Dust Production in the High-Redshift Universe

S. V. Marchenko

Department of Physics and Astronomy, Western Kentucky University, Bowling Green, KY 42101-3576, USA

Abstract. How much dust can be produced in the early Universe? Does dust production depend on the average heavy-metal content of the hosting galaxy? Considering supernova explosions, massive stars (Wolf-Rayet, LBV and RSG), and relatively massive AGB stars among possible dust-generating objects in the early Universe, we find that SN remnants can be regarded as the main source of the primordial dust. However, this conclusion is based on highly uncertain (and probably over-estimated) dust production rates. Despite all the uncertainties, interstellar extinction must be taken into account while observing high-redshift objects.

1. Introduction

Contemplating the general importance of dust, one should take into account the following: \( \sim 50\% \) of optical radiation emitted since the Big Bang by all astrophysical sources has been ‘reprocessed’ by dust. Dust is regarded as an efficient ISM coolant (Lehner, Wakker & Savage 2004), thus controlling accretion and profoundly influencing star-formation rates, especially for massive stars (e.g. Wolfire & Cassinelli 1987). Assembly of \( \text{H}_2 \) on dust grains is far more efficient than in the gas phase. On cosmological scales, dust may distort the cosmic microwave background and change the far-IR background (Elgren & Desert 2004). There are first indications of the presence of dust in high-redshift Lyman-break galaxies (Ando, et al. 2004; Ouchi, et al. 2004) and quasars (Maiolino et al. 2004), which may have serious implication for the estimated star-formation rates (e.g. Schiminovich, et al. 2005).

2. Dust Formation in the Milky Way Galaxy and in the High-Redshift Universe

The detailed galactic census of dust-producing stars (Gehrz 1989) proves that in the modern Universe, relatively low-mass stars dominate the scene. All categories of evolved, post-main-sequence objects (Miras, carbon stars, late-type supergiants, etc.) account for \( \sim 90\% \) of the stellar dust output, while planetary nebulae produce \( < 1\% \). Their high-mass counterparts, supernovae and Wolf-Rayet stars, amount to \( < 10\% \), combined. Dust grains are also manufactured via relatively slow-paced accretion in molecular clouds: \((1-5) \times \) the stellar output. Apparently, in the 1-2 Gyr-old Universe only the high-mass, \( M \geq 3M_\odot \), stellar population may be responsible for accumulation of copious amounts of dust (Table 1). In the Table 1 we provide: (a) the main categories of dust-
producing stars, (b) their initial masses, (c) the total dust yield, per star, (d) the chemistry and (e) the size distribution of dust grains, where ‘st.’ (standard) corresponds to the truncated power-law distribution \cite{Mathis1977}, and ‘sm.’ (small) is used to emphasize the presence of particles with \( a \ll 1 \mu \) sizes.

We separate the cases of normal, solar metallicity and low-Z environments.

| Category          | \( M_{\text{ini}} \) \( \sim M_\odot \) | mass/\( *(M_\odot) \) | Dust composition | Ref. |
|-------------------|-------------------------------|----------------|-----------------|-----|
| SN\(_{\gamma\gamma}\) (PopIII) | 140-260 \( Z \ll Z_\odot \) | \( ?, Z < Z_\odot \) | Si,C,Fe,Al,Mg,O | ‘st.’ (??) 1 |
| SN II             | \( \geq 8 \) | \( 0.1-0.3, Z < Z_\odot \) | Si,C,Fe,Al,Mg,O | ‘st.’, \( \sim 1 \mu \) 2,3 |
| LBV               | \( \geq 75-85 \) \( Z \ll Z_\odot \) | \( 0.01-0.25, Z \sim Z_\odot \) | Si,C,PAH,Al(??) | \( 1 \mu + \text{sm.'} \) 4,5,6,7 |
| WCd               | \( \geq 60-70 \) \( Z \ll Z_\odot \) | \( 10^{-3} - 10^{-2}, Z \sim Z_\odot \) | C(amorph.) | \( 1 \mu + \text{sm.'} \) 8,9,10 |
| sgB[e]            | \( \geq 30-60 \) \( Z \ll Z_\odot \) | \( Z \sim Z_\odot \) | Si | ‘sm.’ 11 |
| B[e]WD            | \( \geq 5 \) | \( Z \ll Z_\odot \) | Si | ‘st.’ (?) |
| RSG               | \( \geq 8-50 \) | \( 10^{-4} - 10^{-3}, Z \sim Z_\odot \) | Si | ‘st.’ \( 0.5 \mu + \text{sm.'} \) 12,13,14 |
| AGB (OH/IR)       | \( \geq 2 - (5-6) \) \( 10^{-3} \) \( M_{\text{ini}}(Z/Z_\odot), Z \ll Z_\odot \) | Si,C,ice | ‘st.’ (?) |

Judging by the multitude of question marks, not much is known about dust formation in low-Z environments. The pair-instability supernovae (SN\(_{\gamma\gamma}\): \cite{Heger2002} belong to the broad category of Population III objects. Though their general characteristics and ability to produce dust are yet to be established, one may assume their dust yields to be comparable with the present-epoch SN events, thus making them the major dust sources in the high-redshift universe. However, one should notice the substantial difference between the total dust outputs of SN events provided by different research groups: the relatively high, \( M_{\text{dust}} \sim 1M_\odot \), estimates of \cite{Dunne2003} and \cite{Morgan2003}, in line with theoretical expectations \cite{Todini2001}, vs. the \( M_{\text{dust}} \sim 10^{-3}M_\odot \) values from \cite{Dwek1992}, \cite{Dwek2004} and \cite{Pozzo2004}. There is a strong indication that at least in some SN events (the Crab nebula, SN2002hh and SN2002ic: \cite{Green2004}; \cite{Barlow2005}; \cite{Kotak2005}) dust comes from a progenitor, either a luminous blue variable (LBV), red supergiant (RSG) or carbon-rich Wolf-Rayet star (WCd). With the lower yields for SN events, the integral output from RSG and WCd stars may rival the SN category. The relatively rare B supergiants with forbidden emission lines, sgB[e] \cite{Lamers1998}, as well as newly discovered
(and probably associated with sgB[e]) class of early-type, luminous stars with warm circumstellar dust, B[e]WD [Miroshnichenko et al. 2005], could be considered as minor contributors, unless the number of related sources is grossly under-estimated. One more category emerges at $z < 9$ and gradually comes to a complete dominance over the dust production in the modern universe: the asymptotic giant-branch stars (AGB). This group shows a clear dependence of dust production on $Z$ [van Loon 2000]. This dependence is less pronounced for SNe [Todini & Ferrara 2001]. For the remaining categories of massive dust-producing stars one may assume that dust production depends on the mass loss rate and use the general $M = f(Z)$ relationship of Vink, de Koter & Lamers [2001].

3. Interstellar Extinction for High-Redshift Objects

Estimating an average extinction for high-redshift objects, we adopt and slightly modify the approach of Loeb & Haiman [1997]. Namely, the dust absorption coefficient, $\alpha_\nu$, is expressed as

$$\alpha_\nu(z, Z) = \rho_{\text{dust}}(z, Z) \kappa_\nu(Z),$$

with dust opacity $\kappa_\nu(Z)$ represented by the Galactic law [Mathis 1990] for a $Z \sim Z_\odot$ environment, or the Small Magellanic Cloud dependence [Cartledge et al. 2005] for $Z < Z_\odot$; $z$ defines the redshift and $Z$ denotes the metallicity. The dust density takes the form

$$\rho_{\text{dust}}(z, Z) = \Omega_b \rho_c (1 + z)^3 \sum_i F_i(z) f_{\text{dep},i}(z) f_{\text{dust},i}(Z),$$

where the sum runs over different categories of dust producers (Table 1), $\rho_c = 9.7 \times 10^{-30} \text{g cm}^{-3}$ provides the current critical density of the universe, and $\Omega_b = 0.044$ gives the total baryonic density. The mass fraction of dust, $f_{\text{dust},i}(Z)$, deposited by a given star depends on the category of dust-producing stars and the ambient metallicity, while the mass fraction of stars being able to produce dust is calculated as

$$f_{\text{dep},i}(z) = \frac{M_2}{M_1} \frac{M_u(z)}{M_u(z)} m^{-(1+x)} dm / \int m^{-(1+x)} dm,$$

with $M_u(z), M_d(z)$ and $x$ depending on the redshift, and $M_1, M_2$ provided by Table 1. Hence, the variable $x$ could be anywhere between $x=0.5$ (‘top-heavy’ mass function) and 1.35 (classical form) at $z \geq 10$, then converging to $x=1.35$ for $z < 10$. We define the $F_i(z)$ term as

$$F_i(z) = \int \eta_i(z') \frac{q_{\text{col}}}{dz'} exp\left(-\frac{t_z - t_{z'}}{T}\right) f_{\text{star}}(z') dz',$$

where the efficiency of star formation $f_{\text{star}}(z)$ is lowered by the presence of compact objects (neutron stars, black holes, white dwarfs) in the overall ‘recycling’
loop: \( f'_{\text{star}}(z) = f_{\text{star}}(z)(1 - \xi f_{\text{star}}(z + dz)) \), with \( \xi = 0.10 - 0.15 \) and \( f_{\text{star}}(z) \) taken from Drory et al. (2005). The upper limit, \( z=20 \), is imposed by the evolution of Population III objects (e.g. Choudhury & Ferrara 2005). We adopt the mass fraction of baryons assembled into collapsed objects, \( F_{\text{col}}(z) \), following Haiman & Loeb (1997). The \( exp(-\frac{t_z - t_z'}{T}) \) term provides the dust survival timescales, with \( T \) ranging from 0.1 to 1.0 Gyr (Draine & Salpeter 1979).

The term \( \eta_i(z) \) introduces evolutionary timescales (i.e. cutoffs) for different categories of dust producers: \( \eta_i(z) = 1 \) for \( z \leq z_{cr,i} \), and \( \eta_i(z) = 0 \) for \( z > z_{cr,i} \).

Then, the optical depth of a dusty medium at a given redshift \( z_s \geq 3 \) is

\[
\tau_{\text{dust}}(\nu, z_s, Z) = \frac{c}{H_0} \int_3^{z_s} \frac{\alpha_\nu(1+z)(z, Z)}{(1+z)^{5/2}} \, dz,
\]

with \( H_0 \) and \( c \) as universal constants. Following the arguments of Loeb & Haiman (1997), we ignore dust production at \( z < 3 \), as it will be generally confined to individual galaxies (dominance of AGB stars; hence, rather low velocities of dust ejecta) rather than \( \sim \)homogeneously distributed along the line of sight.

Figure 1. The dust opacity for a \( z=6 \) object with variable yield from the SN ejecta.

Exploring the different parameters of the model, we confirm the conclusion of Loeb & Haiman (1997) that dust chemistry has relatively small influence on the overall opacity. More serious is the uncertainty in the dust yields of SNe. Considering the theoretical predictions (e.g. Todini & Ferrara 2001), we find that they result in an inappropriately high \( \tau_{\text{dust}} \) for a \( z=6 \) object (Fig. 1). Lowering them by an order of magnitude brings the theoretical yields closer to some estimates from recent observations (e.g. Barlow et al. 2005). With the appropriately adjusted SN output, the average dust opacity may be neglected for \( z \sim 5 \) objects, unless they pass through a star-burst episode, and should be taken into account for \( z \gg 5 \) objects (Fig. 2).

Grouping the dust-producing stars into 3 general categories: SN events vs. massive stars (RGB, LBV, WCd) vs. AGB, and varying the yield from the SN stars, as well as adjusting the dependence of the dust production rate on \( Z \) (metallicity) for the massive stars, we plot two extreme scenarios in Fig. 3.
Figure 2. The average dust opacity for objects with variable $z$. We assume that the re-ionization continues until $z=15$.

Considering the shares of dust production in the modern universe, one may expect that the model with the lowest SN yield and absence of a steep dependence of the dust production rate in massive stars on the ambient metallicity (right panel of Fig. 3) may be closer to reality.

The calculations also show that, on average, the ‘survival’ timescales of the primordial dust, $T \leq 4 \times 10^8$ yr, closely match the current-epoch expectations for the Galaxy (Jones et al. 1994).

Figure 3. Three main groups of dust-producing stars: SN (full lines), massive stars (RSG+LBV+WCd: dotted lines) and AGB (dashed lines). Left panel: the SN rate is lowered to 1/10 of the theoretical predictions and the dust production rate for massive stars depends on $Z$. Right panel: SN rate =1/30 theoretical, no dependence on $Z$ for massive stars.

4. Conclusions

- SN events should be regarded as a major source of dust in the high-redshift ($z > 3$) universe. This conclusion may be independent of the source of dust, unless different sources provide substantially different extinction curves.
It could be either primordial dust coming from a progenitor (LBV, RSG or WCd star), or dust produced in the SN ejecta. However, the most important issue is the ability of dust to survive in the hostile environment: shocks, UV radiation. On an optimistic note, one may mention the case of WCd stars where, facing a similar challenge as in the shocked environments of SN ejecta, the grains of amorphous carbon manage to survive for at least $10^2$ years (Marchenko et al. 2002), thus effectively reaching (and enriching) the ISM.

- Our calculations show that, in order to be comparable to the known output of SN events in the Galaxy (Gehrz 1989), the theoretical estimates of dust production in SNe populating the 1-2 Gyr-old universe should be lowered by an order of magnitude, thus providing a better match to the recent (e.g. Barlow et al. 2005) observations.

- Overall, IS extinction should be appropriately taken into account for all $z \gg 5$ objects in order to estimate their true properties, especially realizing that for some of them, due to the enhanced star-formation rate, the local extinction may substantially exceed the average values (cf. Fig. 2).

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