A&A 522, A15 (2010)
DOI: 10.1051/0004-6361/201014902

Astronomy & Astrophysics

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

M. J. Michałowski[1], E. J. Murphy[2], J. Hjorth[3], D. Watson[3], C. Gall[3], and J. S. Dunlop[1,4]

[1] Scottish Universities Physics Alliance, Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh, EH9 3HJ, UK
e-mail: `mm@roe.ac.uk`
[2] Spitzer Science Center, MC 314-6, California Institute of Technology, Pasadena, CA 91125, USA
[3] Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen Ø, Denmark
[4] Department of Physics & Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada

Received 30 April 2010 / Accepted 28 June 2010

ABSTRACT

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).
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_2 gas masses of these objects.
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.
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.

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 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 1980; Draine 1990, 2009), along with the dust masses of the LMC (Matsuura et al. 2009) and a $z \sim 6.42$ quasar (QSO Dwek 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 & Gail 2006) and $\sim 1.32\,M_\odot$ (Todini & Ferrara 2001; Nozawa 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 et al. 2003, 2009) and Kepler (Morgan et al. 2003; Gomez et al. 2009) have revealed as much as $\sim 1\ M_\odot$ of freshly formed dust, but these results are controversial (Dwek 2004; Krause et al. 2004; Gomez et al. 2005; Wilson & Batrla 2005; Blair et al. 2007; Sibthorpe et al. 2010; Barlow et al. 2010). Dust yields for other SNe are typically in the range 10^{-3}–$10^{-2}\,M_\odot$ (Green et al. 2004; Borkowski et al. 2006; Sugerman et al. 2006; Ercolano et al. 2007; Meikle et al. 2007; Rho et al. 2008, 2009; Kotak et al. 2009; Lee et al. 2009; Sakon et al. 2009; Sandstrom et al. 2009; Wesson et al. 2009).

The situation is even more complex at high redshifts. Dwek et al. (2007) claimed that only SNe can produce dust on timescales <1 Gyr, but Valiante 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 et al. (2010b) 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).

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

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 $H_0 = 70\ \mathrm{km\,s^{-1}\ Mpc^{-1}}$, and $(\Omega_\Lambda, \Omega_\mathrm{m}) = (0.7, 0.3)$.

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 (Table 1).

Table 1. Dust, gas and dynamical masses of $z > 5$ QSOs.

No.	QSO	z	$M_{\rm dust}$ ($10^8\,M_\odot$)	$M_{\rm gas}$ ($10^{10}\,M_\odot$)	$M_{\rm dyn}\sin^2 i$ ($10^{10}\,M_\odot$)	$\frac{M_{\rm gas}}{M_{\rm dust}}$	$T_{\rm dust}$ (K)
1	J0338+0021	5.03	7.1 ± 0.6	2.2^a	3.0^a	31	45.6^d
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	$<40^e$
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. 2006; Maiolino et al. 2007; Riechers et al. 2007; Wang et al. 2007, 2008a,b, 2010; Wu et al. 2009). We calculated dust masses from the detection of 1200 μm emission using Eq. (5) of Michałowski et al. (2009) assuming $\beta = 1.3$. The errors reflect the statistical uncertainties only. For three QSOs we assumed observationally inferred dust temperatures (the last column). For the rest we adopted the average of these estimates $T_{\rm dust} = 50$ K.
[a] Maiolino et al. (2007). [b] Wang et al. (2010). [c] Walter et al. (2004). [d] Wang et al. (2008b). [e] Robson et al. (2004). [f] Beelen et al. (2006).

We calculated dust masses ($M_{\rm dust}$) from the 1200 μm data (rest-frame 160–200 μm) using Eq. (5) of Michałowski et al. (2009) assuming $\beta = 1.3$. For three QSOs we adopted the derived dust temperatures ($T_{\rm dust}$; Table 1). For the rest we assumed the average of these estimates $T_{\rm dust} = 50$ K. We assumed the mass absorption coefficient $\kappa_{1200\,\mu{\rm m}} = 0.67\,{\rm cm}^2\,{\rm g}^{-1}$, a conservatively high value (cf. Alton et al. 2004) resulting in systematically low $M_{\rm dust}$.

In order to explore the impact of systematic uncertainties on $M_{\rm dust}$, we also assumed $\beta = 2.0$ (see Dunne et al. 2000; Dunne & Eales 2001; Vlahakis et al. 2005). This gives $M_{\rm dust}$ smaller by a factor of $\sim$3.75 (see Fig. 3 of Michałowski et al. 2010a). Changing $T_{\rm dust}$ to a very high value of 80 K (compare with Fig. 2 of Michałowski 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 $M_{\rm dust}$ by a factor of $\sim$2.3. Hence, we also assumed $(T_{\rm dust}, \beta) = (80, 2.0)$. This results in strict lower limits on $M_{\rm dust}$ smaller by a factor of $3.75 \times 2.3 = 8.6$. However, this very conservative assumption is only chosen to illustrate an extreme limit on $M_{\rm dust}$. It is not likely that the real values are close to this limit as $T_{\rm dust}$ has been constrained to be below 60 K for four out of nine QSOs in our sample with good wavelength coverage in the infrared (Table 1).

Similar to Wang et al. (2010), we assume that the stellar masses (M_*) of the QSO host galaxies can be approximated as the difference between the dynamical ($M_{\rm dyn}$; i.e. total) and the H_2 gas masses ($M_{\rm gas}$). The true values of M_* are lower, unless QSOs harbour very little atomic gas (H I). Given the significant uncertainties in the conversion from CO line strength to $M_{\rm gas}$, we also performed the calculations with the upper limit setting M_* equal to $M_{\rm dyn}$.

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 Michałowski et al. (2010b). The number of stars with masses between M_0 and M_1 in the stellar population with a total mass of M_* was calculated as $N(M_0 - M_1) = M_* \int_{M_0}^{M_1} M^{-\alpha} {\rm d}M / \int_{M_{\rm min}}^{M_{\rm max}} M^{-\alpha} M {\rm d}M$. We adopted an IMF with $M_{\rm min} = 0.15$, $M_{\rm max} = 120\,M_\odot$, and a slope $\alpha = 2.35$ (Salpeter 1955, or $\alpha = 1.5$ for a top-heavy IMF). The average dust yield per star is $M_{\rm dust}/N(M_0{-}M_1)$.

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 Table 2 and shown in Fig. 1 as a function of redshift. Circles correspond to reasonable estimates of $T_{\rm dust}$, β and M_*, 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 (green area) by a factor of 2–15. The yields remain too high even for $M_* = M_{\rm dyn}$ and $\beta = 2$. They are consistent (though at the high end) with the theoretical predictions only under the unrealistic assumption of $(T_{\rm dust}, \beta) = (80, 2.0)$. Using the $T_{\rm dust}$ limits (Table 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 $M_* \sim 10^{12}\,M_\odot$, exceeding the $M_{\rm dyn}$ by a factor of $\sim$15.

For only two QSOs (2 and 8) are the required SN dust yields marginally within the theoretically predicted limits with dust destruction implemented (dark blue area in Fig. 1). For the remaining seven QSOs, one would need to assume unrealistically high $T_{\rm dust}$ *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).

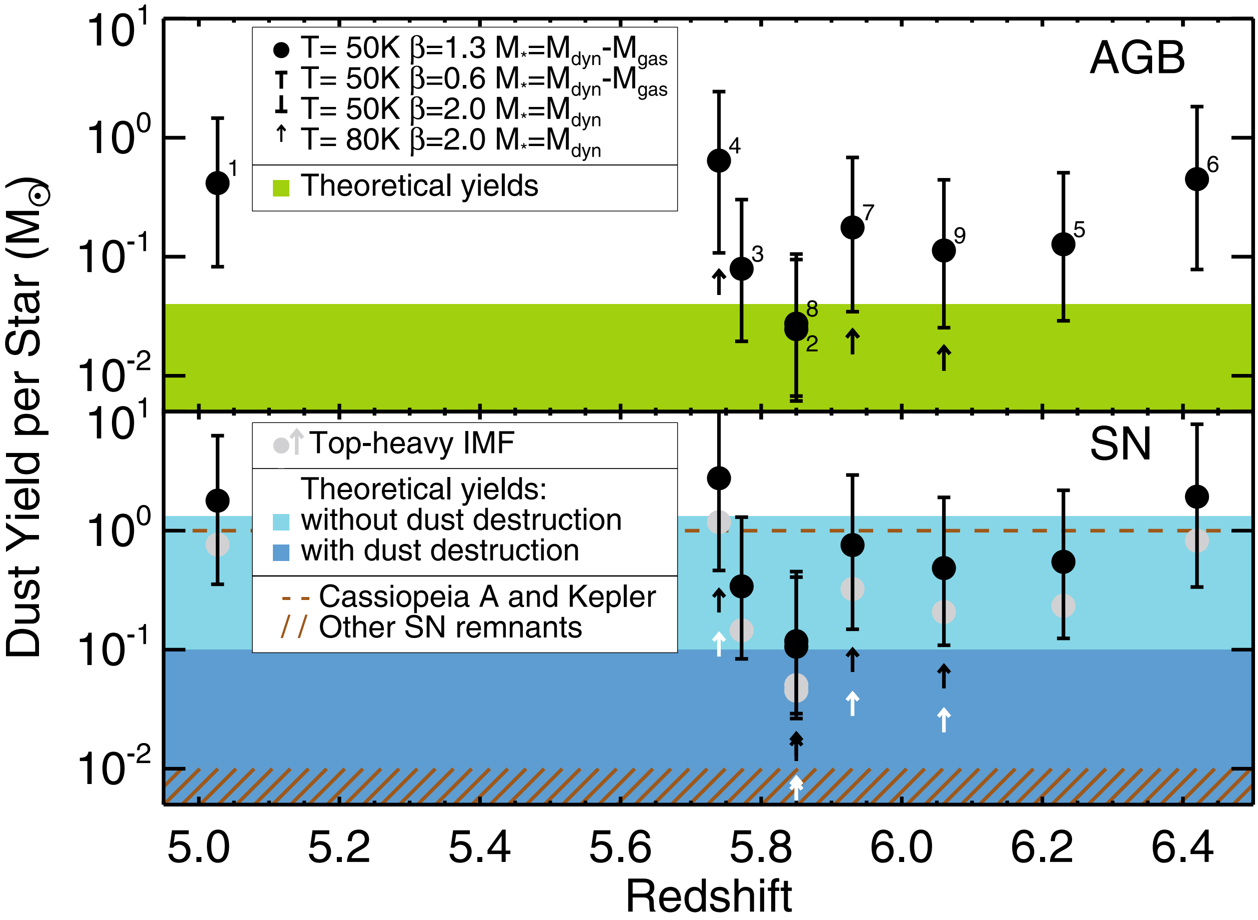

Fig. 1. Dust yields per AGB star (*top*) or per SN (*bottom*) required to explain dust in the $z > 5$ QSOs. For reasonable assumptions on the dust properties, AGB stars are not efficient enough and SNe would need to be unfeasibly efficient to form dust in these sources suggesting rapid grain grown in the ISM is likely to be responsible for the large dust masses. Circles: the best estimates of the required dust yields with error bars reflecting the uncertainty of β and M_*. Numbers indicate the QSOs as in Table 1. Arrows: strict and unlikely lower limits with very high $T_{\rm dust}$ and β shown where data allow it (Table 1). Gray symbols indicate that a top-heavy IMF was adopted. Dashed line and diagonal lines: the dust yields derived for Cassiopeia A, Kepler ($\sim 1\,M_\odot$) and other SN remnants ($\sim 10^{-3}$–$10^{-2}\,M_\odot$), respectively. Green area: theoretical dust yields for AGB stars ($\lesssim 4 \times 10^{-2}\,M_\odot$). Light blue and blue areas: theoretical SN dust yields without ($\lesssim 1.32\,M_\odot$) and with dust destruction implemented ($\lesssim 0.1\,M_\odot$), respectively.

Table 2. Dust yields per star required to explain dust in $z > 5$ QSOs.

Dust Producer	$T_{\rm d}$ (K)	β	IMF	M_*	Dust Yields ($M_\odot$ Per Star) 1	2	3	4	5	6	7	8	9	Sym
AGB (2.5–8 $M_\odot$)	50	1.3	Sal.	$M_{\rm dyn} - M_{\rm gas}$	0.42	0.02	0.08	0.64	0.13	0.45	0.18	0.03	0.11	•
AGB (2.5–8 $M_\odot$)	50	2.0	Sal.	$M_{\rm dyn}$	0.08	0.01	0.02	0.11	0.03	0.08	0.03	0.01	0.03	⊥
AGB (2.5–8 $M_\odot$)	80	2.0	Sal.	$M_{\rm dyn}$	0.031	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.	$M_{\rm dyn} - M_{\rm gas}$	1.79	0.11	0.34	2.76	0.55	1.93	0.76	0.12	0.48	•
SN (8–40 $M_\odot$)	50	1.3	Top	$M_{\rm dyn} - M_{\rm gas}$	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.	$M_{\rm dyn}$	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.	$M_{\rm dyn}$	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	Top	$M_{\rm dyn}$	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_* column indicates either that stellar mass was assumed to be the difference between the dynamical and gas masses ($M_{\rm dyn} - M_{\rm gas}$) or that the strict upper limit to the stellar mass equal to the dynamical mass was adopted (see Sect. 2). The numbered columns contain the required dust yields for all QSOs in the order given in Table 1. Only their numbers are given for brevity. The last column gives the symbol used in Fig. 1.

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

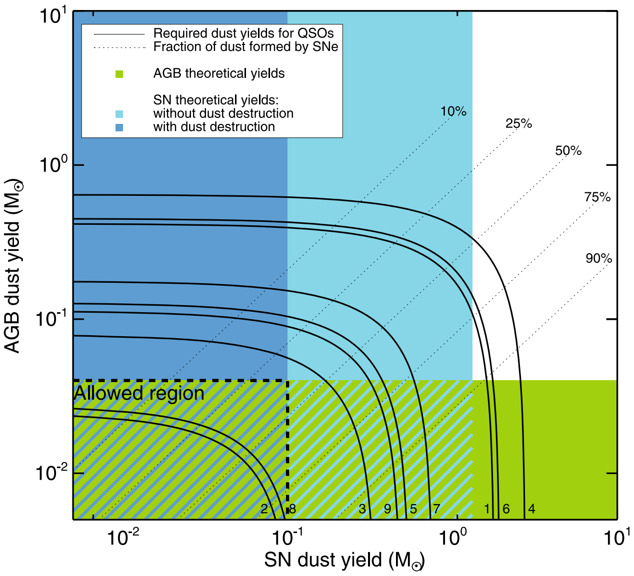

Fig. 2. The relation of the required dust yields per AGB star and per SN for different fractions of dust formed by SNe (shown as dotted lines). This is a combination of panels in Fig. 1 relaxing the assumption that only AGB stars or only SNe produced dust in the $z > 5$ QSOs. The theoretically allowed regions of dust yields are shown as in Fig. 1. 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 Table 1. 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.

before, that combined AGB stars and SNe are efficient enough to form dust in QSOs 2 and 8 and are not efficient enough for QSO 1, 4, and 6. The stellar dust producers may account for dust in QSOs 3, 5, 7 and 9, but only if very little dust is destroyed in SN shocks (light blue area in Fig. 2). For these cases, SNe should be responsible for more than 50–75% of dust in these QSOs. Alternatively, the required dust yields for these four QSOs can be reconciled with theoretical expectations with dust destruction implemented (dark blue area in Fig. 2) if we assume a high value of $\beta = 2$.

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 assumed by Wang et al. (2010, 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_* equal to $M_{\rm dyn}$ 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. 2009).

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 $\lesssim$3 kpc galaxies (Ridgway et al. 2001; Veilleux et al. 2009), 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 SNe would 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; Dwek & Scalo 1980; Draine 2009) on the dust seeds produced by SNe 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 Myr (Draine 1990, 2009; Hirashita 2000; Zhukovska et al. 2008) is $\lesssim$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 $\lesssim 3.5 \times 10^{-2}\,M_\odot$, Morgan & Edmunds 2003). On the other hand, a SN produces as much as $\lesssim 1\,M_\odot$ of heavy elements (Todini & Ferrara 2001; Nozawa et al. 2003; Bianchi & Schneider 2007; Cherchneff & Dwek 2009), close to the required yields for the $z > 5$ QSOs (lower panel of Fig. 1). Hence, even though SNe themselves 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. SNe 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 SNe deliver enough heavy elements to fuel the dust growth.

Acknowledgements. We thank Joanna Baradziej, Karina Caputi, Eli Dwek and our anonymous referee for help with improving this paper. The Dark Cosmology Centre is funded by the Danish National Research Foundation.

References

Alton, P. B., Xilouris, E. M., Misiriotis, A., Dasyra, K. M., & Dumke, M. 2004, A&A, 425, 109
Aravena, M., Bertoldi, F., Schinnerer, E., et al. 2008, A&A, 491, 173
Barlow, M. J., Krause, O., Swinyard, B. M., et al. 2010, A&A, 518, L138
Beelen, A., Cox, P., Benford, D. J., et al. 2006, ApJ, 642, 694
Benford, D. J., Cox, P., Omont, A., Phillips, T. G., & McMahon, R. G. 1999, ApJ, 518, L65
Bertoldi, F., Carilli, C. L., Cox, P., et al. 2003a, A&A, 406, L55
Bertoldi, F., Cox, P., Neri, R., et al. 2003b, A&A, 409, L47
Bianchi, S., & Schneider, R. 2007, MNRAS, 378, 973
Blair, W. P., Ghavamian, P., Long, K. S., et al. 2007, ApJ, 662, 998
Borkowski, K., Williams, B., Reynolds, S., et al. 2006, ApJ, 642, L141

Carilli, C. L., Bertoldi, F., Menten, K. M., et al. 2000, ApJ, 533, L13
Carilli, C. L., Bertoldi, F., Rupen, M. P., et al. 2001, ApJ, 555, 625
Carilli, C. L., Neri, R., Wang, R., et al. 2007, ApJ, 666, L9
Cherchneff, I., & Dwek, E. 2009, ApJ, 703, 642
Cherchneff, I., & Dwek, E. 2010, ApJ, 713, 1
Draine, B. T. 1990, in The Evolution of the Interstellar Medium, ed. L. Blitz, ASP Conf. Ser., 12, 193
Draine, B. T. 2009, in Cosmic Dust – Near and Far, ed. Th. Henning, & J. S. E. Grun, ASP Conf. Ser., 453
Draine, B. T., & Salpeter, E. E. 1979, ApJ, 231, 438
Dunne, L., & Eales, S. A. 2001, MNRAS, 327, 697
Dunne L., Eales S., Edmunds M., et al. 2000, MNRAS, 315, 115
Dunne, L., Eales, S., Ivison, R., Morgan, H., & Edmunds, M. 2003, Nature, 424, 285
Dunne, L., Maddox, S. J., Ivison, R. J., et al. 2009, MNRAS, 394, 1307
Dwek, E. 2004, ApJ, 607, 848
Dwek E., & Scalo J. M. 1980, ApJ, 239, 193
Dwek, E., Galliano, F., & Jones, A. P. 2007, ApJ, 662, 927
Ercolano, B., Barlow, M. J., & Sugerman, B. E. K. 2007, MNRAS, 375, 753
Ferrarotti, A. S., & Gail, H. P. 2006, A&A, 447, 553
Gallerani, S., Maiolino, R., Juarez, Y., et al. 2010, A&A, accepted, `[arXiv:1006.4463]`
Gehrz, R. 1989, in Interstellar Dust, ed. L. J. Allamandola, & A. G. G. M. Tielens, IAU Symp., 135, 445
Gomez, H. L., Dunne, L., Eales, S. A., Gomez, E. L., & Edmunds, M. G. 2005, MNRAS, 361, 1012
Gomez, H. L., Dunne, L., Ivison, R. J., et al. 2009, MNRAS, 397, 1621
Green, D. A., Tuffs, R. J., & Popescu, C. C. 2004, MNRAS, 355, 1315
Haas, M., Chini, R., Meisenheimer, K., et al. 1998, ApJ, 503, L109
Hauser, M. G., & Dwek, E. 2001, ARA&A, 39, 249
Hirashita, H. 2000, PASJ, 52, 585
Knudsen, K. K., van der Werf, P. P., & Jaffe, W. 2003, A&A, 411, 343
Kotak, R., Meikle, W. P. S., Farrah, D., et al. 2009, ApJ, 704, 306
Krause, O., Birkmann, S. M., Rieke, G. H., et al. 2004, Nature, 432, 596
Lee, H., Koo, B., Moon, D., et al. 2009, ApJ, 706, 441
Leech, K. J., Metcalfe, L., & Altieri, B. 2001, MNRAS, 328, 1125
Leipski, C., Meisenheimer, K., Klaas, U., et al. 2010, A&A, 518, L34
Maiolino, R., Schneider, R., Oliva, E., et al. 2004, Nature, 431, 533
Maiolino, R., Neri, R., Beelen, A., et al. 2007, A&A, 472, L33
Matsuura, M., Barlow, M., Zijlstra, A., et al. 2009, MNRAS, 396, 918
Meikle, W. P. S., Mattila, S., Pastorello, A., et al. 2007, ApJ, 665, 608
Michałowski, M. J., Hjorth, J., Castro Cerón, J. M., & Watson, D. 2008, ApJ, 672, 817
Michałowski M. J., Hjorth J., Malesani D., et al. 2009, ApJ, 693, 347
Michałowski, M., Hjorth, J., & Watson, D. 2010a, A&A, 514, A67
Michałowski, M. J., Watson, D., & Hjorth, J. 2010b, ApJ, 712, 942
Morgan, H. L., & Edmunds, M. G. 2003, MNRAS, 343, 427
Morgan, H. L., Dunne, L., Eales, S. A., Ivison, R. J., & Edmunds, M. G. 2003, ApJ, 597, L33
Nozawa, T., Kozasa, T., Umeda, H., Maeda, K., & Nomoto, K. 2003, ApJ, 598, 785
Perley, D. A., Bloom, J. S., Klein, C. R., et al. 2010, MNRAS, 406, 2473
Petric, A. O., Carilli, C. L., Bertoldi, F., et al. 2003, AJ, 126, 15
Polletta, M., Weedman, D., Hönig, S., et al. 2008, ApJ, 675, 960
Priddey, R. S., & McMahon, R. G. 2001, MNRAS, 324, L17
Priddey, R. S., Isaak, K. G., McMahon, R. G., Robson, E. I., & Pearson, C. P. 2003, MNRAS, 344, L74
Priddey, R. S., Ivison, R. J., & Isaak, K. G. 2008, MNRAS, 383, 289
Rho, J., Kozasa, T., Reach, W. T., et al. 2008, ApJ, 673, 271
Rho, J., Reach, W. T., Tappe, A., et al. 2009, ApJ, 700, 579
Ridgway, S. E., Heckman, T. M., Calzetti, D., & Lehnert, M. 2001, ApJ, 550, 122
Riechers, D., Walter, F., Carilli, C., & Bertoldi, F. 2007, ApJ, 671, L13
Robson, I., Priddey, R. S., Isaak, K. G., & McMahon, R. G. 2004, MNRAS, 351, L29
Sakon, I., Onaka, T., Wada, T., et al. 2009, ApJ, 692, 546
Salpeter, E. E. 1955, ApJ, 121, 161
Sandstrom, K. M., Bolatto, A. D., Stanimirović, S., van Loon, J. T., & Smith, J. D. T. 2009, ApJ, 696, 2138
Sibthorpe, B., Ade, P. A. R., Bock, J. J., et al. 2010, ApJ, 719, 1553
Sloan, G. C., Matsuura, M., Zijlstra, A. A., et al. 2009, Science, 323, 353
Stratta, G., Maiolino, R., Fiore, F., & D'Elia, V. 2007, ApJ, 661, L9
Sugerman, B., Ercolano, B., Barlow, M., et al. 2006, Science, 313, 196
Todini P., & Ferrara A. 2001, MNRAS, 325, 726
Valiante, R., Schneider, R., Bianchi, S., & Andersen, A. C. 2009, MNRAS, 397, 1661
Veilleux, S., Kim, D., Rupke, D. S. N., et al. 2009, ApJ, 701, 587
Vlahakis, C., Dunne, L., & Eales, S. 2005, MNRAS, 364, 1253
Walter, F., Bertoldi, F., Carilli, C., et al. 2003, Nature, 424, 406
Walter, F., Carilli, C., Bertoldi, F., et al. 2004, ApJ, 615, L17
Walter, F., Riechers, D., Cox, P., et al. 2009, Nature, 457, 699
Wang, R., Carilli, C. L., Beelen, A., et al. 2007, AJ, 134, 617
Wang, R., Carilli, C. L., Wagg, J., et al. 2008a, ApJ, 687, 848
Wang, R., Wagg, J., Carilli, C. L., et al. 2008b, AJ, 135, 1201
Wang, R., Carilli, C. L., Neri, R., et al. 2010, ApJ, 714, 699
Wesson, R., Barlow, M. J., Ercolano, B., et al. 2009, MNRAS, 403, 474
Wilson, T. L., & Batrla, W. 2005, A&A, 430, 561
Wu, J., Vanden Bout, P., Evans, N., & Dunham, M. 2009, ApJ, 707, 988
Zafar, T., Watson, D. J., Malesani, D., et al. 2010, A&A, 515, A94
Zhukovska, S., Gail, H. P., & Trieloff, M. 2008, A&A, 479, 453