Dust grain growth in the interstellar medium of $5 < z < 6.5$ quasars

Michal J. Michałowski\textsuperscript{1}, Eric J. Murphy\textsuperscript{2}, Jens Hjorth\textsuperscript{3}, Darach Watson\textsuperscript{3}, Christa Gall\textsuperscript{3}, and James S. Dunlop\textsuperscript{1,4}

\textsuperscript{1} Scottish Universities Physics Alliance, Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh, EH9 3HJ, UK
\textsuperscript{2} Spitzer Science Center, MC 314-6, California Institute of Technology, Pasadena, CA 91125, USA
\textsuperscript{3} Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen \O, Denmark
\textsuperscript{4} Department of Physics \& Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada

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\textbf{ABSTRACT}

\textbf{Aims.} We investigate whether stellar dust sources i.e. asymptotic giant branch (AGB) stars and supernovae (SNe) can account for dust detected in $5 < z < 6.5$ quasars (QSOs).

\textbf{Methods.} We calculate the required dust yields per AGB star and per SN using the dust masses of QSOs inferred from their millimeter emission and stellar masses approximated as the difference between the dynamical and the H\textsubscript{$\alpha$} gas masses of these objects.

\textbf{Results.} We find that AGB stars are not efficient enough to form dust in the majority of the $z > 5$ QSOs, whereas SNe may be able to account for dust in some QSOs. However, they require very high dust yields even for a top-heavy initial mass function.

\textbf{Conclusions.} This suggests additional non-stellar dust formation mechanism e.g. significant dust grain growth in the interstellar medium of at least three out of nine $z > 5$ QSOs. SNe (but not AGB stars) may deliver enough heavy elements to fuel this growth.

\textbf{Key words.} dust, extinction - galaxies: high-redshift - galaxies: ISM - submillimeter: galaxies - quasars: general

1. Introduction

Studies of the extragalactic background light have revealed that roughly half of the energy emitted in the Universe apart from the CMB is reprocessed by dust (e.g. Hauser \& Dwek 2001). Thus, understanding the physical processes responsible for the formation of dust throughout cosmic time has important cosmological implications.

Dust can either be formed by asymptotic giant branch (AGB) stars (even at low metallicities; Sloan \textit{et al.} 2009), or supernovae (SNe). Alternatively, the bulk of the dust mass accumulation may occur in the interstellar medium (ISM) on dust seeds produced by stars. This process can successfully explain gas depletions in the Milky Way (Draine \& Salpeter 1979; Dwek \& Scalo 1984; Draine 1991, 2001), along with the dust masses of the LMC (Matsuura \textit{et al.} 2009) and a $z \sim 6.42$ quasar (QSO; Dwek \textit{et al.} 2007).

Theoretical works have shown that an AGB star and a SN produce up to $\sim 4 \times 10^{-2} M_{\odot}$ (Morgan \& Edmunds 2003; Ferrarotti \& Gall 2006) and $\sim 1.32 M_{\odot}$ (Todini \& Ferrara 2001; Nozawa \textit{et al.} 2003) of dust, respectively. However, for the case of SN dust, only $\lesssim 0.1 M_{\odot}$ of the dust actually survives in the associated shocks (Bianchi \& Schneider 2007; Cherchneff \& Dwek 2010).

The dust in the Milky Way was predominantly formed by evolved stars with only a minor SN contribution (Gehrz 1989), but individual SNe may form significant amounts of dust. Submillimeter observations of the SN remnants Cassiopeia A (Dunne \textit{et al.} 2003, 2009) and Kepler (Morgan \textit{et al.} 2003; Gomez \textit{et al.} 2004) have revealed as much as $\sim 1 M_{\odot}$ of freshly formed dust, but these results are controversial (Dwek 2004; Krause \textit{et al.} 2004; Gomez \textit{et al.} 2005; Wilson \& Battria 2003; Blair \textit{et al.} 2007; Shibahara \textit{et al.} 2009; Barlow \textit{et al.} 2010). Dust yields for other SNe are typically in the range $10^{-3} - 10^{-2} M_{\odot}$ (Green \textit{et al.} 2004; Borkowski \textit{et al.} 2004; Sugerman \textit{et al.} 2006; Ercolano \textit{et al.} 2007; Meikle \textit{et al.} 2007; Rho \textit{et al.} 2008; 2009; Kotak \textit{et al.} 2008; Lee \textit{et al.} 2008; Sakon \textit{et al.} 2009; Sandstrom \textit{et al.} 2009; Wesson \textit{et al.} 2009).

The situation is even more complex at high redshifts. Dwek \textit{et al.} (2007) claimed that only SNe can produce dust on timescales $\lesssim 1$ Gyr, but Valiante \textit{et al.} (2009) showed that AGB stars dominate dust production over SNe as early as $150 - 500$ Myr after the onset of star formation.

Michałowski \textit{et al.} (2010) concluded that in three out of six $4 < z < 5$ submillimeter galaxies, only SNe are efficient enough to form dust provided that they have high dust yields. This would then be suggestive of a significant dust growth in the ISM and/or a top-heavy initial mass function (IMF).
Table 1. Dust, gas and dynamical masses of z > 5 QSOs

| No. | QSO     | z       | $M_{\text{dust}}$ (10$^6 M_\odot$) | $M_{\text{gas}}$ (10$^9 M_\odot$) | $M_{\text{dynam}} \sin^2 i$ (10$^9 M_\odot$) | $M_{\text{dyn}}$ (10$^9 M_\odot$) | $T_{\text{dust}}$ (K) |
|-----|---------|---------|----------------------------------|----------------------------------|------------------------------------------|---------------------------------|----------------|
| 1   | J0338+0902 | 5.03 | 7.1±0.6 | 2.2$^a$ | 3.0$^a$ | 31 | 45.6$^a$ |
| 2   | J0840+5624 | 5.85 | 4.7±0.9 | 2.5$^b$ | 24.2$^b$ | 53 | ... |
| 3   | J0927+2001 | 5.77 | 7.2±1.1 | 1.8$^b$ | 11.8$^b$ | 25 | 51.1$^d$ |
| 4   | J1044−0125 | 5.74 | 2.7±0.6 | 0.7$^b$ | 0.8$^b$ | 26 | ... |
| 5   | J1048+4637 | 6.23 | 4.3±0.6 | 1.0$^b$ | 4.5$^b$ | 23 | <40$^c$ |
| 6   | J1148+5251 | 6.42 | 5.9±0.7 | 1.6$^c$ | 4.5$^c$ | 27 | 55.0$^f$ |
| 7   | J1335+3533 | 5.93 | 3.4±0.7 | 1.8$^b$ | 3.1$^b$ | 53 | ... |
| 8   | J1425+3254 | 5.85 | 3.3±0.7 | 2.0$^b$ | 15.6$^b$ | 60 | ... |
| 9   | J2054−0005 | 6.06 | 3.4±0.8 | 1.2$^b$ | 4.2$^b$ | 35 | ... |

Notes. The sample includes QSOs detected in their dust continuum and CO line emission (Carilli et al. 2000, 2001, 2007; Bertoldi et al. 2003a,b; Petric et al. 2003; Priddey et al. 2003, 2008; Walter et al. 2003, 2004; Robson et al. 2004; Beelen et al. 2005). This gives an upper limit setting $T_{\text{dust}} = 50$ K. (a) Maiolino et al. (2004). (b) Wang et al. (2008b). (c) Robson et al. (2004). (d) Wang et al. (2008a). (e) Robson et al. (2004). (f) Beelen et al. (2004).

Signatures of SN-origin dust have been claimed in the extinction curves of a z ~ 6.2 QSO (Maiolino et al. 2004 see also Gallieri et al. 2010) and of two gamma-ray burst host galaxies, one at z ~ 6.3 (Stratta et al. 2007, but this result was undermined by Zafar et al. 2010) and one at z ~ 5 (Perley et al. 2009).

The objective of this paper is to investigate if SNe and AGB stars are efficient enough to form dust at redshifts $5 < z < 6.5$ (1.15–0.85 Gyr after the Big Bang), or if grain growth in the ISM is required. We use a cosmological model with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, and $(\Omega_M, \Omega_{\Lambda}) = (0.7, 0.3)$.

2. Methodology

In order to constrain the dust production efficiency in the early Universe, we selected z > 5 QSOs detected in both the millimeter continuum and CO lines allowing estimates to be made of their dust, gas and dynamical masses (Tab. 1). We calculated dust masses ($M_{\text{dust}}$) from the 1200 µm data (rest-frame 160–200 µm) using Eq. 5 of Michalowski et al. (2009) assuming $\beta = 1.3$. For three QSOs we adopted the derived dust temperatures ($T_{\text{dust}}$, Tab. 1). For the rest we assumed the average of these estimates $T_{\text{dust}} = 50$ K. We assumed the mass absorption coefficient $k_{1200\mu m} = 0.67$ cm$^2$ g$^{-1}$, a conservatively high value (cf. Alton et al. 2004) resulting in systematically low $M_{\text{dust}}$.

In order to explore the impact of the systematic uncertainties on $M_{\text{dust}}$, we also assumed $\beta = 2.0$ (see Dunne et al. 2000, Dunne & Eales 2001, Vlahakis et al. 2003). This gives $M_{\text{dust}}$ smaller by a factor of ~ 3.75 (see Fig. 3 of Michalowski et al. 2010a). Changing $T_{\text{dust}}$ to a very high value of 80 K (compare with Fig. 2 of Michalowski et al. 2008), i.e., an upper bound for other QSOs (Haas et al. 1998, Benford et al. 1999, Leech et al. 2001; Priddey & McMahon 2001; Knudsen et al. 2003; Beelen et al. 2006; Aravena et al. 2008; Leipski et al. 2010), decreases the $M_{\text{dust}}$ by a factor of ~ 2.3. Hence, we also assumed ($T_{\text{dust}}, \beta$) = (80, 2.0). This results in strict lower limits on $M_{\text{dust}}$ smaller by a factor of 3.75 x 2.3 = 8.6. However, this very conservative assumption is only chosen to illustrate an extreme limit on $M_{\text{dust}}$. It is not likely that the real values are close to this limit as $T_{\text{dust}}$ has been constrained to be below 60 K for four out of nine QSOs in our sample with good wavelength coverage in the infrared (Tab. 1).

Similar to Wang et al. (2010), we assume that the stellar masses ($M_\star$) of the QSO host galaxies can be approximated as the difference between the dynamical ($M_{\text{dyn}}$; i.e. total) and the H$_2$ gas masses ($M_{\text{gas}}$). The true values of $M_\star$ are lower, unless QSOs harbour very little atomic gas (H1). Given the significant uncertainties in the conversion from CO line strength to $M_{\text{gas}}$, we also performed the calculations with the upper limit setting $M_\star$, equal to $M_{\text{dyn}}$.

The inclination angle of the gas disk, $i$, was adopted to be 65° for QSO 6 (Walter et al. 2004) and 40° for the others (Wang et al. 2010). The latter assumption is a major source of uncertainty in our analysis and is discussed below.

We calculated the dust yields per AGB star and per SN (amount of dust formed in ejecta of one star) required to explain the inferred dust masses in the z > 5 QSOs as described in Michalowski et al. (2010a). The number of stars with masses between $M_0$ and $M_1$ in the stellar population with a total mass of $M_s$ was calculated as $N(M_0−M_1) = M_s \int_{M_0}^{M_1} M^{-\alpha}dM / \int_{M_0}^{M_{\text{max}}} M^{-\alpha}dM$. We adopted an IMF with $M_{\text{min}} = 0.15$, $M_{\text{max}} = 120 M_\odot$, and a slope $\alpha = 2.35$ (Salpeter 1955, or $\alpha = 1.5$ for a top-heavy IMF). The average yield per star is $M_{\text{dust}}/N(M_0−M_1)$.

3. Results and Discussion

First, we consider a single dust producer i.e. assume that dust in the z > 5 QSOs was produced by either AGB stars or SNe. The required dust yields per AGB star and per SN are listed in Tab. 2 and shown in Fig. 3 as a function of redshift. Circles correspond to reasonable estimates of $T_{\text{dust}}$, $\beta$ and $M_\star$, whereas other values are shown to quantify the impact of the systematic uncertainties (error bars extend down to the reasonable lower limits, whereas arrows represent strict and unlikely lower limits).

Except for QSOs 2 and 8 the required yields for AGB stars exceed the theoretically allowed maximum values.
∼ the claim of Valiante et al. (2009) that $M_{\text{dust}} \sim M_{\text{gas}}$ be traced to the fact that they assumed rule out their contribution in QSOs 7 and 9, unless their rule out a significant contribution of AGB stars to the dust (80% dust in the majority of the QSOs). For the remaining seven QSOs, one would need to assume unrealistically high $T_{\text{dust}}$ and steep spectral slopes (green area) by a factor of 2–15. The yields remain too high even for $M_{\text{AGB}} = M_{\text{dyn}}$ and $\beta = 2$. They are consistent (though at the high end) with the theoretical predictions only under the unrealistic assumption of $(T_{\text{dust}}, \beta) = (80, 2.0)$. Using the $T_{\text{dust}}$ limits (Tab. 1), we can robustly rule out a significant contribution of AGB stars to the dust formation in five out of nine QSOs (1, 3, 4, 5 and 6) and rule out their contribution in QSOs 7 and 9, unless their emission is dominated by hot ($\sim 80$ K) dust.

Therefore AGB stars are not efficient enough to form dust in the majority of the $z > 5$ QSOs. This contradicts the claim of Valiante et al. (2009) that $\sim 80\%$ of dust in QSO 6 was created by AGB stars. The disagreement can be traced to the fact that they assumed $M_{\text{AGB}} \sim 10^{12} M_{\odot}$, exceeding the $M_{\text{dyn}}$ by a factor of $\sim 15$.

For only two QSOs (2 and 8) are the required SN dust yields marginal within the theoretically predicted limits with dust destruction implemented (dark blue area on Fig. 1). For the remaining seven QSOs, one would need to assign unrealistically high $T_{\text{dust}}$ and steep spectral slopes and in some cases an IMF more top-heavy than the Salpeter IMF.

For these seven QSOs (including QSO 5 for which Maiolino et al. (2004) claimed SN-origin dust) the required SN dust yields are within the theoretical limits without dust destruction (light blue area) and the values observed for SN remnants Cassiopeia A and Kepler (dashed line).

We checked that allowing AGB stars to form only a fraction of dust in the $z > 5$ QSOs and assigning the rest to SNe may have an impact on our conclusions for only four out of nine QSOs (3, 5, 7 and 9). This is illustrated in Fig. 2, where we show the required dust yields assuming different fractions of dust attributed to SNe. Solid lines represents the required yields for the QSOs. An increase in the fraction of SN dust corresponds to moving towards bottom-right corner (i.e. higher SN yields and lower AGB yields are required). If a curve corresponding to a QSO crosses the hatched region, corresponding to the allowed yields for both AGB stars and SNe, then these stellar objects can account for dust in this QSO. Hence we conclude similarly as before, that combined AGB stars and SNe are...
Table 2. Dust yields per star required to explain dust in $z > 5$ QSOs

| Dust Producer | $T_d$ (K) | $\alpha$ | IMF | $M_\star$ | Dust Yields ($M_\odot$ Per Star) |
|---------------|-----------|--------|-----|----------|-------------------------------|
| AGB (2.5-8.0 M$_\odot$) | 50 | 1.3 | Sal. | $M_{\text{syn}}$-$M_{\text{gas}}$ | 0.42 | 0.02 | 0.08 | 0.64 | 0.13 | 0.45 | 0.18 | 0.03 | 0.11 |
| AGB (2.5-8.0 M$_\odot$) | 50 | 2.0 | Sal. | $M_{\text{syn}}$ | 0.08 | 0.01 | 0.02 | 0.11 | 0.03 | 0.08 | 0.03 | 0.01 | 0.03 |
| AGB (2.5-8.0 M$_\odot$) | 80 | 2.0 | Sal. | $M_{\text{syn}}$ | 0.03 | 0.003 | 0.009 | 0.048 | 0.012 | 0.039 | 0.015 | 0.003 | 0.011 |
| SN (8-40 M$_\odot$) | 50 | 1.3 | Sal. | $M_{\text{syn}}$-$M_{\text{gas}}$ | 0.76 | 0.05 | 0.15 | 1.18 | 0.23 | 0.82 | 0.32 | 0.05 | 0.21 |
| SN (8-40 M$_\odot$) | 50 | 2.0 | Sal. | $M_{\text{syn}}$ | 0.35 | 0.03 | 0.08 | 0.46 | 0.12 | 0.34 | 0.15 | 0.03 | 0.11 |
| SN (8-40 M$_\odot$) | 80 | 2.0 | Sal. | $M_{\text{syn}}$ | 0.13 | 0.01 | 0.04 | 0.21 | 0.05 | 0.17 | 0.06 | 0.01 | 0.05 |
| SN (8-40 M$_\odot$) | 80 | 2.0 | Sal. | $M_{\text{syn}}$ | 0.057 | 0.005 | 0.016 | 0.088 | 0.023 | 0.072 | 0.028 | 0.005 | 0.020 |

Notes. The IMF is either [Salpeter 1955] with $\alpha = 2.35$ or top-heavy with $\alpha = 1.5$. The $M_\star$ column indicates either that stellar mass was assumed to be the difference between the dynamical and gas masses ($M_{\text{dyn}}-M_{\text{gas}}$) or that the strict upper limit to the stellar mass equal to the dynamical mass was adopted (see Sec. 4). The numbered columns contain the required dust yields for all QSOs in the order given in Table I. Only their numbers are given for brevity. The last column gives the symbol used on Fig. 1.

We stress that our results are sensitive to the assumed gas disk inclinations. The required AGB and SN dust yields for individual QSOs decrease to theoretically allowed values (with dust destruction) for inclinations lower than 5–20°. It is however unlikely that all our QSOs exhibit such low inclination (e.g., Polletta et al. 2008) did not find any preferred inclination for luminous QSOs). At least this is not the case for QSO 6 with a measured inclination of ~65°.

Moreover, our derived required dust yields should be corrected towards lower values if i) the gas disk radius of QSOs is larger than 2.5 kpc, then the dynamical mass would be larger; or ii) the stellar component is more extended than the gas disk (then our upper limit on $M_\star$ equal to $M_{\text{dyn}}$ would apply only to the stellar component distributed within the extent of the gas disk).

It is however unlikely that these conditions are fulfilled in our sample. Using the high-resolution CO line observations, the sizes of the gas disks have been constrained for QSO 1 (<3 kpc; Maiolino et al. 2007), QSO 5 (2.2 × 5.0 kpc; Wang et al. 2010) and QSO 6 (2.5 kpc; Walter et al. 2004). Moreover, the star-forming gas of QSO 6 has been found to be distributed within a radius of 0.75 kpc (Walter et al. 2000).

There is no estimate of the extent of the stellar component of the $z > 5$ QSOs, but at redshifts ~0 – 3 QSOs are typically hosted in ≤3 kpc galaxies (Ridgway et al. 2001; Veilleux et al. 2000), consistent with a value of 2.5 kpc assumed by Wang et al. (2010).

Hence, we conclude that, unless the inclinations are biased low or the extent of stellar component are significantly larger than 2.5 kpc, both AGB stars and SN could have to form unfeasibly large amounts of dust to account for dust present in the z > 5 QSOs. This may be taken as an indication of another (non-stellar) dust source in these objects, e.g., significant grain growth in the ISM (e.g., Draine & Salpeter 1979, Drwek & Scalo 1980; Draine 2009) on the dust seeds produced by SN or possibly AGB stars. Assuming that star formation in these QSOs began at $z \sim 10$, a timescale for in situ grain growth of a few × 10^7 years (Draine 1990, 2009; Hirashita 2000, Zhukovska et al. 2008) is ×10% of the available time, suggesting ample time for grain growth in the ISM to explain the observed dust masses.

Do stellar sources deliver enough additional heavy elements (not incorporated in dust) necessary for grain growth? The majority of heavy elements produced by AGB stars are already bound in dust grains (yields of carbon and other heavy elements are $\leq 3.5 \times 10^{-2} M_\odot$; Morgan & Edmunds 2003). On the other hand, a SN produces as much as $\leq 1 M_\odot$ of heavy elements (Todini & Ferrara 2001; Nozawa et al. 2003, Bianchi & Schneider 2007, Christeufel & Drwek 2009), close to the required yields for the $z > 5$ QSOs (lower panel of Fig. 1). Hence, even though SN sources do not produce enough dust, they may deliver enough heavy elements to fuel the dust grain growth in the ISM.

4. Conclusions

We have derived the dust yields per AGB star and per SN required to explain observationally determined dust masses in $5 < z < 6.5$ QSOs. We find that the yields for AGB stars typically exceed the theoretically allowed values making these objects inefficient to produce dust at high redshifts. SN could in principle be responsible for dust in some of the QSOs, but with a requirement of high dust yields. This advocates for non-stellar dust source e.g. significant dust grain growth in the ISM of at least three out of nine QSOs. We argue that SN deliver enough heavy elements to fuel the dust grain growth.

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Fig. 2. The relation of the required dust yields per AGB star and per SN for different fractions of dust formed by SNe (shown as dotted lines). This is a combination of panels in Fig. relaxing the assumption that only AGB stars or only SNe produced dust in the $z > 5$ QSOs. The theoretically allowed regions of dust yields are shown as in Fig. [hashed region outlined by the dashed line corresponds to the the allowed region, where the dust yields for both AGB stars and SNe are within theoretical limits (with the dust destruction implemented). The solid lines correspond to the $z > 5$ QSOs numbered as in Tab. [if higher fraction of dust is attributed to SNe then the QSOs move towards bottom-right corner. The combined effort of AGB stars and SNe can explain dust in QSO 2 and 8, but not in QSO 1, 4 and 6. Dust in QSOs 3, 5, 7 and 9 may have been formed by these stellar sources, but only if little dust is destroyed in SN shocks and that SN account for more than 50-75% of dust in these QSOs.

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