemental composition of carbon normal and carbon-enhanced metal-poor stars

**S. Marassi**[*a†], **R. Schneider**[a], **M. Limongi**[a], **A. Chieffi**[b]

[a] *INAF/Osservatorio Astronomico di Roma, via di Frascati 33, 00040, Roma, Italy*
[b] *INAF/IASF, via Fosso del Cavaliere 100, 00133, Roma, Italy*

*E-mail:*
stefania.marassi@oa-roma.inaf.it,raffaella.schneider@oa-roma.inaf.it
marco.limongi@oa-roma.inaf.it, alessandro.chieffi@inaf.it

The first (Pop III) supernovae (SNae) to explode in the Universe start the process of metal enrichment and have a major impact on early structure formation. The metals and dust grains released and dispersed by Pop III SNae change the cooling properties of the interstellar medium out of which second generation stars form, allowing the first low-mass and long-lived stars to form. Stellar archaeology of the most metal-poor stars observed in the halo of our galaxy and its dwarf satellites is providing strong constraints on these early star formation and chemical enrichment phases. We investigate the metal and dust yields released by Pop III SNae with the aim to reproduce the properties of the environment out of which the most metal poor stars have formed. Following Bianchi and Schneider [1], we apply classical nucleation theory and grain growth to follow the properties of newly condensed grains and their partial destruction through the passage of the reverse shock in the supernova remnants. Besides, we follow the non steady-state molecule formation and, due to the key role played by the molecules in the dust formation process, we have upgrated our molecular network taking into account other molecules, such as $O_2$ and $C_2$ and other chemical reactions that involve formation/destruction of carbon monoxide (CO) and silicon oxide (SiO). Dust formation calculations are performed assuming both unmixed and uniformly mixed ejecta and varying the mass cut and explosion energies so as to reproduce the observed elemental composition of carbon-normal and carbon-enhanced metal poor stars in the Galactic halo.

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| Dust species | $Al_2O_3$ | $Fe_3O_4$ | $MgSiO_3$ | $Mg_2SiO_4$ | AC | Total |
|---|---|---|---|---|---|---|
| 4A | 4.4 (0.45) | 0.24 (0) | 0.016 (0) | 3.5 (0.27) | 0.12 (0) | 8.3 (0.72) |
| 4B | 0.36 (0.35) | 0.55 (0) | 0.001 (0) | 5.3 ( 0.25) | 28 (0) | 34 (0.6) |

**Table 1:** Mass of dust species (from left to right: corundum, magnetite, enstatite, fosterite and amorphous carbon) and total mass of dust in $10^{-4}M_\odot$ at 1500 days for 4A and 4B layers of the $Z = Z_\odot$, $15\,M_\odot$ SN model with a $^{56}$Ni mass of $0.075M_\odot$ by [5]. In parenthesis, we report the corresponding values found by [5].



## 1. Upgrade of the molecular network: comparison with chemical kinetic approach

To model dust formation in SNae ejecta different methods have been followed: (i) classical nucleation theory (CNT) in steady state conditions (see [2, 1] and reference therein) and (ii) chemical kinetic approach ([3, 4, 5]). As recently pointed out in [3, 4, 5], these methods lead to different estimates of the mass and composition of newly formed dust due to the questionable applicability of steady state CNT to SN ejecta and to non-equilibrium chemical processes related to formation/destruction of molecules (in particular CO) are not taken into account. However, the lack of chemical equilibrium at nucleation (assumed in CNT) has been shown to have only a minor effect on the grain mass and size distribution ([6]) and that a steady-state nucleation rate is a good approximation in SN ejecta, at least until the collisional timescales of the key molecule is much smaller than the timescale with which the supersaturation ratio increases ([7]). Hence, to better understand the origin of these differences, we have upgraded the molecular network and we have included additional processes for the formation/destruction of CO and SiO molecules; we then compare the molecular masses with recent results obtained with the chemical kinetic approach ([5]).

The formation of molecules represents a bottleneck to the formation of dust grains, e.g CO molecules subtract C-atoms, limiting the formation of carbon grains. In [1] the authors followed a non-steady state chemistry involving CO and SiO molecules, that in the absence of grains, form in the gas phase through radiative association. The CO and SiO molecules are destroyed by the collision with energetic electrons produced by the radioactive decay of $^{56}$Co, with a destruction rate coefficient calibrated on the SN1987A observed light curve ([8]). The new molecular network takes into account updated radiative association reactions for CO, SiO, $O_2$ and $C_2$ molecules and additional formation/destruction processes between molecules. A detailed description of the model is presented in [9]. Here we apply the model to the stratified ejecta of a type II-P SN with solar metallicity and $15M_\odot$ progenitor described in [5]. Fig. 1 shows the predicted time evolution of the mass of CO, SiO and of different dust compounds in the two stratified region 4A and 4B where CO molecules form efficently. At 1500 days after the explosion, we find that a CO mass of $9.5 \times 10^{-2}\,M_\odot$ ($0.14\,M_\odot$) has formed in layer 4A (layer 4B), in excellent agreement with [5] (see their Table 4). Dust condensation starts between 300 and 450 days after the explosion, and SiO and CO molecules are depleted to form, respectively, silicates and amorphous carbon grains. The resulting dust masses at 1500 days are reported in Table 1 (for comparison, we also show in parenthesis the corresponding values found by [5]). We point out that [5] follow only the the first phase of formation of molecular clusters (dust precursors) and do not consider the growth of existing dust grains via accretion of atoms or molecules. Having this in mind, we note that, (i) in layer 4B we obtain the same value for the mass of corundum, a greater amount of fosterite

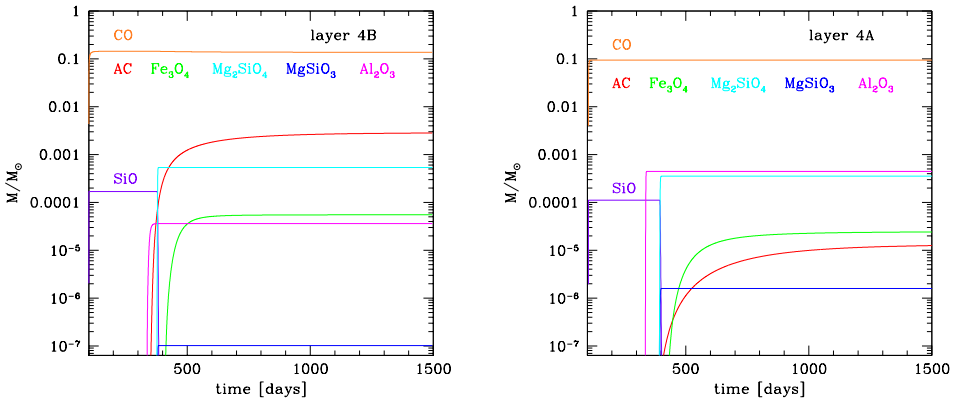


**Figure 1:** Time evolution of the CO, SiO and dust masses for the 4A (left) and 4B (right) layers of the $Z = Z_\odot$, $15\,M_\odot$ SN model with a $^{56}$Ni mass of $0.075 M_\odot$ by [5].

and, differently from [5], we find a small amount of magnetite and of amorphous carbon; (ii) in layer 4A we find a greater mass of corundum and fosterite and a small amount of magnetite and of amorphous carbon; (iii) in both layers, we find a larger total mass of dust. This suggests that differences in the resulting dust masses can not be ascribed to differences in the evolution of molecular species. In fact, at the onset of nucleation, the improved molecular network predicts CO and SiO masses that are in excellent agreement with the values obtained by [5].

## 2. Dust formation in Population III Supernovae

Pop III SNae are the first metal pollutors. Yet, theoretical predictions have to rely on poorly constrained physical parameters, such as the mass of Pop III stars and their physical properties. We use detailed pre-supernova and supernova explosion models for metal free stellar progenitors with mass ranging between 13 to 80 $M_\odot$ developed by Limongi & Chieffi (2012). A detailed description of the dust mass produced is presented in [9], where we also discuss the dependence of the dust mass and composition on the level of mixing of the ejecta. Here we present the results for a metal-free $15 M_\odot$ progenitor in two test cases, where the energy of the explosion and the mass-cut where chosen so as to minimize the scatter between the predicted elemental composition of the ejecta and the observed surface abundance pattern of the "average" Cayrel star ([11]) and of a carbon-enhanced hyper-iron poor star ([12]) in the Galactic halo. Fig. 2 shows that the resulting dust masses are, respectively, $0.31 M_\odot$ and $0.17 M_\odot$, large enough to change the cooling properties of the star forming gas, allowing the formation of these hyper-iron poor low-mass stars. The dust composition, however, is very different in the two cases, being dominated by silicate grains in the first case and by carbon grains in the second case, reflecting the initial chemical composition of the SN ejecta. Our results show the potential of stellar archaeology with the most metal-poor stars to constrain the physical properties of the first supernovae and their role in the earliest phases of star formation and chemical enrichment of the Universe.

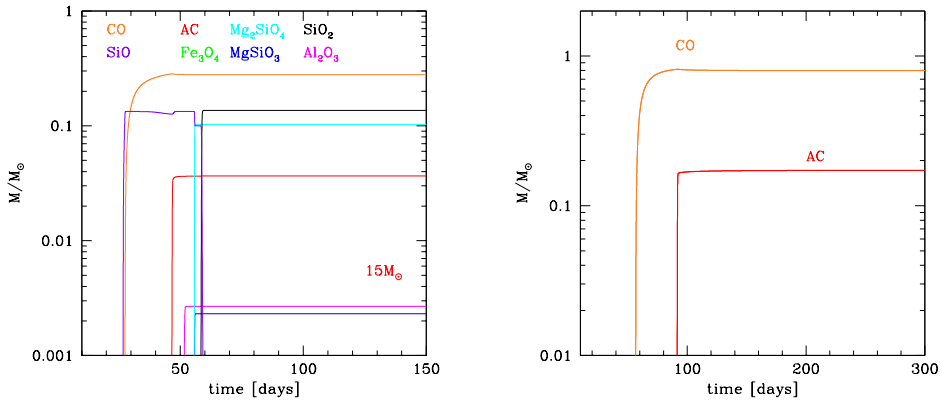


**Figure 2:** Time evolution of molecules and dust masses for a $Z = 0$, $15\,M_\odot$ SN model. Explosion properties are set to minimize the difference between the elemental composition and the surface abundance pattern of the "average" Cayrel star (left) and of a C-enhanced hyper-iron poor star (right, see text).

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