Dust Formation in Very Massive Primordial Supernovae

R. Schneider 1,2, A. Ferrara 3 & R. Salvaterra 3

1INAF/Osservatorio Astrofisico di Arcetri, L.go E. Fermi 5, 50125 Firenze, Italy
2"Enrico Fermi" Center, Via Panisperna 89/A, 00184 Roma, Italy
3SISSA/International School for Advanced Studies, Via Beirut 4, 34100 Trieste, Italy

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ABSTRACT

At redshift \( z \gtrsim 5 \) Type II supernovae (SNII) are the only known dust sources with evolutionary timescales shorter than the Hubble time. We extend the model of dust formation in the ejecta of SNII by Todini & Ferrara (2001) to investigate the same process in pair-instability supernovae (SN\( \gamma \)), which are thought to arise from the explosion of the first, metal free, very massive (140-260 \( M_\odot \)) stars in the Universe. We find that 7%-20% of the SN\( \gamma \) progenitor mass is converted into dust, a value > 10 times higher than for SNII of zero metallicity; however, SN\( \gamma \) dust depletion factors (fraction of produced metals locked into dust grains) are smaller (< 40%) than SNII ones. These conclusions depend very weakly on the thermodynamics of the ejecta, which instead affect considerably the grain formation epoch, composition and size distribution. For the fiducial adiabatic index \( \gamma = 1.25 \) grain condensation starts \( \approx 50 \) yr after the explosion; silicate (magnetite) grains form in stars with mass \( M < 200M_\odot \) (\( M > 200M_\odot \)); carbon grains never form as the available C is locked into CO molecules; typical grain sizes are very small (\( \approx 10 \) Å). We give the dust depletion factors for various elements of observational relevance and a brief discussion of the implications of dust formation for the IMF evolution of the first stars, cosmic reionization and the intergalactic medium.

Key words: galaxies: formation - first stars - supernovae:general - dust - cosmology: theory

1 INTRODUCTION

In the recent years, dust has been recognized to have an increasingly important role in our understanding of the near and distant Universe. The dramatic effect of dust at low and moderate redshifts has been immediately recognized when a reconstruction of the cosmic star formation history from rest-frame UV/visible emission was first attempted: dust grains absorb stellar light and re-emit it in the FIR. Thus, even a tiny amount of dust extinction can lead to a severe underestimate of the actual star formation rate (Pettini et al. 1998; Steidel et al. 1999). New IR, FIR and submm facilities have revealed the existence of populations of sources, such as SCUBA \( z \gtrsim 1 \) sources, that are thought to be dust-enshrouded star forming galaxies or AGNs (Smail et al. 1997; Hughes et al. 1998) or the Extremely Red Objects, which are at least partly populated by dusty star-forming systems at \( z \sim 1 \) (Cimatti et al. 2002). Finally, dust plays a critical role in galaxy evolution, accelerating the formation of molecular hydrogen (\( H_2 \)), dominating the heating of gas through emission of photoelectrons in regions where UV fields are present and contributing to gas cooling through IR emission (see Draine 2003 for a recent thorough review).

These observational evidences have motivated a series of studies aimed at including a treatment of dust formation within galaxy evolution models (Granato et al. 2000; Hirashita & Ferrara 2002; Morgan & Edmunds 2003). Since dust formation in the interstellar medium (ISM) is extremely inefficient (Tielens 1998), the preferential sites of formation are considered to be the atmospheres of evolved low-mass (\( M < 8M_\odot \)) stars, from where it is transported into the ISM through stellar winds (Whittet 1992). However, this mechanism can not explain the presence of dust at redshifts > 5 because at these high redshifts the evolutionary timescales of low-mass stars start to be comparable with the age of the Universe (0.1 - 1 Gyr).

Evidences for the presence of dust at high redshifts come from observations of damped Ly\( \alpha \) systems (Pettini et al. 1994; Prochaska & Wolfe 2002; Peroux et al. 2002) and from the detection of dust thermal emission from high redshift QSOs selected from the SDSS survey out to redshifts 5.5 and re-observed at mm wavelengths (Omont et al. 2001; Carilli et al. 2001; Bertoldi & Cox 2002). Very recently, Bertoldi et al. (2003) have reported the observations of three \( z > 6 \) SDSS QSOs at 1.2 mm, detecting thermal dust radiation. From the IR luminosities, the estimated dust masses are huge (> \( 10^8 M_\odot \)) implying a high abundance of heavy elements and dust at redshifts as high as 6.4 that...
can not be accounted by low-mass stars. Thus, dust enrichment must have occurred primarily on considerably shorter timescales in the ejecta of supernova explosions (Dwek & Scalo 1980; Kozasa, Hasegawa & Nomoto 1989; Todini & Ferrara 2001).

The strongest evidence for dust formation in supernova explosions was seen in SN 1987A (Moseley et al. 1989; Wooden 1997). In this event, the increased IR emission was accompanied by a a corresponding decrease in the optical emission and the emission-line profiles were observed to shift toward the blue (McCray 1993). In another supernova explosion, SN 1998S, the observed evolution of the hydrogen and helium line profiles argues in favor of dust formation within the ejecta as the redshifted side of the profile steadily faded while the blueshifted side remained constant (Gerardy et al. 2000). Dust emission has been seen in the supernova remnant Cassiopea A: similarly to SN 1987A, the total dust mass derived from IR luminosities is less than expected from theory, suggesting that a colder population of dust grains may be present that emit at longer wavelengths (see Gerardy et al. 2002 and references therein). This IR excess has been generally interpreted as due to thermal emission from dust forming in the ejecta but alternative explanations exist; in particular, new IR observations of five Type II SNe have shown late-time emission that remains bright many years after the maximum and that it is hard to reconcile with emission from newly formed dust; IR echoes from pre-existing dust in the circumstellar medium heated by the supernova flash might represent an alternative interpretation (Gerardy et al. 2002).

Theoretical studies have started to investigate the process of dust formation in expanding SN ejecta. Most of the available models are based on classical nucleation theory and grain growth (Kozasa et al. 1980; Todini & Ferrara 2001). The model developed by Todini & Ferrara (2001) is able to predict the dust mass and properties as a function of the initial stellar progenitor mass and metallicity. In spite of the many uncertainties and approximations, this model has been shown to satisfactorily reproduce the observed properties of SN 1987A and of the young dwarf galaxy SBS 0335-052 (Hirashita, Hunt & Ferrara 2002).

In this paper, we investigate the formation of dust grains in the ejecta of very massive primordial supernovae, which are commonly known as pair instability SNe (SN$_{\gamma\gamma}$). These violent explosions are thought to terminate the life of metal-free stars with initial mass in the range 140$M_\odot \lesssim M \lesssim 260M_\odot$ (Heger & Woosley 2002). Indeed, detailed theoretical modelling of the nucleosynthesis and internal structure of these very massive stars has shown that after central helium burning electron/positron pairs are created, converting a large fraction of internal energy into rest mass of the pairs; as a consequence, the stars rapidly contract until explosive oxygen and silicon burning is able to revert the collapse and the stars are completely disrupted in giant explosions, leaving no remnants (Fryer, Woosley & Heger 2001). Below and above the mass range of SN$_{\gamma\gamma}$, the most likely outcome of the evolution of metal-free stars appears to be black hole formation, cleanly separating the contribution to metal and eventually dust production of such very massive stars from those of other masses.

We base our analysis on the model developed by Todini & Ferrara (2001) and apply it to SN$_{\gamma\gamma}$. This means that we change the initial chemical composition of the ejecta and also the thermodynamical/dynamical properties which determine the ejecta evolution. The positive aspects are that we expect a larger amount of dust as a consequence of the larger amount of metals released by SN$_{\gamma\gamma}$ with respect to Type II SNe and the absence of fallback of material onto the compact remnant (no remnant is expected to survive SN$_{\gamma\gamma}$ explosions). The main shortcoming of this approach is that we still have to calibrate some properties of the model on the observed features of SN1987A.

The main motivation of the present study comes from the increasing number of evidences which seem to indicate that the first stars that were able to form in the early Universe from the collapse of metal-free gas clouds were indeed very massive, with characteristic masses of a few 100 $M_\odot$. These include detailed numerical simulations (Abel, Bryan & Norman 2000, 2002; Bromm, Coppi & Larson 1999, 2002; Bromm et al. 2001; Ripamonti et al. 2002), semi-analytic models (Omukai & Nishi 1998; Nakamura & Umemura 2001, 2002; Schneider et al. 2002) and several pieces of observations (Hernandez & Ferrara 2001; Oh et al. 2001; Salvaterra & Ferrara 2003; Schneider et al. 2003). In particular, some of these studies have pointed out that because of the reduced gas cooling efficiency, low-mass star formation is strongly inhibited before a minimum level of metal enrichment of the collapsing gas cloud has been reached (Bromm et al. 2001, Schneider et al. 2002). The value of this minimum level, $Z_{cr}$ is very uncertain, but likely to be between $10^{-6}$ and $10^{-4}Z_\odot$ (Schneider et al. 2002). Within this critical range of metallicities, the presence of dust appears to have a major role, providing an additional pathway for cooling the gas, that fragments into lower mass clumps enabling the formation of second-generation low-mass stars (Schneider et al. 2003). Thus, to estimate the efficiency of this dust-regulated low-mass star formation channel in very metal-poor gas clouds, it is crucial to develop a model which is able to predict the efficiency of dust formation in the ejecta of SN$_{\gamma\gamma}$.

The outcomes of this study have several important cosmological implications: if dust formation efficiencies in SN$_{\gamma\gamma}$ appear to be significant, this will affect the mechanisms which ultimately lead to a transition from a high-mass star formation mode (or from a top-heavy IMF) to a normal star formation mode (or to a Salpeter-type IMF). This so-called chemical feedback of the first episodes of star formation onto the subsequent generations of stars has a tremendous impact on the metal-enrichment and reionization histories of the intergalactic medium (IGM), especially after the strong indications for an early epoch of reionization by the first year of observations of WMAP (Kogut et al. 2003).

The paper is organized as follows: in Section 2 we present the dust formation model, which is an extension of the model already described in Todini & Ferrara (2001). In Section 3 we show the basic results and we illustrate how variations in some input parameters affect the final dust mass and composition. Finally, in section 4 we discuss the implications of the above findings and evaluate their cosmological impact.
2 DUST FORMATION MODEL

The process of dust formation and the resulting dust grain properties depend on the physical conditions at the site of formation. In particular, several studies (see Kozasa, Hasegawa & Nomoto 1989 and references therein) have shown that the time of onset of grain formation depends on the temperature structure in the supernova ejecta whereas the grain composition mainly reflects its chemical composition, which depends on the nucleosynthesis occurring during stellar lifetime (i.e. on the progenitor mass) and explosion.

Thus, models of dust formation in supernova ejecta are based on specific prescriptions for the chemical composition and thermodynamics of the expanding gas. At the onset of shock generation, which occurs at the boundary of the innermost Fe-Ni core, the progenitor star is characterized by the standard stratified (onion-skin) structure. During shock propagation through the star, the gas undergoes a new phase of (explosive) nucleosynthesis and mixing of the internal layers is thought to occur at least up to the outer edge of the helium layer, as suggested by observations of early emergence of \( \gamma \) and X-rays in SN 1987A (Kumagai et al. 1988 and references therein).

The model of Todini & Ferrara (2001) (but see also Kozasa et al. 1989) is based on the assumption that materials are uniformly mixed from the center to the helium outer edge. As a consequence, the temperature and density within this metal-rich volume are assumed to be constant. When the shock reaches the surface of the progenitor, the star starts to expand and the expansion becomes homologous. Thus, the velocity of gas at a given layer is constant in time and proportional to the radius from the center, i.e. \( v = R/t \), where \( t \) is the time from the explosion and the expansion velocity is assumed to be

\[
v = \left( \frac{E_{\text{kin}}}{M_{\text{tot}}} \right)^{1/2}
\]

where \( E_{\text{kin}} \) and \( M_{\text{tot}} \) are the kinetic energy and total mass ejected by the supernova. The temperature of the expanding ejecta is determined by various heating and cooling mechanisms. However, Todini & Ferrara (2001) following Kozasa et al. (1988) assumed that when the gas reaches the photosphere, the gas temperature is equal to the photospheric temperature and thereafter the temperature evolution follows from the assumptions of adiabatic expansion for a perfect-gas, so that

\[
T = T_i \left( 1 + \frac{v}{R_i t} \right)^{3(1-\gamma)}.
\]

where \( \gamma \) is the adiabatic index and the quantities \( T_i \) and \( R_i \) are the photospheric temperature and radius obtained from the observational results of SN 1987A (Catchpole et al. 1987). As a consequence of the expansion, the gas density decreases and the photosphere moves inward and overlaps with the outer edge of the helium layer about 70 days after the explosion when the photospheric temperature and radius are 5400 K and 1.6 \( \times \) 10\(^{15} \) cm respectively. Therefore, these latter values are considered to be the “effective” \( T_i \) and \( R_i \) in the above equation and the adiabatic index is set to be constant and equal to 1.25, following Kozasa et al. (1989). The evolution and internal structure of SN\( \gamma \gamma \) have been studied in detail through numerical simulations (Fryer, Woosley & Heger 2001; Heger & Woosley 2002).

Zero-metallicity progenitor stars with masses between 140 \( M_\odot \) and 260\( M_\odot \) evolve without significant mass loss until central helium burning. These stars, after central helium depletion, have enough central entropy that they enter a temperature and density regime in which electron/positron pairs are created in abundance, converting internal gas energy into rest mass of the pairs, without contributing much to the pressure. When this instability is encountered, the stars contract rapidly until explosive oxygen and silicon burning produce enough energy to revert the collapse and the stars are completely disrupted in a giant explosion. The maximum central temperature and density during the bounce as a function of the SN\( \gamma \gamma \) progenitor mass together with the elemental composition of the emerging ejecta are shown in Fig. 1. The dominant metal yields show that nucleosynthesis in SN\( \gamma \gamma \) produce a total mass of O, Si, Mg and Al which is roughly independent of the initial progenitor mass but an Fe mass which varies greatly with the mass of the progenitor, being almost negligible for initial stellar masses \(< 200 M_\odot \). It is important to stress that this should be interpreted as the iron mass only after all unstable isotopes have decayed. Indeed, unlike Type II SN progenitors, SN\( \gamma \gamma \) progenitors do not build up an iron core before the explosion and the final Fe mass is generated through the decay of \( ^{56}Co \). We will consider this process in detail as this decay provides the relevant destruction process of CO molecules.

The internal structure of the star at this maximum central density appears to have an approximately constant den-
Dynamics and thermodynamics of the ejecta for a 200 $M_{\odot}$ SN$_{\gamma\gamma}$. Top panel: time evolution of the radius of the ejecta, Log [R/km]. Medium panel: time evolution of the number density of the ejecta, Log [n/cm$^3$]. Bottom panel: time evolution of the temperature, Log [T/K], assuming adiabatic expansion with three different values of the adiabatic index, $\gamma = 5/3, 4/3$ and 1.25. The two horizontal lines mark the temperature regime suitable for grain condensation.

In the model of Todini & Ferrara (2001), the formation of dust grains from a gaseous metal-rich medium is described as a two step process: (i) the formation of “critical clusters” at the corresponding condensation barrier and (ii) the subsequent growth of these clusters into macroscopic dust grains through mass accretion. A thorough description of the model, which follows the classic theory of nucleation, can be found in the paper of Todini & Ferrara (2001) to which we refer interested readers.

In the present study, we follow the formation of six solid compounds, namely, Al$_2$O$_3$ (corundum), iron, Fe$_3$O$_4$ (magnetite), MgSiO$_3$ (ensatite), Mg$_2$SiO$_4$ (forsterite) and amorphous carbon (AC) grains. The chemical reactions and numerical constants used in the calculations are summarized in Table 1 of Todini & Ferrara (2001). It is important to note that, as we will see, AC grains can form also if the ejecta composition is richer in oxygen than in carbon ($O > C$) as Clayton, Liu & Dalgarno (1999) have shown. The formation of CO and SiO molecules in SN ejecta can be very important for dust formation, because carbon atoms bound in CO molecules are not available to form AC grains and SiO molecules take part in the reactions which lead to the formation of MgSiO$_3$ and Mg$_2$SiO$_4$. Thus, the process of molecule formation in the expanding ejecta is followed at temperatures $T \lesssim 2 \times 10^4$ K together with the $^{56}$Co $\rightarrow$ $^{56}$Fe radioactive decay as the impact with energetic electrons produced during this decay represents the main destruction process of CO molecules.

The formation of dust grains is followed until the temperature of the ejecta has decreased to about 500 K, where the condensation processes are terminated for all solid compounds.

The time evolution of the dust mass synthetized in different compounds is shown in Fig. 3 for three SN$_{\gamma\gamma}$ progenitor masses, 150$M_{\odot}$, 200$M_{\odot}$ and 250$M_{\odot}$. Dust grains start to condensate when the temperature of the expanding gas has dropped below 1100 K, about 40-60 yrs after the explosion (see the dotted lines). During this long time interval, all the $^{56}$Co initially present in the ejecta has decayed to Fe (the e-folding time of $^{56}$Co is 111.26 days). Thus, at the onset of grain condensation, C atoms are mostly bound in CO molecules and AC grains are not formed. The resulting dust mass is mainly composed by silicates and magnetite grains. Silicates are the first to form, followed by Fe$_3$O$_4$. This evolutionary sequence simply reflects the different condensation temperatures (higher for silicates than for magnetite grains).

The total dust mass formed in different solid compounds and the total mass of CO and SiO molecules as a function of the progenitor stellar mass are shown in Fig. 4. During the explosion, a significant amount of CO mass is produced, independently of the initial progenitors mass. As expected, all C initially present in the ejecta has decayed to Fe and the total CO mass is depleted onto CO molecules and AC grains are not formed. The O mass which is not bound in CO molecules is available to form other dust compounds. At the lowest mass bin, 140$M_{\odot}$, the Si mass is not large enough to favour the formation of silicates and Al$_2$O$_3$ grains are formed. At higher initial stellar masses, silicates form binding all the available O and consequently corundum is no longer present in the ejecta. Finally, progenitors with $M \geq 200M_{\odot}$ produce a significantly larger mass...
of Fe favouring the formation of magnetite grains, which appear to be the dominant compound in this mass range.

### 3.1 Dependence on model parameters

Finally, we have investigated the sensitivity of the above results to variations of the adiabatic index. In particular, so far our model was based on a particular choice of the adiabatic index, \( \gamma = 1.25 \), taken from Kozasa et al. (1989). There is no explicit estimate of the appropriate value of \( \gamma \) in expanding SN\(_{\gamma\gamma}\) ejecta in the literature. However, the internal structure of the 250\(M_\odot\) star at maximum central density in the simulation of Fryer et al. (2001), shows a density and temperature profiles in the outer H-envelope compatible with a value for the adiabatic index of \( \sim 4/3 \) (see their Fig. 1). Since the adiabatic index is a measure of the ability of the gas to cool, we expect that assuming \( \gamma = 4/3 \) the gas in the ejecta will reach the supersaturation phase much earlier in time, when the volume of the ejecta is smaller and the gas density is higher. This, in turn, controls the efficiency of grain accretion and favours the formation of larger grains. In Table 1, we show the characteristic size of different compounds formed by a 200\(M_\odot\) SN\(_{\gamma\gamma}\) assuming \( \gamma = 1.25 \) and \( \gamma = 4/3 \). As expected, in the first case the typical grain sizes for all compounds formed are less than 10\(\text{Å}\) whereas in the second case much larger grains are able to form. In spite of their large condensation temperatures, magnetite grains can only grow up to a few hundreds \(\text{Å}\) because of the relatively small abundance of Al in the ejecta. Conversely, AC grains grow very efficiently until complete carbon depletion, forming grains with radii which can be as large as 20000\(\text{Å}\).
Table 1. Characteristic grain sizes (in Å) synthetized in the ejecta of a 200 $M_\odot$ SN$_{\gamma\gamma}$ for different dust compounds and assuming two possible values for the adiabatic index, $\gamma = 1.25$ and $\gamma = 4/3$.

<table>
<thead>
<tr>
<th>$\gamma$</th>
<th>Al$_2$O$_3$</th>
<th>Fe$_3$O$_4$</th>
<th>MgSiO$_3$</th>
<th>Mg$_2$SiO$_4$</th>
<th>AC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25</td>
<td>[4 - 10]</td>
<td>[1 - 8]</td>
<td>[1 - 10]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4/3</td>
<td>[30 - 400]</td>
<td>[70 - 500]</td>
<td>[500 - 4000]</td>
<td>[2000 - 20000]</td>
<td></td>
</tr>
</tbody>
</table>

3.2 Depletion factors

The cosmological relevance of dust synthetized in SN$_{\gamma\gamma}$ explosions will depend mainly on the global properties of dust rather than on the nature and size of the different compounds. In Fig. 7 we show the total dust depletion factor, defined as the dust-to-metal mass ratio released in the explosion, $f_{dep} = M_{dust}/M_{met}$ as a function of SN$_{\gamma\gamma}$ progenitor mass assuming $\gamma = 1.25$ and $\gamma = 4/3$. In the first case, $f_{dep}$ depends sensibly on the initial progenitor mass and ranges between 1% for a 155$M_\odot$ SN$_{\gamma\gamma}$ up to 40% for the highest progenitor masses whereas in the second case we find an almost constant depletion factor of $f_{dep} \approx 0.1$. In the bottom panel of the same Figure, we show the ratio of the total dust mass and the initial progenitor stellar mass. In the model with adiabatic index $\gamma = 4/3$, approximately 7% of the initial progenitor mass is synthetized in dust grains. Conversely, if an adiabatic index $\gamma = 1.25$ is assumed, this ratio ranges between 0.7% up to 20% for the highest progenitor masses.

For comparison, in Fig. 8 we show the same quantities but for Type II SNe. Following Todini & Ferrara (2001), we show two cases corresponding to two different choices for the total kinetic energy released in the explosion: case A corresponds to the low kinetic energy model ($1.2 \times 10^{51}$erg) and case B refers to the high kinetic energy model ($1.9 \times 10^{52}$erg) (see also the original paper of Woosley & Weaver 1995). We also assume two different values for the initial metallicity of the progenitor stars, $Z = 0$ (dots) and $Z = Z_\odot$ (squares).

The moderate metal yields in Type II SNe and the effect of fallback of material after the explosion onto the compact remnant are responsible for depletion factors which are significantly higher than for SN$_{\gamma\gamma}$, with values ranging from 20% up to 70% for $Z = 0$ progenitors with masses $< 22M_\odot$. 

Figure 5. Time evolution of the dust mass in different solid compounds synthetized by a 150$M_\odot$ (top panel), 200$M_\odot$ (medium panel) and 250$M_\odot$ (bottom panel) SN$_{\gamma\gamma}$ assuming a model for the ejecta evolution with an adiabatic index $\gamma = 4/3$. The different lines correspond to Mg$_2$SiO$_4$ (short-dashed), Al$_2$O$_3$ (long-dashed), Fe$_3$O$_4$ (solid) and AC grains (dot-dashed). The dotted lines indicate the corresponding values of the temperature of the ejecta.

Figure 6. Final mass of different dust compounds (top panel and molecules bottom panel) formed in SN$_{\gamma\gamma}$ ejecta as a function of the progenitor mass assuming a model for the ejecta evolution with adiabatic index $\gamma = 4/3$. Iron grains are never formed but in this case corundum and AC grains are able to form for almost all stellar masses (see text).
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Figure 7. Top panel: total dust depletion factor defined as the dust-to-metal mass ratio as a function of the initial progenitor mass. The two curves refer to two different values of the adiabatic index, $\gamma = 1.25$ and $\gamma = 4/3$. Bottom panel: corresponding values of the ratio between the total dust mass synthetized and the initial progenitor mass.

For larger masses, the depletion factor decreases in case B scenarios (higher kinetic energy) because of the larger amount of metals released. For case A scenarios (lower kinetic energy), instead, 25 $M_\odot$ and 30 $M_\odot$ Type II SNe are predicted to have an $f_{\text{dep}} = 1$. This is due to the fact that because of fallback, these stars eject only a rather small amount of metals, mostly in the form of carbon, which is completely depleted into AC grains. If the stellar progenitors have solar metallicities, the depletion factor ranges between 10% and 50% with a much reduced scatter between case A and B.

In spite of these large depletion factors, the total mass of dust synthetized by SN$_{\gamma\gamma}$ is significantly higher than that produced by Type II SNe. Indeed, as already discussed in Todini & Ferrara (2001), in case A scenarios, $Z = 0$ Type II SNe synthetize a total dust mass which corresponds to a fraction between 0.3 and 4 % of the original stellar progenitor mass (thus, $\sim 0.1 - 0.3 M_\odot$ of dust per SN). These values are slightly larger if case B models are considered. When the initial stellar progenitors have solar metallicity, the resulting dust mass is typically a factor $\sim 3$ larger than for the metal-free case but it is always less than 8 % of the initial stellar mass.

4 DISCUSSION

We have investigated the process of dust formation in the ejecta of first stellar explosions, assuming that the first stars form with characteristic masses of a few 100 $M_\odot$ and explode as pair-instability supernovae. The study is based on an extension of the model developed by Todini & Ferrara (2001) for Type II SNe, which accounts for the different initial chemical compositions of the ejecta and on different dynamical/thermodynamical properties of the ejecta evolution.

The main results of our analysis can be summarized as follows:

(i) In the expanding ejecta of SN$_{\gamma\gamma}$, a significant amount of dust is synthetized out of the heavy elements produced in the progenitor stellar interiors during the main sequence lifetime and at the onset of the explosion due to explosive nucleosynthetic processes. The fraction of the original progenitor mass which is converted into dust depends on the thermodynamics of the explosion and on the progenitor mass, with values ranging between 7 % and 20 %, resulting in $10 M_\odot - 50 M_\odot$ of dust produced per SN. These values are much larger than those found for $Z = 0$ Type II SNe resulting from stars with masses between 12 $M_\odot$ and 40 $M_\odot$ ($0.1 M_\odot - 1 M_\odot$), even if these stars are assumed to be of solar metallicity ($0.1 M_\odot - 2 M_\odot$).

(ii) Because of the large amount of metals released in the explosions, dust depletion factors, defined as the dust-to-metal mass ratios, are smaller for SN$_{\gamma\gamma}$ than for Type II SNe, with values ranging between 1 % and 40 % depending on the thermodynamics of the ejecta and on the progenitor stellar mass.

(iii) The composition and size of the dominant compounds
As a byproduct of the computation, we have estimated different solid compounds. The amount of dust formed and the relative abundance of elements depend critically on the thermodynamics of the ejecta, i.e. on the assumed value of the adiabatic index which controls the temperature evolution of the ejecta and thus determines the epochs and density regimes favorable to dust condensation. In particular, for the two limiting cases explored we find that:

- for $\gamma = 1.25$, grain condensation starts only 40-60 years after the explosions: as a result, AC grains never form and the dominant compounds are silicates (MgSiO$_3$ and MgSiO$_4$) for initial stellar masses $< 200 M_{\odot}$ and magnetite grains for progenitors with larger mass. Because of the large volume of the ejecta, the process of grain accretion is rather inefficient and the typical grain sizes never exceed 10 Å.
- for $\gamma = 4/3$ the grain properties are closer to those found for Type II SNe by Todini & Ferrara (2001): grain condensation starts only 50 - 150 days after the explosion and silicates, magnetite and AC grains are formed. The dominant compound for all progenitor masses is forsterite MgSiO$_3$ while the contribution of AC grains and magnetite grows with progenitor mass. In this case, grain accretion is much more efficient, leading to grain sizes which are never smaller than a few 10 Å and that can be as large as 10$^4$ Å.

(iv) As a byproduct of the computation, we have estimated the total mass of SiO and CO molecules synthesized in the explosions: a SiO mass which ranges between 0.1$M_{\odot}$ and 0.4$M_{\odot}$ is produced, nearly independent of the assumed value for the adiabatic index. Conversely, the mass of CO molecules formed depends on the adiabatic index: for $\gamma = 1.25$ all C initially available in the ejecta is depleted onto CO molecules and roughly 10$M_{\odot}$ of CO are formed, independently of the progenitor mass. For $\gamma = 4/3$, the total mass of CO molecules formed decreases with progenitor mass, with values ranging from 0.1$M_{\odot}$ to 10$M_{\odot}$.

The above results have been obtained under the assumption that the heavy elements present in the ejecta at the onset of the explosion are uniformly mixed up to the outer edge of the helium core. In dust formation models developed so far (Kozasa et al. 1989; Todini & Ferrara 2001, Nozawa et al. 2003) this approximation was motivated by the early emergence of X-rays and $\gamma$-rays in SN 1987A, which suggested mixing in the ejecta at least up to the helium core edge (Kumagai et al. 1988). The use of multi-dimensional hydrodynamic codes to model the observed light curves has made clear that mixing occurs on macroscopic scales through the development of Rayleigh-Taylor instabilities: these instabilities arise at the interface between elemental zones and grow non-linearly to produce (i) fingers of heavy elements projected outwards with high velocities and (ii) mixing of lighter elements down to regions that have lower velocities (Wooden 1997). As a result, the gas in the ejecta is mixed into regions which are still chemically homogeneous and which cool with different timescales, whereas only small clumps in the ejecta are microscopically mixed. It is reasonable to expect that such a structure would affect the process of dust formation, changing both the total amount of dust formed and the relative abundance of different solid compounds.

A related aspect of the model which requires deeper investigation is the assumed temperature structure of the gas within the ejecta, i.e. the assumed adiabatic index. As we have emphasized above, the resulting dust mass and composition depends critically on the cooling timescales of the gas. The temperature and density structure of the stellar interior at the onset of the 250 $M_{\odot}$ SN$_{\gamma\gamma}$ explosion in the simulation of Fryer et al. (2001) seems to favour a value for the adiabatic index of $\gamma = 4/3$ but a self-consistent model which takes into account the impact of the decays of radioactive elements would be highly desirable.

Finally, to quantify the cosmic relevance of dust formation in the early Universe, we should restrict the analysis to the fraction of the newly formed dust which is able to survive the impact of the reverse shock, following thereafter the fate of the surrounding metal-enriched gas. The process of dust sputtering dissociates the grains into their metal components and might have an important role in cosmic metal enrichment (Bianchi & Ferrara 2003). However, new theoretical models seem to indicate that the post-shock temperature enters the regime suitable for dust condensation inside the oxygen layer, because of the high cooling efficiency of this element, but remains substantially higher in the outer He and H layers. If this is the case, then the reverse shock might lead to an increase in the total amount of dust formed rather than decreasing it.

5 COSMOLOGICAL IMPLICATIONS

Our analysis shows that if the first stars formed according to a top-heavy IMF and a fraction of them exploded as SN$_{\gamma\gamma}$, a large amount of dust is produced in the early Universe. In this section, we discuss some of the main cosmological implications of this result, with particular emphasis on its role in the thermodynamics of the gas that will be later incorporated into subsequent generations of objects.

Recent numerical and semi-analytical models for the collapse of star-forming gas clouds in the early Universe have shown that because of the absence of metals and the reduced cooling ability of the gas, the formation of low-mass stars is strongly inhibited. In particular, below a critical threshold level of metallicity of $Z_{\text{crit}} = 10^{-5.5} Z_{\odot}$ cooling and fragmentation of the gas clouds stop when the temperature reaches a few hundreds K (minimum temperature for H$_2$ cooling) and the corresponding Jeans mass is of the order of $10^3 - 10^4 M_{\odot}$ (Schneider et al. 2002). Gas clouds with mass comparable to the Jeans mass start to gravitationally collapse without further fragmentation, until a central protostellar core is formed which rapidly grows in mass through gas accretion from the surrounding envelope. The absence of metals and dust in the accretion flow and the high gas temperature favour very high accretion efficiencies and the resulting stars can be as massive as 600 $M_{\odot}$ (Omukai & Palla 2003).

As the gas becomes more and more enriched with heavy elements, the cooling rate increases because of metal (especially C and O) line emission. More importantly, if a fraction of the available metals is depleted onto dust grains, dust-gas thermal exchanges activate a new phase of cooling and fragmentation which enables the formation of gas clumps with low-mass (Schneider et al. 2003). In particular, if the metallicity of the star forming gas clouds exceeds $10^{-4} Z_{\odot}$, this dust-driven cooling pathway is irrelevant because cooling via
metal-line emission by itself is able to fragment the gas down to characteristic Jeans masses in the range $10^{-2} - 1 M_\odot$. At the same time, if the metallicity of the gas is below $10^{-5} Z_\odot$, even if all the available metals are assumed to be depleted onto dust grains, the resulting cooling efficiency is too low to activate fragmentation and the resulting Jeans masses are as large as in the metal-free case ($10^3 - 10^4 M_\odot$). Thus, we can conclude that the presence of dust is crucial to determine the final mass of stars forming out of gas clouds with metallicities in the critical range $Z_{cr} = 10^{-5 \pm 1} Z_\odot$. As a reference value, for a metallicity of $Z = 10^{-5} Z_\odot$, if 20% of the metals are depleted onto dust grains ($f_{dep} = 0.2$) the resulting mass of the collapsing clouds is reduced to $10^{-2} - 10^{-1} Z_\odot$ and can lead to low-mass stars. This is marginally consistent with the dust formation model with $\gamma = 4/3$ and progenitor masses larger than $150 M_\odot$ and fully consistent with the model with $\gamma = 1.25$ and progenitor masses larger than $220 M_\odot$ (see Fig. 7).

Finally, we can not neglect that our models predict the formation of a significant amount of CO molecules, which can contribute to gas cooling. This aspect needs to be investigated further though we expect that the presence of CO molecules will be complementary to that of dust in the critical range of metallicities.

Therefore, in the emerging picture of galaxy evolution, the first episodes of star formation were characterized by very massive stars forming according to a top-heavy IMF. It is only when the metals and dust ejected by the first SNs are able to pollute a substantial fraction of the IGM, that an overall transition to a normal IMF forming stars with masses comparable to those that we presently observe in the nearby Universe occurs. The epoch of this transition depends crucially on the filling factor of the emitted metals: within metal-enriched regions of the Universe, if the metallicity lies within the critical range, the presence of dust becomes critical and can no longer be neglected in the thermodynamics of the star forming gas. It is very likely that the transition will not occur at a single redshift because of the highly inhomogeneous process of metal enrichment (Scannapieco, Schneider & Ferrara 2003) and that there will be epochs when the two modes of star formation will be coeval in different regions of the Universe.

This might be very important for the reionization history of the IGM. Indeed, very massive metal-free stars are powerful sources of ionizing photons and an early epoch of star formation with a top-heavy IMF can easily match the required high optical depth to electron scattering measured by WMAP (for a general discussion see Ciardi, Ferrara & White 2003). However, an early epoch of reionization is difficult to reconcile with the observed Gunn-Peterson effect in the spectra of z > 6 quasars (Fan et al. 2002) which implies a mass averaged neutral fraction of ~ 1%. These two observational constraints seem to indicate that the reionization history of the Universe might have been more complex than previously thought, with probably two distinct epochs of reionization separated by a relatively small redshift interval in which the Universe might have recombined again. This intermediate epoch of recombination could be the result of a decrease in the ionizing power of luminous sources, probably due to their metal-enrichment and consequent IMF transition.

Finally, an early epoch of reionization, as required by WMAP data, poses another critical issue: after reionization, the temperature of the IGM starts to decline as a consequence of cosmic expansion. By the time it reaches the observable range of redshifts $z < 6$ the temperature of the IGM might be too low to match the observed thermal history (Schaye et al. 2000). The presence of a significant amount of dust synthetized by the first very massive supernovae might be extremely important to raise the IGM temperature through dust photoelectric heating. To estimate the amount of dust in the IGM required to match the observed thermal history, it is necessary to make specific assumptions about the UV background radiation, the reionization history of the IGM and the grain composition and size distribution (Inoue & Kamaya 2003). Furthermore, the properties of dust grains in the IGM may differ from those directly predicted by dust formation models as a consequence of specific selection rules in the transfer of grains from the host galaxies to the IGM (Bianchi & Ferrara 2003), who find that only grains larger than $\approx 0.1 \mu m$ are preferentially ejected in the IGM. These complications are beyond the scope of the present analysis.

Neglecting selection rules in the transfer of dust from host galaxies to the IGM, our model allows us to predict depletion factors for specific elements that may be used in the interpretation of abundance data in the Lyman $\alpha$ forest and damped Lyman $\alpha$ systems (Pettini et al. 1994; Prochaska & Wolfe 2002; Peroux et al. 2002). In Fig. 9 we plot the dust depletion factors for various elements as a function of the progenitor mass assuming two different values for the adiabatic index. In the model with $\gamma = 1.25$ O and Fe depletion are particularly important (more than 10%) for progenitor masses $\gtrsim 180 - 200 M_\odot$. If $\gamma$ is taken to be equal to $4/3$, a

![Figure 9. Dust depletion factors for individual elements as a function of the progenitor stellar mass for adiabatic index $\gamma = 1.25$ (top panel) and adiabatic index $\gamma = 4/3$ (bottom panel).](image-url)
larger variety of elements show significant depletion, particularly Al, C, Si and O.

Finally, it is well known that the presence of dust at high redshifts offers an alternative formation channel for molecular hydrogen, the dominant coolant in the early Universe, which, in the absence of dust, can form only from the gas phase. In small protogalaxies, the H$_2$ formation rate on grain surface becomes dominant with respect to the formation rate from the gas phase, when the dust-to-gas ratio exceeds roughly 5% of the galactic value (Todini & Ferrara 2001). This, in turn, might have very important consequences for the star formation activity at high redshift (Hirashita & Ferrara 2002).

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