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The problematic growth of dust in high-redshift galaxies

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ABSTRACT

Dust growth via accretion of gas species has been proposed as the dominant process to increase the amount of dust in galaxies. We show here that this hypothesis encounters severe difficulties that make it unfit to explain the observed UV and IR properties of such systems, particularly at high redshifts. Dust growth in the diffuse ISM phases is hampered by (a) too slow accretion rates, (b) too high dust temperatures, and (c) the Coulomb barrier that effectively blocks accretion. In molecular clouds these problems are largely alleviated. Grains are cold (but not colder than the CMB temperature, $T_{\text{CMB}} \approx 20$ K at redshift $z = 6$). However, in dense environments accreted materials form icy water mantles, perhaps with impurities. Mantles are immediately ($\lesssim 1$ yr) photo-desorbed as grains return to the diffuse ISM at the end of the cloud lifetime, thus erasing any memory of the growth. We conclude that dust attenuating stellar light at high- z must be ready-made stardust largely produced in supernova ejecta.

Key words: dust, extinction – galaxies: high-redshift.

1 INTRODUCTION

Dust grains are a fundamental constituent of the interstellar medium (ISM) of galaxies. A large fraction (≈ 50 per cent in the Milky Way) of the heavy elements produced by nucleosynthetic processes in stellar interiors can be locked into these solid particles. They are vital elements of the ISM multiphase gas life-cycle, and key species for star formation, as they absorb interstellar UV photons, heat and cool the gas. They also catalyse the formation of H_2 on their surfaces, the first step towards the formation of all other ISM molecules, including CO.

The presence of dust at high ($z \gtrsim 6$) redshift implies that conventional dust sources (AGB and evolved stars) are not the dominant contributors. This is because their evolutionary time-scales are close or exceed the Hubble time at that epoch (≈ 1 Gyr). Following the original proposal by Todini & Ferrara (2001), it is now believed that the first cosmic dust grains were formed in the supernova ejecta ending the evolution of fast-evolving massive stars (Hirashita & Ferrara 2002; Bianchi & Schneider 2007; Nozawa et al. 2007; Gall, Hjorth & Andersen 2011; Bocchio et al. 2016). Thus, albeit quasar host galaxies show remarkably high dust masses (Bertoldi et al. 2003; Beelen et al. 2006; Michałowski et al. 2010), in general the dust content of early galaxies rapidly decreases (Capak et al. 2015;

Bouwens et al. 2016). This does not come as a complete surprise given that the mean metallicity of the Universe¹ increases with time.

Usually the presence of dust in high- z galaxies is assessed via a specific observable, the so-called β slope. This is defined as the slope of the rest-frame UV galaxy emission spectrum, $F_\lambda^i \propto \lambda^\beta$, in the wavelength range 1600–2500 Å. As dust extinction typically rises towards shorter wavelengths, a flatter slope indicates the presence of larger amounts of dust. Indeed, this is what has been recently shown by ALMA observations (Capak et al. 2015; Bouwens et al. 2016).

It has been claimed that current observations cannot be explained purely by dust production by sources (either SNe or AGB/evolved stars). Instead, the dominant contribution to the dust mass of high- z galaxies should come from grain growth (Michałowski et al. 2010; Hirashita & Voshchinnikov 2014; Mancini et al. 2015) in the ISM. This can happen only if gas-phase atoms and molecules can stick permanently to grain surfaces (typically consisting of silicate or amorphous carbonaceous materials) and remain bound to the grain solid structure. Simplistic approaches based on a ‘sticking coefficient’ argument predict that the growth time of the grains could be very fast ($\lesssim 1$ Myr). However, such conclusion fails to catch some critical points that we examine here.

¹ Throughout the paper, we assume a flat Universe with the following cosmological parameters: $\Omega_m = 0.308$, $\Omega_\Lambda = 1 - \Omega_m = 0.692$, and $\Omega_b = 0.048$, where Ω_m , Ω_Λ , Ω_b are the total matter, vacuum, and baryonic densities, in units of the critical density, and h is the Hubble constant in units of 100 km/s (Planck Collaboration et al. 2015).

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The first problem is linked to the type of material that silicate or carbonaceous cores tend to accrete. As we will argue in this *Letter*, accretion can only occur in MCs. There, silicate or carbonaceous refractory cores must predominantly accrete the most abundant elements, namely oxygen and carbon, either in atomic or in molecular form (CO). These species condense on grain surfaces where they are hydrogenated, forming icy mantles mainly made up of water, CO, CO₂, ammonia, methane and, possibly, other impurities (Boogert, Gerakines & Whittet 2015). Mantles do not share the same optical properties as refractory cores. However, this is not a relevant point, given that icy mantles are very volatile and rapidly photo-desorbed as grains re-emerge from MCs.

A second problem with the growth scenario arises from the increasing CMB temperature, $T_{\text{CMB}} = T_0(1+z)$ K with $T_0 = 2.725$. While dust in Milky Way molecular clouds typically attains temperatures ≈ 10 – 20 K (Stutz et al. 2010), at high- z dust cannot cool below T_{CMB} . This might represent a serious problem for dust growth, as the warmer surface hampers the sticking ability of particles.

It then appears that if early galaxy properties require a larger amount of UV-absorbing dust particles, we are forced to conclude that the observed grains must be ready-made products of the most efficient high- z factories, i.e. SNe. In the following we show that this is indeed the case.

2 DUST ACCRETION: WHAT AND WHERE

After solid particles condense out of early supernova ejecta, and are possibly processed by the reverse shock, they are injected in the pervasive diffuse phases of the ISM, i.e. the Cold Neutral Medium (CNM; density $n_{\text{C}} \approx 30 \text{ cm}^{-3}$, temperature $T_{\text{C}} \approx 100$ K) and the Warm Neutral Medium (WNM, $n_{\text{W}} \approx 0.4 \text{ cm}^{-3}$, $T_{\text{W}} \approx 8000$ K). Usually, these two phases are considered to be in thermal equilibrium (Field, Goldsmith & Habing 1969; Wolfire et al. 2003; Vallini et al. 2013). However, the multiphase regime exists only in a narrow, metallicity-dependent range of pressures. Outside this regime, the gas settles on a single phase. At high pressures (a more typical situation for denser high- z galaxies), the CNM dominates; at low pressures the WNM takes over. We therefore concentrate in what follows on the CNM. As both destruction and production processes ultimately rely on supernova explosions (Dayal, Hirashita & Ferrara 2010), the equilibrium dust abundance is essentially independent on star formation rate (SFR).

Even if they initially reside in the CNM, grains become periodically embedded into MCs forming out of this phase. This happens on the gas depletion time-scale, $\tau_{\text{g}} \approx M_{\text{g}}/\text{SFR}$, where M_{g} is the total gas mass. In galaxies, τ_{g} decreases with redshift, but it remains close to 10 per cent of the Hubble time at any epoch, i.e. $\tau_{\text{g}} \approx \text{few} \times 100 \text{ Myr}$ at $z = 6$. This time-scale should be compared with the lifetime of MCs, which is much shorter, i.e. $\approx 10 \text{ Myr}$. Thus, it is reasonable to conclude that grains spend a large fraction of their lifetime in the diffuse phase. An important point is that, while in MCs, dust grains are largely shielded from UV radiation and therefore have lower temperatures.

2.1 The grain accretion process

Before analysing the specific cases of the CNM and MCs in high- z galaxies, we recall here the basic theory of grain accretion. Consider grains whose temperature is T_{d} . The grain accretion time-scale, τ_{a} , is set by kinetics and is given by (Spitzer 1978; Umebayashi &

Nakano 1980):

$$\tau_{\text{a}}^{-1} \approx S n_{\text{d}} \pi a^2 v_{\text{s}} \quad (1)$$

where n_{d} is the grain number density (proportional to the hydrogen number density, n_{H} , and metallicity, Z) and a is the average (spherical) grain radius. The most probable species velocity (the maximum of the Maxwell distribution function) is $v_{\text{s}} = (2k_{\text{B}}T/m_{\text{s}})^{1/2}$, i.e. the square root of the ratio of gas temperature and species mass; $S(T_{\text{d}}, m_{\text{s}})$ is the accreting species sticking probability. The latter is a poorly known function of the dust temperature and composition, and of the accreting species. Recently, He, Acharyya & Vidali (2016) reported an experimental determination of the S value for different species and dust temperatures. They propose a general formula to evaluate S from the species binding energy and dust temperature. In the following, we adopt their prescription (namely their equation 1). In practice, though, for $T_{\text{d}} \lesssim 30$ K, and binding energies larger than about $E_{\text{b}}/k_{\text{B}} = 1100$ K, the sticking probability is equal to unity.

Once an atom or molecule has stucked on to the dust grain, its fate depends on the species binding energy, E_{b} , the dust temperature, T_{d} , and the irradiation from FUV and cosmic rays. First, the atom/molecule might be thermally desorbed after a time

$$\tau_{\text{d}}^{-1} \approx \nu_0 \exp(-E_{\text{b}}/k_{\text{B}}T_{\text{d}}) \quad (2)$$

where ν_0 is the vibrational frequency of the sticking species. In general, ν_0 depends on the properties of the grain surface and adsorbed species (Hasegawa, Herbst & Leung 1992). In practice, it is $\approx 10^{12} \text{ s}^{-1}$ for the cases relevant to the present study, namely H, O and Si atoms and water molecules (Minissale, Congiu & Dulieu 2016). The binding energy refers to the van der Waals force, typically a small fraction of eV for many species (see below). Therefore, the desorption rate is very sensitive to T_{d} and it is almost a step function (Collings et al. 2004). In addition to thermal desorption, FUV and cosmic rays may provide enough energy to the accreted species to evict a fraction of them back into the gas (Leger, Jura & Omont 1985; Shen et al. 2004; Bertin et al. 2013). This desorption rate depends on E_{b} and the specific microphysics of the process. It suffices to note here that equation (1) provides, therefore, a lower limit to the actual accretion time.

Finally, a third relevant time-scale is that needed by a species to hop and scan the grain surface. This is known as the ‘scanning time’, and it is given by:

$$\tau_{\text{s}}^{-1} \approx N_{\text{s}}^{-1} \nu_0 \exp(-E_{\text{d}}/k_{\text{B}}T_{\text{d}}). \quad (3)$$

N_{s} is the number of sites of the grain; for $a = 0.1 \mu\text{m}$ and a mean distance between sites of 3.5 \AA , $N_{\text{s}} \approx 10^5$. The diffusion energy, E_{d} , is a poorly known parameter. Usually, this is taken to be a fraction, f_{d} , of the binding energy, i.e. $E_{\text{d}} = f_{\text{d}}E_{\text{b}}$. Experiments give often rather contradictory results, but tend to justify values in the range $f_{\text{d}} = 0.3$ – 0.8 [see discussion in Taquet, Ceccarelli & Kahane (2012)]. For highly reactive species, like H and O, laboratory experiments provide diffusion energies rather than E_{b} . For oxygen, Minissale et al. (2016) find $E_{\text{d}}/k_{\text{B}} = 750$ K and $E_{\text{b}}/k_{\text{B}} = 1320$ K. For H atoms, experiments find $210 \text{ K} < E_{\text{d}}/k_{\text{B}} < 638$ K, depending on adsorbing surface and site (Hornekær et al. 2005; Matar et al. 2008; Hama et al. 2012). However, Hama et al. (2012) showed that the majority of sites have $E_{\text{d}}/k_{\text{B}} = 210$ K. In this study, we assume $E_{\text{b}}/k_{\text{B}} = 500$ K and $E_{\text{d}}/k_{\text{B}} = 210$ K for H, following the majority of astrochemical models. No experimental measurements or theoretical calculations exist for the binding energy of Si atoms, apart from the 2700 K heuristic estimate by Hasegawa & Herbst (1993). Finally, the water binding energy has been measured to be 1870 and 5775 K on bare silicates/amorphous water, respectively (Fraser et al. 2001).

In the following we investigate whether grain growth is possible and what type of condensables can be actually accreted on the bare soil surfaces of the grains. We consider separately the case of the CNM and MC environments and study processes as a function of the galaxy redshift. We will also concentrate on silicates as Weingartner & Draine (2001) showed that for SMC-like extinction curve appropriate for high- z galaxies, the silicate/carbonaceous mass ratio is $\approx 11 : 1$, i.e. C-based grains negligibly contribute to total dust mass.

2.2 Residence in the diffuse phase

Let us consider the case of the CNM, whose properties have been defined above, namely a gas temperature of 100 K and hydrogen nuclei density of 30 cm^{-3} . Assume also that the sticking species is a Si atom (of mass 28 amu). Plugging these values into equation (1) we find

$$\tau_a \approx 1.2 \text{ Gyr} \left(\frac{0.1 Z_\odot}{Z} \right) \left(\frac{a}{0.1 \mu\text{m}} \right) S^{-1}. \quad (4)$$

The binding energy of Si atoms is estimated to be $E_b/k_B = 2700 \text{ K}$ (Hasegawa & Herbst 1993; see above), so that the sticking probability is essentially unity, according to He et al. (2016). This time-scale is very long and even exceeds the Hubble time at $z = 6$. Smaller grains, $a \approx 0.01 \mu\text{m}$, due to their larger surface/mass area, might have proportionally shorter τ_a . However, time scales remain comparable or longer than the depletion time-scale, τ_g , discussed above.

Thus, grain growth in the diffuse ISM is overwhelmingly difficult for at least three reasons. First, the accretion time-scale τ_a is at best comparable to the residence time in the ISM. This means that by the time at which accretion from the gas phase *might* become important, the grain moves from the diffuse to the dense molecular phase. However, the situation is worse than this due to two additional complications.

Grain temperatures in the CNM are rather high (at least compared to that in MCs). Due to their compactness (sizes $\lesssim 1 \text{ kpc}$) and consequently high surface SFR per unit area ($\dot{\Sigma}_* \approx 1 \text{ M}_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$ – about 100 times that of the Milky Way), the interstellar UV field is correspondingly more intense. Roughly scaling the value of the Habing flux with $\dot{\Sigma}_*$ gives a value of $G_0 \approx 100$. Grains achieve temperatures ranging from 30 to 50 K for a typical $a = 0.1 \mu\text{m}$ grain. Smaller grains, which provide most of the surface area for accretion, are even hotter, $T_d = 42\text{--}72 \text{ K}$ (Bouwens et al. 2016, Ferrara et al. 2016). Under these conditions, Si, and O atoms will not remain attached to the grain surface. Instead, they almost instantaneously (fraction of a second) bounce back into the gas (see equation 2).

Further complications arise from the grain charge. Under the action of strong UV irradiation, grains attain a positive charge. For example, Bakes & Tielens (1994) show that a spherical grain located in the CNM and exposed to a UV flux of intensity $G_0 = 1$ (in standard Habing units) attains an equilibrium charge $Z_g \approx +10$. This value must be seen as a lower limit as we mentioned already that G_0 can be up to a factor of 100 higher in early systems. This represents a problem for accretion of key condensable species as, e.g. Si and C. Their ionization potential (11.26 eV for C and 8.15 eV for Si) is lower than 1 Ryd. Thus, even in neutral regions as the CNM these species are ionized. As a result, the Coulomb repulsion between the charged grains and these ions represents a virtually unsurmountable barrier in order for these species to reach the grain surface.

These processes acting against accretion of materials from the surrounding gas by grains lead to conclude that, under the conditions prevailing in high- z galaxies, grain growth in the diffuse ISM phases can be safely excluded. We now turn to the analysis of the MC case.

2.3 Residence in molecular clouds

Accretion conditions become apparently more favourable when grains are incorporated into a newly born MC. There, due to the higher mean gas density ($n = 10^{3-4} \text{ cm}^{-3}$) the gas accretion time-scale becomes shorter. In spite of the lower temperatures ($\approx 10 \text{ K}$), the large density found in MCs boosts the accretion rate with respect to the diffuse ISM by a factor of $\approx 10\text{--}100$. While residing in MCs, dust grains can evolve mostly because of the growth of icy mantles coating the grain refractory cores (e.g. Caselli & Ceccarelli 2012; Boogert et al. 2015).

Due to the attenuation or total suppression of the UV field, grains are colder in MCs. However, at high redshift heating by CMB becomes important and sets the minimum temperature of gas and grains in MCs. This value depends on redshift, and at $z \geq 6$ it is $T_d \geq 19 \text{ K}$. This is about a factor of 2 larger than MC temperatures in the local universe. At these warmer temperatures, processes like thermal desorption (see equation 2) may dominate (or even impede) grain growth.

In the case of MW dust, a grain embedded in MCs is coated with several (≈ 100) layers of water ice (Taquet et al. 2012). This is because oxygen, the most abundant element after H and He, after landing on the grain surface, is rapidly² hydrogenated, and forms water molecules (Dulieu et al. 2010). Water remains then stuck on the grain surface. Besides being the most abundant element, O condenses also faster than other heavier elements, like Si or SiO (which are particularly relevant for this study), according to equation (1).

The water formation process on grains is a two-step process.³ First, an impinging oxygen atom must become bound to the surface. Secondly it must react with H atoms landed on the grain on a time-scale shorter than their desorption time-scale, τ_d , during which they scan the grain surface. As dust and gas temperatures are likely higher in MCs at high redshifts due to CMB, we need to re-consider the efficiency of this process, in terms of the above time-scales.

Consider the formation of the first H_2O layer. The desorption (or permanence on the grain surface) time (equation 2) for O atoms is larger than the Hubble time for $z \lesssim 6.5$ (see Fig. 1). H atoms permanence time depends on z (Fig. 1) and it is $\approx 240 \text{ ms}$ at $z = 6$. These time-scales have to be compared with the time necessary for H atoms to scan the grain surface, τ_s (equation 3). Taking again $a = 0.1 \mu\text{m}$, and $N_s = 10^5$ sites to scan, it takes $\tau_s = 6 \text{ ms}$ for H atoms to scan a grain at temperature $T_d = T_{\text{CMB}}(z = 6)$, and form H_2O molecules. Hence, the time required to form the first water layer is set by the accretion rate of oxygen atoms. Assuming a MC hydrogen density $n_H = 10^4 \text{ cm}^{-3}$, a temperature $T_{\text{CMB}}(z = 6)$, and that a layer contains $N_s \approx 10^5$ molecules, we get that the first layer is formed in $\approx 1500 \text{ yr}$. Once formed, water (whose E_b is larger than the O atom binding energy) will remain frozen forming a mantle.

² When the dust temperature is 10 K, the permanence time of H atoms on the grain surface is $\approx 165 \text{ yr}$, while it takes only $\approx 132 \text{ s}$ for each H atom to scan the full grain surface (Fig. 1).

³ Here we neglect a number of subtleties and complications related to water formation, which does not involve only the simple direct addition of H and O atoms (Dulieu et al. 2010).

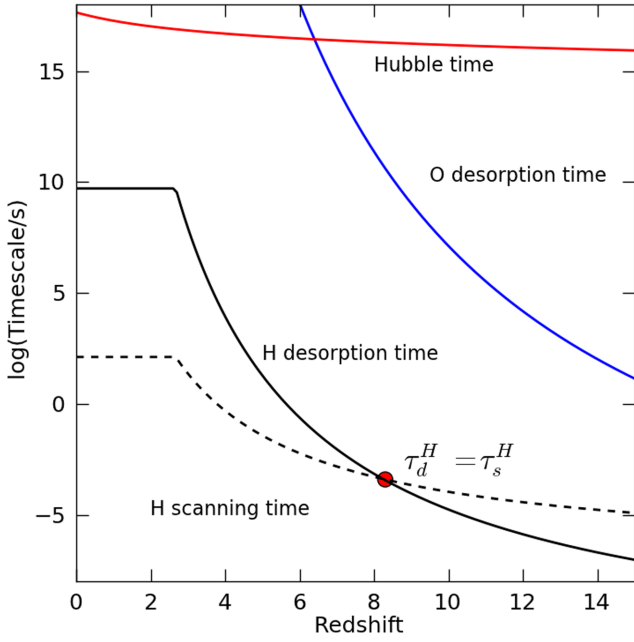


Figure 1. Comparison among the different relevant times scales for ice formation on grain surfaces. The H-atom (solid line) desorption time, τ_d^H , is compared against the H scanning time (dashed) of the grain surface, τ_s^H . Ice formation is possible only when $\tau_s^H < \tau_d^H$, i.e. at all redshifts $z < 8.3$. A pre-requisite is that the analogous oxygen desorption time (blue solid curve) is larger than both previous time-scales to ensure that oxygen atoms are always available to react and form H_2O . Note that the O desorption time is very long and also larger than the Hubble time (red solid curve) for $z \lesssim 6.5$. We have assumed a grain temperature $T_d = \max(10 \text{ K}, T_{\text{CMB}})$.

The key point here is that, once a first layer of water ice is formed, this will prevent Si atoms or SiO molecules to get in contact with the silicate surface. On the contrary, given the much smaller Si abundance (for solar ratios $\text{Si}/\text{O} \approx 1/200$ by number), these species will be – at best – trapped in the ice layer, forming impurities but not silicate-like bonds.⁴ As a final remark, we underline that the above rapid hydrogenation process applies also to the case of carbonaceous grains.

2.4 Mantle photo-desorption in the diffuse ISM

The results of the previous subsection lead us to conclude that grain growth in molecular clouds is largely in the form of icy mantles. Once the parent molecular cloud is dispersed (typical lifetime 10 Myr) as a result of radiative and mechanical feedback from stars born in its interior, core-mantle grains are returned to the ISM. However, the memory of growth occurred in the MC will be promptly erased as icy mantles are photo-desorbed by the FUV field (Barlow 1978; Fayolle et al. 2013). A simple calculation shows that this time-scale is very short. Suppose that the ice mantle is made by $\ell = 100$ layers, each containing $N_s = 10^5$ sites. The time necessary to completely photo-desorb the mantle, τ_p , is that required to provide

each site with an UV photon. Thus, for a given Habing band (6 – 13.6 eV) UV flux intensity, G_0 (in cgs units), and mean photon energy $\langle h\nu \rangle \approx 10 \text{ eV}$

$$y_{\text{H}_2\text{O}} \frac{G_0}{\langle h\nu \rangle} \pi a^2 \tau_p = N_s \ell, \quad (5)$$

or $t_p = 10\text{--}1000 \text{ yr}$ for $G_0 = 100\text{--}1$, respectively. In the previous calculation we have further assumed a H_2O photo-desorption yield, $y_{\text{H}_2\text{O}} = 0.001$, following Öberg et al. (2009). To all purposes the accreted mantle material (along with the impurities) is almost instantaneously ‘lifted’ from the core. The bare grain then finds itself back in the ISM with (optical) properties essentially identical to those prevailing before the journey into the MC, and set by nucleation processes in sources.

3 CONCLUSIONS

We have shown that grain growth by accretion is a problematic process hampered by a number of difficulties which become additionally more severe at high redshifts as the temperature floor set by the CMB increases (i.e. grains are hotter). In the CNM (for the WNM the situation is even less favourable) grain growth is essentially prevented by the (i) low accretion rates related to low densities; (b) higher dust temperatures (particularly in compact, high- z galaxies) causing very short thermal desorption times; (c) Coulomb repulsive forces preventing positively charged ions (Si, C) to reach the grain surface.

Molecular clouds offer more favourable conditions, due to their high density and low dust temperature. However, we have shown that once the bare grain cores are immersed in the MC environment, they are covered by a water ice mantle on a time-scale of a few thousand years at $z = 6$. As hydrogenation is very fast ($\approx \text{ms}$), such time-scale is set by the accretion rate of oxygen atoms. This process fully operates in spite of CMB heating up to $z \approx 8.3$. Beyond that epoch, predictions become uncertain due to the lack of a precise knowledge of the diffusion energies of the various species. As the grains are returned to the diffuse phase at the end of the MC lifetime, the mantles are photo-desorbed and the bare core is exposed again. That is, the memory of the ice growth phase in the MC is completely erased.

If grain growth is as problematic as we point out, it is necessary to re-evaluate the arguments, often made, invoking it. These are generically based on a comparison between the dust production rate by sources (planetary nebulae, evolved stars, and SNe) and destruction rate in supernova shocks (Draine 2009). According to such, admittedly uncertain, estimates *made for the Milky Way*, dust production fails by about a factor of 10 to account for the observed dust mass once shock destruction is accounted for.

In the light of the present results, reconciliation of this discrepancy must necessarily come from either (a) an upward revision of the production rate, or (b) downward reappraisal of the dust destruction efficiency by shocks. Interestingly, there appears to be evidence for both solutions, and perhaps even a combination of the two. Recent studies (Matsuura et al. 2011; Indebetouw et al. 2014) have determined the dust mass produced by SN1987A. The observations revealed the presence of a population of cold dust grains with $T_d = 17\text{--}23 \text{ K}$; the emission implies a dust mass of $\approx 0.4\text{--}0.7 M_\odot$. Such value is 20–35 times larger than that usually assumed in the above argument. Moreover, Gall et al. (2014) found that the 0.1–0.5 masses of dust detected in the luminous SN2010jl are made of μm -sized grains which easily resist destruction in (reverse) shocks. Alternatively, the puzzle can be solved also by decreasing the

⁴ Note that the seminal and important experimental results by Krasnokutski et al. (2014) suggesting the formation of silicate-like bonds from accreting Si and SiO molecules refer to ultra-low temperatures ($\sim 0.34 \text{ K}$) where quantum chemical effects might largely enhance the efficiency of the reaction. This is caused by trapping of the very cold molecules in a van der Waals energy potential which is easily overcome at higher temperatures [see for example, a conceptually similar experiment by Shannon et al. (2013)].

destruction rate. Indeed, Jones & Nuth (2011) thoroughly reanalyzed this issue and found that the destruction efficiencies might have been severely overestimated. They additionally conclude that ‘the current estimates of global dust lifetimes could be uncertain by factors large enough to call into question their usefulness’. Given the situation, the results presented here do not seem to create any additional challenge. On the contrary, the hope is that they will stimulate deeper studies on the key problem of dust evolution in a cosmological context.

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