Submillimetre observations of $z > 6$ quasars

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ABSTRACT

We report on submillimetre (submm) observations of three high-redshift quasars ($z > 6$) made using the SCUBA camera on the James Clerk Maxwell Telescope (JCMT). Only one of the sample was detected ($>10\sigma$ significance) at 850 $\mu$m – SDSS J1148+5251 ($z = 6.43$). It was also detected at 450 $\mu$m ($>3\sigma$ significance), one of the few quasars at $z > 4$ for which this has been the case. In combination with existing millimetric data, the 850- and 450-$\mu$m detections allow us to place limits on the temperature of the submm-emitting dust. The dust temperature is of no trivial importance given the high redshift of the source, since a cold temperature would signify a large mass of dust to be synthesized in the little time available (as an extreme upper limit in only 0.9 Gyr since $z = \infty$). We find, however, that the combined millimetre and submm data for the source cannot simply be characterized using the single-temperature greybody fit that has been used at lower redshifts. We discuss the results of the observing and modelling, and speculate as to the origin of the deviations.

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

1 INTRODUCTION

A number of independent lines of investigation over the last 10 years have placed submillimetre (submm) observations of high-redshift quasars into the spotlight. Observations have unveiled a population of extremely luminous submm sources lying at high redshift, believed to be the dust-obscured, star-forming ancestors of massive elliptical galaxies. Contemporaneously, it was realized that a tight correlation exists between the stellar velocity dispersion of galactic spheroids, and the mass of their central, supermassive black hole (Gebhardt et al. 2000). Taken together, these indicate that luminous active galactic nuclei (AGN) at high redshift – the build-up phase of a supermassive black hole – are prime sites at which to search for the dust-enshrouded starburst phase through which, according to the new galaxy formation paradigm, their massive spheroids necessarily must pass.

The high, sustained luminosity of quasars across the electromagnetic spectrum allows them to be studied over a wide range of both redshift and observing wavelength. Early observations of $z \sim 4.5$ quasars by McMahon et al. (1994) and Isaak et al. (1994) established that some high-redshift quasars were prodigious far-infrared emitters with $L_{\text{fir}} = 6 \times 10^{12} L_{\odot}$ and estimated masses of cool dust of $\sim 10^9 M_{\odot}$ (e.g. BR B1202–0725).

The discovery of quasars at $z > 6$ (Fan et al. 2003) now makes it possible to compile homogeneous, well-defined samples over a significant span of the lifetime of the cosmos, from recent times to the threshold of reionization. Follow-up is simplified by the accurately known optical positions and the spectroscopic redshifts of the host galaxies, which can readily be determined to the precision required to pinpoint emission lines from molecular gas – a key indicator of the conditions required for star formation.

Recent SCUBA studies of the submm emission from high-redshift ($z > 4$), radio-quiet quasars have been reported by McMahon et al. (1999), Isaak et al. (2002) and Priddey et al. (2003b), along with a sample at lower redshift ($z \sim 2$) by Priddey et al. (2003a). A considerable fraction of the targets have been shown to be luminous submm sources. Interestingly, this fraction appears to have no significant dependence upon redshift. Similar conclusions have been drawn from observations at millimetre (mm) wavelengths (e.g. Omont et al. 2001; Carilli et al. 2001).

2 OBSERVATIONS

2.1 The sample

Our source list comprised three of the $z \geq 6$ quasars identified by the Sloan Digital Sky Survey (SDSS) team, and reported by Fan et al. (2003). Source parameters are given in Table 1. Observations of the other two quasars known (as of 2003 January) to be at $z > 6,$

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**2.2 Observations and data analysis**

Sources were observed using the Submillimetre Common User Bolometer Array (SCUBA) (Holland et al. 1999) on the JCMT on the nights of 2003 January 31 and February 1 (UT). Simultaneous observations were made at 850 and 450 μm using photometry mode (placing the source on the central bolometers H7 and C14 of the two arrays respectively) with a 60-arcsec azimuth chop at 7.8 Hz. Data were taken in groups of 40 samples, with observations repeated until $S_{850} \mu m \leq 2$ mJy was achieved. Telescope pointing was checked hourly, and found to be better than 3 arcsec. Mars and Uranus, along with IRC +10216, were used as primary and secondary calibrators respectively. The derived, mean, flux conversion factors were 213 ± 5 Jy V$^{-1}$ (850 μm) and 355 ± 15 Jy V$^{-1}$ (450 μm), with a variation of <0.1% per cent seen over the course of the observing period. The sky opacity was measured using sky-dips and the recently commissioned water vapour radiometer which measures the direct line-of-sight atmospheric extinction.

Observing conditions on both nights were moderately good, with $0.1 < \tau_{850} < 0.23$ and $0.27 < \tau_{850} < 0.32$ (zenith atmospheric transmission at 850 μm in the ranges 79–90 and 72–76 per cent) respectively. Data were reduced using both the semi-automated ORAC-DR pipeline data reduction package (Jenness & Economou 1999), and a custom reduction procedure based on a series of routines taken from the SURF reduction package (Jenness & Lightfoot 1998a,b). In each case, the final flux represents the weighted (by the individual rms) average taken of all data for a particular source/filter combination.

The initial analysis of the SDSS J1148+5251 data set revealed considerable variation between both the flux and the rms of the individual 40-sample data groups. One explanation of this discrepancy was revealed upon the subsequent publication of a MAMBO-2 image of SDSS J1148+5251 by Bertoldi et al. (2003). It seemed feasible that our fixed, azimuth chop had placed the off-source position over a second, millimetre-bright source in the quasar field during the latter stages of our observation. In order to eliminate this possibility, we therefore obtained subsequent SCUBA photometry on SDSS J1148+5251, in UK service time during the nights of 2003 July 9, 10 and 12. This time, a specified chop throw, and position angle fixed relative to RA–Dec., was chosen to avoid the potential contaminant sources. The atmospheric extinction during the observing period was low with $0.14 < \tau_{850} < 0.19$ and the sky stable. Guided by these new, more reliable and consistent observations, we re-analysed the initial data sets, testing alternative explanations for their disagreement.

### Table 1. Summary of the source parameters of the SCUBA photometry observations.

<table>
<thead>
<tr>
<th>Source</th>
<th>Redshift</th>
<th>$M_B$</th>
<th>$S_{850 \mu m}$/S$_{1.2,\text{mm}}$</th>
<th>$S_{450 \mu m}$/S$_{850 \mu m}$</th>
<th>$t(\infty) - t(t)$ (Gyr)</th>
<th>$M_{\text{d}}$ (10$^8$ M$_\odot$)</th>
<th>$M_{\text{acc}}$ (10$^9$ L$_\odot$)</th>
<th>$L_{\text{FIR}}$ (10$^{13}$ L$_\odot$)</th>
<th>$M_{\text{bh}}$ (M$_\odot$)</th>
<th>$M_\ast$ (M$_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDSS J1048+4637</td>
<td>6.23</td>
<td>$-28.15$</td>
<td>$&lt; 3.4$</td>
<td>$&lt; 3.4$</td>
<td>0.94</td>
<td>$&lt; 4.6$</td>
<td>$&lt; 50$</td>
<td>$&lt; 0.9$</td>
<td>6.0</td>
<td>130</td>
</tr>
<tr>
<td>SDSS J1148+5251</td>
<td>6.43</td>
<td>$-28.42$</td>
<td>$1.6^{+0.9}_{-1.3}$</td>
<td>$3.2^{+5.0}_{-2.7}$</td>
<td>0.90</td>
<td>5.3</td>
<td>60</td>
<td>1.1</td>
<td>7.7</td>
<td>170</td>
</tr>
<tr>
<td>SDSS J1630+4012</td>
<td>6.05</td>
<td>$-26.71$</td>
<td>$-     $</td>
<td>$1.6^{+0.9}_{-1.3}$</td>
<td>0.97</td>
<td>$&lt; 4.5$</td>
<td>$&lt; 45$</td>
<td>$&lt; 0.9$</td>
<td>1.6</td>
<td>35</td>
</tr>
<tr>
<td>Mean quasar</td>
<td>6.24</td>
<td>$-27.76$</td>
<td>$2.13$</td>
<td>$1.65$</td>
<td>0.94</td>
<td>$-     $</td>
<td>$-     $</td>
<td>$-     $</td>
<td>4.2</td>
<td>90</td>
</tr>
</tbody>
</table>

Positions and optical magnitudes have been taken from Fan et al. (2003); 1.2-mm MAMBO-2 data have been taken from Bertoldi et al. (2003).

### 3 RESULTS AND DISCUSSION

The measured flux densities of the three sources are tabulated in Table 1, along with the observational parameters of the three sources. For comparison, the mm fluxes, taken from Bertoldi et al. (2003), have also been included. In all cases the numbers in brackets are the 1σ rms values.

Tabulated in Table 2 are the derived 850-μm/1.2-mm and 450/850-μm flux ratios for the sample where sufficient data exist. The superscripts and subscripts in columns 4 and 5 give the 1σ upper and lower values of the flux ratios. Also listed are the equivalent numbers for the fiducial single-temperature spectral energy distribution (SED) model of a quasar at the mean redshift of the $z > 6$ sample, $\tau_{850} = 6.24$, based on a fit to a sample of $z > 4$ quasars by Priddy & McMahon (2001).

#### 3.1 Individual sources

##### 3.1.1 SDSS J1630+4012 ($z = 6.05$)

Not detected in either the 850- or 450-μm filters; also undetected at 1.2 mm.

##### 3.1.2 SDSS J1048+4637 ($z = 6.23$)

Detected at neither 850 nor 450 μm. Based on the detection at 1.2 mm (Bertoldi et al. 2003), the SCUBA 850-μm limit is deep enough that we should have been able to detect the source with a 4σ significance were its emission at 1.2 mm to be characteristic of a greybody at $T_d = 40$ K. Our non-detection thus suggests that the dust in this object is colder than 40 K.

### Table 2. Summary of quantities derived from submm and optical photometry. See text for an explanation of the quantities and notes on their derivation.

<table>
<thead>
<tr>
<th>Source</th>
<th>$z$</th>
<th>$M_B$</th>
<th>$S_{850 \mu m}$/S$_{1.2,\text{mm}}$</th>
<th>$S_{450 \mu m}$/S$_{850 \mu m}$</th>
<th>$t(\infty) - t(t)$ (Gyr)</th>
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<td>4.2</td>
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Submillimetre observations of three \( z > 6 \) quasars

Figure 1. Top panel: observed submm and mm fluxes for SDSS J1148+5251. Note that, for each point, the plotted error bars are the square root of the sum of the squares of the radiometric rms and systematic calibration errors. Superposed over the points are three model SEDs: the solid locus traces the isothermal dust model of \( T = 40 \) K, \( \beta = 2.0 \) derived by Priddey & McMahon (2001) from a sample of mm and submm observations of \( z > 4 \) quasars, and fitted here through the 850-\( \mu \)m flux; the dotted line traces the SED of a single-temperature dust model with \( T_d = 180 \) K, \( \beta = 0 \); the dashed line traces a two-component fit using a \((T_d, \beta)\) of \((140, 1.5)\) and \((40, 0)\). The two-component model is included for illustrative purposes only, as the number of independent data points is smaller than the number of independent constraints on the model. Bottom panel: a plot of the Priddey & McMahon (2001) SED superimposed on to the observed mm and submm fluxes for SDSS J1148+5251 (filled squares) and BR B1202–0725 (open circles), redshifted to the quasar rest frame. The observed fluxes have been normalized to the 850-\( \mu \)m values appropriate to the individual sources.

3.1.3 SDSS J1148+5251 (\( z = 6.48 \))

The most optically luminous of the three sources, detected at both 850 and 450 \( \mu \)m with fluxes of 7.8(0.7) and 24.7(7.4) mJy respectively—one of very few quasars at \( z > 4 \) where this has been achieved. The observed fluxes are not consistent with a Priddey & McMahon (2001) single-temperature SED, as can be seen in Fig. 1. This can be seen more clearly in Figs 2(a)–(c), where the 850-\( \mu \)m/1.2-mm and 450/850-\( \mu \)m ratios have been plotted as a function of redshift, both for the single-temperature model (locus) and for a selection of high-\( z \) quasars, including those observed in this sample. The observed flux ratios are discrepant at the 1\( \sigma \) level; however they are well within the 2\( \sigma \) limits.

3.2 Observed fluxes

The three sources observed show quite different submm properties, in spite of their similar absolute B-band (\( M_B \)) magnitudes (column 3 in Table 2), and so inferred black hole/bulge masses (see column 10 in Table 2). This is not surprising as, to date, it has not been possible to establish a correlation between the optical luminosity of...
a quasar and the submm emission from its quasar host galaxy using samples of radio-quiet, optically loud quasars at $z > 4$ and $z \approx 2$ (Isaak et al. 2002; Priddey et al. 2003a). What are striking, however, are the detections at both 850 and 450 $\mu$m of SDSS J1148+5251.

It is not possible to fit the two fluxes reported here and the 1.2-mm flux with a single-temperature SED parameterized by $T_d = 40$ K and $\beta = 2$ (see Fig. 1: solid line). A better fit can be achieved with a much hotter characteristic dust temperature $T_d = 180$ K and $\beta = 0$ (Fig. 1: dotted line), or using a two-component model with a cool component characterized by $T_d = 40$ K, $\beta = 0$ and a hotter component with $T_d = 140$ K, $\beta = 1.5$. However, we stress that there are insufficient data points to constrain such a two-component model. If, in the first instance, we assume that the underlying SED is indeed best characterized by a single temperature, then there are a number of different factors that need to be explored to establish the origin of the anomalous flux ratios, which can be broadly grouped into those that result in an anomalously high mm flux, and those that may result in systematically low submm fluxes. However, it is clear that observations with a higher signal-to-noise ratio are urgently needed in order to constrain the model fitting better. Furthermore, the high photometric precision of ALMA, of the order of a few per cent, will be crucial for future analyses of this type.

3.2.1 A high 1.2-mm flux

If we assume that the observed 850-µm flux is correct, then there are a number of observational and physical reasons why the observed 1.2-mm and 450-µm fluxes might deviate from values expected for a single-temperature SED model.

(i) Relative calibration. Calibration at mm and long-submm wavelengths is relatively straightforward, particularly under periods of high and stable atmospheric transmission. A comparison of calibrators common to the JCMT and IRAM by Lisenfeld and collaborators suggests that the calibrator fluxes measured at 850 $\mu$m and 1.2 mm are consistent with thermal SED profiles. We have included calibration errors of 10–15 per cent in our plotted rms estimates. Accurate calibration at 450 $\mu$m, however, is far more difficult with small, temporal variations in atmospheric extinction, $\tau$, contributing significantly to the final, overall flux. We estimate the combined random and systematic error in the individual flux measurements to be about 30 per cent. We have included calibration errors in the error bars plotted in Fig. 1, calculated by taking the square root of the sum of the squares of the different error components.

(ii) Synchrotron contamination. Synchrotron emission can contribute significantly to the observed mm fluxes of radio-loud quasars, with boosting either from the synchrotron tail in the quasar itself, or from a source in its neighbourhood. Very Large Array (VLA) observations at 43 GHz by Bertoldi et al. (2003) place a $S(3\sigma)_{43\text{GHz}} < 0.33$ mJy on radio emission from the quasar at 43 GHz. This strongly suggests that the 1.2-mm emission is thermal rather than non-thermal given the positive spectral shape. A search of the NRAO VLA Sky Survey (NVSS) (Condon et al. 1998) and the VLA FIRST (Becker et al. 1995) radio catalogues did not reveal any radio sources within a 30-arcsec radius of the optical position of the quasar. The FIRST survey has a 0.138 mJy beam$^{-1}$ rms at the quasar position (1.4 GHz), which places a $3\sigma$ upper limit to the synchrotron contamination of the 1.2-mm flux by radio sources in the quasar field of 0.5 mJy, based on the worse case of a flat-spectrum radio source.

(iii) Lensing. Gravitational lensing can boost observed flux measurements considerably (e.g. F10214+4724 (Broadhurst & Lehar 1995), APM 08279+5255 (Irwin et al. 1998; Ibata et al. 1999)). In general, however, the magnification is achromatic. Thus all (sub)mm fluxes will be scaled by the same factor unless the physical extent of the regions emitting at the different wavelengths were quite different – for example, if the mm flux ($\lambda_{\text{rest}} = 170$ $\mu$m) traced a cooler and, most importantly, highly extended region whilst the shorter wavelength emission traced much more compact emission. It is not possible to establish this, however, without the high spatial resolution achievable using mm interferometers.

(iv) Spectral line contamination. Line contamination of submm continuum fluxes observed in local galaxies is widely recognized. Observations by Zhu et al. (2003) have shown that the CO(3–2) rotational line can contribute as much as 70 per cent to the 850-µm continuum flux. At $z \sim 6.43$ the CO(3–2) ($\lambda_{\text{rest}} = 867$ µm) line is redshifted to 6.46 mm (46.4 GHz), well outside the 1.2-mm and 850-µm filter passbands. Under good observing conditions, the 1.2-mm filter has an effective passband of around 80 GHz, which at $z \sim 6.43$ includes the forbidden, rest-frame far-infrared (FIR) transition of C$^+$ ($\lambda_{\text{rest}} = 157.74$ µm). Significant flux boosting by this line is, however, unlikely: observations with ISO have shown that the line-to-FIR ratio in local starbursts and ultraluminous infrared galaxies (ULIRGs) (Luhman et al. 1998, 2003) is a factor of 10 or more lower than that seen in normal galaxies (0.1–1 per cent; Stacey et al. 1991). If we assume an equivalent filter width of the MAMBO-2 camera at 1.2 mm of around 80 GHz, then the C$^+$ line peak would need to be over 500 mJy to account for the excess emission at 1.2 mm (1.5 mJy) above that expected for a single-temperature SED fit. This would be equivalent to a line contribution to the FIR luminosity of about 1 per cent. A search by Isaak et al. (1994) for the redshifted C$^+$ emission line in the optically luminous, radio-quiet quasar BR B1202–0725 at $z = 4.695$ placed a $3\sigma$ upper limit of $\sim 3 \times 10^4$ mJy on the line contribution to the FIR luminosity (equivalent to a $3\sigma$ upper limit to the line of $\sim 60$ mJy, and a line-to-continuum ratio of just over 1 in a linewidth of 250 km s$^{-1}$) in this, the most submm-bright of the $z > 4$ quasars. Thus, whilst an intriguing possibility, it is unlikely that contamination by C$^+$ is responsible for the high 1.2-mm flux. (Note added in proof: This has been confirmed by recent measurements at the JCMT by Bolatto, Di Francesco & Willott (2004).)

3.2.2 A low 850-µm flux

If, in contrast, we assume that the 1.2-mm flux is correct, then the observed submm fluxes at 850 and 450 µm are factors of 1.4 and 0.7 lower than one would expect from a single-temperature, $T_d = 40$ K, $\beta = 2$ SED fit. The 850-µm detection flux is at $>10 \sigma$ and as such is, at first glance, almost $3\sigma$ below the single-temperature fit derived from the 1.2-mm flux. The statistical significance of the difference however, is in the range 0.7 < ($S_{850}^{\text{est}} - S_{850}^{\text{obs}}$)/$S_{850}^{\text{obs}}$ < 6.7, where $S_{850}^{\text{obs}}$ is the 850-µm flux estimated from the observed 1.2-mm flux when one factors in the uncertainties in the 1.2-mm flux and the error bars in the SED fit itself. The statistical significance of the difference between the observed and predicted 450-µm fluxes is much less, as the detection itself is only at $3\sigma$. Interestingly, the discrepancy between the observed 450-µm flux and that derived from the 1.2-mm flux [scale factor of 3.3 from Figs 2(a)–(c)] is smaller.

Thus the observations of SDSS J1148+5251 suggest that the dust emission is not well characterized by a single-temperature SED fit. One cannot, however, attach high significance to this statement because of the relatively low value of the signal-to-noise ratio at 450 µm in particular. Bearing this in mind, there is very tentative evidence that alludes to a change in the properties of the high-$z$ quasar hosts with redshift. There is a considerable spread in the
3.3 Inferred properties

SDSS J1148+5251 is unique for two reasons: first, on account of its redshift; secondly, because it is detected not only at 1.2 mm and 850 µm, but, uncommonly for a high-redshift quasar, also at 450 µm.

The consequence of assuming a low $T_d$ – as suggested by the 1.2 mm–850 µm flux ratio – is a prohibitively large dust mass. This burdens us with explaining how so much dust synthesis could have taken place without the formation redshift being unacceptably high.

If, in contrast, $T_d$ is high – as suggested by the 450–850 µm ratio – there is no problem accounting for the dust mass, which is small as a result. This is, however, the cost of a large FIR luminosity.

Indeed, if the dust really is this hot, then the far-infrared luminosity approaches the blue luminosity of the quasar, which would suggest that reprocessed AGN emission is not the dominant mechanism heating the dust.

Notwithstanding the uncertainty in dust temperature, Table 2 lists the properties that all the targets would have if they were ‘average’ $z > 4$ quasars, i.e. possessing the $T_d = 40$ K and $\beta = 2$ fit by Priddey & McMahon (2001). The cosmological parameters $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$ are assumed. $t(\infty) - t(z)$ is the difference in look-back time between redshift $z$ and redshift $\infty$. As in Priddey et al. (2003b), we adopt a dust opacity of $\kappa(\lambda) = 30$ cm$^2$ g$^{-1} \times \lambda^{-2}$; $M_d$ is thus the mass of dust. $M_d(\text{min})$ is the absolute minimum sustained star formation rate needed to synthesize $M_d$ within the available time. $M_{\text{bh}}$ and $M_{\text{acc}}$ are the black hole mass and accretion rate calculated from the absolute $B$ magnitude ($M_B$) assuming Eddington accretion (e.g. Isaak et al. 2002). We have, however, shown that observed submm emission from SDSS J1148+5251 is not consistent with the Priddey & McMahon (2001) fit. In Fig. 1 we have considered instead a selection of alternative SEDs; the ‘hot’ model ($T_d = 180$ K, $\beta = 0$) has ($L_{\text{FIR}}, M_d$) = (1.1 × 10$^{14}$ L$_\odot$, 0.3 × 10$^8$ M$_\odot$), whilst the two-component model illustrated has ($L_{\text{FIR}}, M_d$) = (2.9 × 10$^{14}$ L$_\odot$, 3.3 × 10$^8$ M$_\odot$). The ‘mean’ SED, on the other hand, gives ($L_{\text{FIR}}, M_d$) = (0.1 × 10$^{14}$ L$_\odot$, 5.3 × 10$^8$ M$_\odot$).

4 CONCLUSIONS

The rest-frame FIR spectral energy distribution is key to determining the thermal origin of the observed submm emission from high-redshift quasars. The observations presented here suggest that the host galaxies of quasars out to redshifts of $z > 6$ are actively undergoing star formation. Multi-wavelength observations spanning the mm and submm are crucial to providing constraints on the dust mass, far-infrared luminosity and inferred star formation rate, thus further exploring the role of star formation in high-redshift quasar host galaxies.

ACKNOWLEDGMENTS

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