Submillimetre observations of luminous $z > 4$ radio-quiet quasars and the contribution of AGN to the submm source population

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ABSTRACT

We present sensitive 850$\mu$m SCUBA photometry of a statistically-complete sample of six of the most luminous ($M_B < -27.5$, $\nu L_\nu(1450 \AA) \gtrsim 10^{13} L_\odot$), $z > 4$ radio-quiet quasars, reaching noise levels (1$\sigma$ $\sim 1.5$ mJy) comparable with the deep blank sky surveys. These observations probe the rest frame far infrared region ($\sim 150\mu$m), at luminosity levels for thermal sources comparable with those that IRAS permitted for low redshift quasars. One quasar (BR2237–0607; $z = 4.55$) is detected at 850$\mu$m with a flux of 5.0$\pm$1.1 mJy (4.5$\sigma$), whilst a second (BR0019–1522; $z = 4.52$) has a detection at the 2$\sigma$ level. When combined with our previous millimetre measurements of $z > 4$ quasars, we find that there is a large range (5–10) in far infrared (FIR) luminosity ($L_{\text{FIR}}$) at fixed UV luminosity, and that the typical quasar has a $L_{\text{FIR}}$ and mass of cool (50K) dust similar to that of the archetypal low redshift ($z = 0.018$) ultraluminous IRAS galaxy (ULIRG) Arp220 ($L_{\text{FIR}} \sim 5 \times 10^{12} L_\odot$; $M_\text{d}(\text{cool}) \sim 10^8 M_\odot$). If one assumes a fiducial FIR luminosity of $5 \times 10^{12} L_\odot$ for all quasars with $M_B < -23$, we find that $\gtrsim 15$ per cent of the sources in the SCUBA deep surveys could be classical broad-lined radio-quiet AGN. Thus if one considers the observed ratio of Seyfert II to Seyfert I galaxies at low redshift and any contribution from totally optically obscured AGN, a significant fraction of the SCUBA source population will harbour AGN and hence the inferred star formation rates from submm fluxes may be overestimated if the active nuclei are bolometrically dominant or the IMF is top heavy.

Key words: quasars: general – quasars: individual BR2237–0607 – cosmology: observations – galaxies: starburst – infrared: galaxies – ISM: dust

1 INTRODUCTION

Recent deep SCUBA surveys (Smail, Ivison & Blain 1997; Hughes et al. 1998; Barger et al. 1998; Eales et al. 1998) have revealed a significant population of discrete submillimetre sources, amounting to $\sim 1000$ deg$^{-2}$ above $\sim 3$ mJy at 850$\mu$m. If these objects lie at redshifts greater than 1, they have a far infrared (FIR) luminosity $L_{\text{FIR}} \sim 10^{12–13} L_\odot$, assuming a dust temperature of $\sim 50$K. Since the large negative $K$-correction of the dust thermal spectrum means that for $1 \lesssim z \lesssim 10$, this luminosity is insensitive to source redshift (cf. Arp 220 in Figure 1). Prior to the SCUBA surveys, the only significant known high redshift population with comparable bolometric luminosity were the quasars. However, the characterisation of the FIR properties of the high redshift quasars is rather meagre. Following the first detections of rest frame FIR emission from $z > 3$ radio quiet quasars (McMahon et al. 1994), our current knowledge is still biased towards more luminous objects with 850$\mu$m fluxes in the $\sim 10–50$ mJy range (Isaak et al. 1994; McMahon et al. 1994; Omont et al. 1996a).

The onset of nuclear activity seems to be closely connected with significant structure-formation events. At high redshift, black holes form in rare overdense regions and are fuelled by their collapsing host objects (Haehnelt & Rees 1993); at low redshifts, interactions/mergers provoke inflow of gas to the galactic nuclei (Barnes & Hernquist 1996), fuelling central black holes. These processes would be expected...
to trigger a major starburst, though the relative prominence of
either component, starburst or AGN, would depend on the
precise dynamical details of the collapse or interaction.

In this paper, we report SCUBA 850 µm photometry of
a statistically complete sample of six of the most luminous,
\( z > 4 \), radio-quiet quasars. Our previous work at 800 µm
with the JCMT (Isaak et al. 1994) and 1.25 mm with the
IRAM 30 m (McMahon et al. 1994, Omont et al. 1996a) and
was only sensitive to relatively high luminosity sources.
The aim of the current work is to carry out more sensitive obser-
vations of a small sample of radio quiet quasars in an effort
to make an initial estimate of the contribution of AGN at
high redshift to the submillimetre source population.

Unless stated otherwise, we assume \( H_0 = 50 \times 50 \) km
s\(^{-1}\) Mpc\(^{-1}\) and \( q_0 = 0.5 \) throughout this paper.

### 2 OBSERVATIONS

The quasars for study were selected from the APM sam-
ple of high redshift quasars (Storrie-Lombardi et al. 1996,
McMahon et al. in prep.) and PSS survey (Kennefick et al.
1995). From extant radio data as tabulated in Table 1,
the quasars are radio quiet based on the definition, Log
\( R_{8.4} < 4 \), where \( R_{8.4} = L_{8.4}/L_B \), is the ratio of radio
and optical luminosities as defined by Hooper et al.(1996),
where spectral indices of \(-0.5\) and \(-0.7\) have been used to extrap-
olate to the rest frame optical and radio fluxes. Moreover,
based on the observed median spectral index of \(-0.7\) found
for radio loud quasars over the wavelength range, the
expected contamination at 850 µm is \( < 0.1 \) mJy is all cases.
The most luminous \( z > 4 \) objects were selected in the HA range
15–08 as determined by the telescope scheduling, providing
effectively sparse sampling for \( M_B < -27.5 \).

Observations were carried out during three 8 hr observ-
ing shifts over the period 1998 August 16 to 19, with the Sub-
millimetre Common-User Bolometer Array (SCUBA) (Hol-
land et al. 1998) on the 15 m James Clerk Maxwell Tele-
scope. We used SCUBA in standard point-source photome-
try mode at 450 and 850 µm. This involves placing the target
on the central bolometer of each array, whilst ‘jiggling’ the
secondary mirror in a 9-point pattern with 2 arcsec offsets,
integrating for 1 second at each. Superimposed on this is a
chop of the secondary mirror by 60 arcsec (in azimuth) at
7 Hz, to remove sky emission; after the first 9-point jiggle,
the telescope is nodded such that the chop position lies on
the opposite side of the source. Uranus was used as the pri-
mary flux calibrator. Skydips were taken regularly to deter-

### Table 1. Program objects, observing conditions and results.

| Object name  | \( z \) | \( M_B \) | \( S_{1.4 \, GHz} \) (3σ) | \( R_{8.4} \) | \( t_{int} \) (min) | \( \tau_{225 \, GHz} \) (mean) | \( \tau_{850 \, \mu m} \) | \( \tau_{450 \, \mu m} \) | \( F_{850} \) (mJy) | \( F_{450} \) (mJy) |
|------------|-----|---|-------------|--------|-----------|----------------|-------------|-------------|----------------|-------------|
| BR B0019−1522 | 4.52 | -27.6 | <0.5 | <2 | 108 | 0.08 | 0.21–0.26 | 1.1–2.4 | 3.3±1.6 | 11±33 |
| PSS J0134+3307 | 4.52 | -28.2 | <1.5 | <3 | 108 | 0.08 | 0.27–0.34 | 1.8–2.5 | 0.4±1.5 | -3±54 |
| PSS J0248+1802 | 4.43 | -27.9 | <1.5 | <5 | 36 | 0.10 | 0.23–0.46 | 2.4–3.2 | 6.4±4.5 | -233±264 |
| PSS J0747+4434 | 4.42 | -28.2 | <0.5 | <5 | 54 | 0.08 | 0.27–0.39 | 1.8–2.5 | 0.0±2.2 | 72±105 |
| BR B1600+0729 | 4.35 | -28.1 | <0.5 | <2 | 108 | 0.09 | 0.28–0.33 | 1.7–2.0 | 1.8±1.6 | -7±55 |
| BR B2237−0607 | 4.55 | -28.1 | <0.5 | <5 | 144 | 0.07 | 0.29–0.41 | 1.8–2.7 | 5.0±1.1 | 19±53 |

Notes: Radio flux limits taken from (1) McMahon et al., in preparation; (2) Condon et al., 1998; (3) Becker et al., 1995

![Figure 1.](image-url) The current status of the high redshift \( (z > 1) \) 850 µm Hubble diagram using the observations presented in Table 2. Radio galaxies are shown as filled circles; open circles show the submm detected lensed sources with vertical lines connecting the observed flux with the unlensed fluxes; open stars show previously detected radio quiet \( z > 4 \) quasars; filled stars show our new observations. Upper limits are plotted at the 2σ limit with arrow length equal to the 1σ uncertainty. Also plotted is the expected flux from a thermal source like Arp220 as function of redshift for two cosmologies using the observed SED from Klaas et al. (1997).

3 RESULTS

At 850 µm, one quasar, BR2237−0607 at \( z = 4.55 \), is
detected with high significance \( (4.5 \sigma) \), while the quasar
BR0019−1522 has a detection at 2σ. Two of the remain-
ing objects have good 1σ \( \approx 1.5 \) mJy upper limits. None of
the objects are detected at 450 µm; at this wavelength, the

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observations are noisy, because weather was on the whole unfavourable, so we disregard data in this band. Our observed fluxes are compared with those of other cosmological submillimetre sources in Figure 1.

We can derive dust masses and FIR luminosities from our observations as described in more detail in McMahon et al. (1994). There is considerable uncertainty in these procedures (e.g. Figure 2), but we can assume physical parameters derived for better-studied objects and extrapolate from our 850 µm measurements. The mass of a dust cloud optically-thin in the FIR is given by

\[
M_d = \frac{S_\nu (\nu_{\text{abs}}) D_L^2}{\kappa_d B_\nu (T_d) (1+z)},
\]

where \(D_L\) is the luminosity distance and \(\kappa_d\) is the absorption coefficient:

\[
\kappa_d = \kappa_{500} \times \left( \frac{\nu_{\text{rest}}}{353 \text{ GHz}} \right)^{\beta}.
\]

We assume a frequency dependence of absorption coefficient of \(\beta = 1.5\), as shown to be a good fit for both low redshift luminous infrared galaxies (Carico et al., 1992) and luminous high redshift quasars (Benford et al., in prep.) and \(\kappa_{500} = 0.11 \text{ m}^2 \text{kg}^{-1}\), based on the widely-used Hildebrand (1983) normalisation at 125 \(\mu\text{m}\) \((\kappa = 1.875 \text{m}^2/\text{kg})\), which we have extrapolated to longer rest wavelengths assuming \(\beta = 1.5\).

The above assumes that the rest-frame FIR continuum is thermal emission from dust which is optically thin to FIR photons, which is justified since spectral indices in the Rayleigh–Jeans region for typical \(z > 4\) quasars are \( \gtrsim 3 \) (Buffey et al. in prep., Isaak et al., 1994). It also assumes that the dust is isothermal: a single temperature of 50 K is a typical value derived from fits to well-covered FIR SEDs. If the dust were not isothermal, fits to the currently-available data would be biased towards the higher temperatures, causing us to underestimate the true dust mass. ISO Photometry of nearby ULIRGs (Klaas et al. 1997) suggests that two-component fits are more appropriate, low-temperature dust being us to underestimate the true dust mass. Since the existing \(z > 4\) data do not constrain two-component fits, we assume that the 850 µm flux is dominated by the low-temperature component.

The FIR luminosity is obtained by integrating under a single modified blackbody curve. Given, \(T_d = 50\)K and \(\beta = 1.5\), \(L_{\text{FIR}}\) is directly proportional to \(M_d\):

\[
L_{\text{FIR}} \approx 3.3 \times \left( \frac{M_d}{10^8 M_\odot} \right) \times 10^{12} L_\odot.
\]

Assuming that the FIR flux is due to dust heated by a starburst, the star formation rate is given by:

\[
SFR = \alpha \times 10^{-10} \frac{L_{\text{FIR}}}{L_\odot} M_\odot \text{yr}^{-1},
\]

where the value of \(\alpha\) depends upon the stellar initial mass function (IMF) adopted and the timescale for the burst. For example, Scoville & Young (1983) deduce \(\alpha = 0.77\) by

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**Table 2. Physical properties of representative 850 µm sources, assuming \(T_d = 50\) K and \(\beta = 1.5\)**

| Object name | Type       | Redshift \(z\) | \(F_{650}\) \,(mJy) | \(M_d\) \(\left(h_{50}^{-2}10^8 M_\odot\right)\) | \(L_{\text{FIR}}\) \(\left(h_{50}^{-2}10^2 L_\odot\right)\) | \(SFR\) \(\left(M_\odot \text{yr}^{-1}\right)\) | \(M_{\text{B}}\) \(\left(10^9 M_\odot\right)\) |
|-------------|------------|----------------|---------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| BR0019−1522 | Quasar     | 4.52           | 3.3±1.6\(^d\)       | 1.5±0.7                                        | 5.0±2.4                                        | 500                                           | −27.6                                         |
| PSS0134+3307| Quasar     | 4.52           | < 3.0\(^d\)         | < 1.4                                          | < 4.5                                          | < 450                                         | −28.2                                         |
| BR1600+0729 | Quasar     | 3.35           | < 3.2\(^d\)         | < 1.5                                          | < 4.9                                          | < 490                                         | −28.1                                         |
| BR2327+0607 | Quasar     | 4.55           | 5.0±1.1\(^d\)       | 2.3±0.5                                        | 7.5±1.6                                        | 750                                           | −28.1                                         |
| BR10952−0115\(^a\) | Quasar     | 4.43           | 14±2\(^d\)          | 6.5±0.9                                        | 21.2±3.0                                       | 2120                                          | −27.7                                         |
| BR1033−0327 | Quasar     | 4.50           | 7±2\(^d\)           | 3.2±0.9                                        | 10.5±3.0                                       | 1050                                          | −27.6                                         |
| BR1117−1329 | Quasar     | 3.96           | 13±1\(^d\)          | 6.4±0.5                                        | 29.8±1.6                                       | 2080                                          | −28.1                                         |
| BR1144−0723 | Quasar     | 4.14           | 7±2\(^d\)           | 3.4±1.0                                        | 11.0±3.1                                       | 1100                                          | −27.5                                         |
| BR1202−0725 | Quasar     | 4.60           | 42±2\(^d\)          | 19.0±0.9                                       | 62.0±3.0                                       | 6200                                          | −28.5                                         |
| BR1335−0417 | Quasar     | 4.40           | 14±2\(^d\)          | 6.5±0.5                                        | 21.3±1.5                                       | 2130                                          | −27.3                                         |
| 8C1435+635  | Radio Galaxy | 4.25         | 7.77±0.76\(^d\)     | 3.7±0.4                                        | 12.0±1.2                                       | 1200                                          | −24.4                                         |
| 4C14.17     | Radio Galaxy | 3.80         | 17.4±3.14\(^m\)     | 7.5±1.3                                        | 24.5±4.4                                       | 2450                                          | −25.0                                         |
| APM08279+5255\(^a\) | Quasar     | 3.91           | 75±4\(^d\)          | 2.6±0.1                                        | 8.6±0.5                                        | 860                                           | −31.0                                         |
| SMM02399−0136\(^c\) | Seyfert 2 | 2.80           | 26±3\(^d\)          | 6.1±0.7                                        | 19.8±2.3                                       | 1980                                          | −24.0                                         |
| H1413+117\(^d\) | Quasar     | 2.55           | 66±7\(^d\)          | 3.4±0.4                                        | 11.1±1.2                                       | 1110                                          | −28.5                                         |
| F10214+4724\(^l\) | Seyfert 2 | 2.29           | 50±5\(^d\)          | 0.9±0.1                                        | 2.9±0.3                                        | 290                                           | −23.1                                         |
| Arp220      | Starburst  | 0.0183         | 67000\(^m\)         | 1.7                                            | 5.5                                            | 550                                           | −21.3                                         |

**Notes:** † The uncertainty only reflects the flux uncertainty. ‡ Computed from observed optical continuum magnitudes assuming a spectral index of −0.5, except in the cases of the radio galaxies, where K-band magnitudes were used. ¹ Lensed objects. Magnification factors for the FIR continuum are (a) uncertain; (b) 10; (c) 2.5 (Ivison et al., 1998b); (d) 10 (Yun et al., 1997); (e) 30 (Eisenhardt et al. 1996). Derived physical quantities are corrected by these factors. ² m 800 µm fluxes; equivalent 850 µm fluxes would be 15, 56 and 42 mJy, respectively. ³ ISO 170 µm flux (N.B., at \(z \approx 4\), 850 µm corresponds to a rest wavelength of \(\sim 170\) µm).

**References:** 1. This work; 2. Buffey et al. (in prep.); 3. Ivison et al. (1998a); 4. Dunlop et al. (1994); 5. Lewis et al. (1998); 6. Ivison et al. (1998b); 7. Hughes et al. (1997); 8. Rowan-Robinson et al. (1993); 9. Klaas et al. (1997).
considering the total energy radiated by main sequence O, B and A stars \((M > 1.6 \, M_\odot)\), over \(\sim 10^9\) yr; whereas Thronson & Telesco (1986) obtain \(\alpha = 2.1\), assuming a Salpeter IMF. Allowing for the low mass \((1.6 \, M_\odot > M > 0.1 \, M_\odot)\) stars, \(\alpha\) rises by a further factor \(\sim 3\).

Table 2 shows results derived for a sample of cosmological submillimetre sources, in a self-consistent manner, to enable comparison of observed and derived properties. The uncertainties inherent in our assumptions are illustrated in Figure 2. Note that the uncertainties in FIR luminosities reflect solely the uncertainty in the flux, and do not include the uncertainty due to the assumed single temperature. In Figure 3 are plotted the inferred FIR luminosities against optical luminosity for the \(z \geq 4\) quasars. Since the quasar BR1202–0725 has been resolved into two millimetre and optical sources (Omont et al. 1996a; Hu, McMahon & Egami 1996b) is plotted as two discrete points, since its extreme luminosity might be explained if it represents the merger of two gas-rich galaxies or of an AGN and a gas-rich galaxy.

4 DISCUSSION

From the results presented in Figure 3, there is no obvious correlation between \(L_{\text{FIR}}\) and \(L_{\text{UV}}\). Indeed, over a range of a factor of 1.5 in UV luminosity, the scatter in \(L_{\text{FIR}}\) is \(\sim 10\). The absence of a strong correlation between \(L_{\text{FIR}}\) and \(L_{\text{UV}}\) is supported by the results tabulated in Table 2, with the obvious caveat that this compilation, is rather heterogeneous and consists primarily of detected objects. This conclusion has the implication that the high redshift AGN population may have a FIR luminosity function that is independent of UV luminosity.

In earlier mm/submm work (Isaak et al. 1994; Omont et al. 1996a), only a small fraction \((\sim 20\%\) of the observed sources were detectable, and the observational limits were at quite high FIR luminosities. These new observations indicate that the typical luminous quasar has a FIR luminosity less than or equal to that of Arp220.

We can investigate the AGN contribution to the deep SCUBA source counts using a simple model where all AGN have a fiducial FIR luminosity of \(\sim 5 \times 10^{12} \, L_\odot\) with an Arp220-like spectrum in the submm range. We assign this FIR luminosity to each quasar and adopt a standard Boyle, Shanks & Peterson (1988) quasar luminosity function, extrapolating to high redshifts by assuming no evolution between \(z = 2\) and \(z = 3\), and a density fall-off by a factor of 2 per unit redshift thereafter. Integrating the luminosity function down to \(M_B = -23.0\), we find that there are \(\sim 140\) quasars deg\(^{-2}\). This absolute magnitude limit is primarily based on historical convention from ground based image quality, and if we relax this limit and extrapolate down to \(M_B = -21.0\), the source density reaches \(\sim 400\) deg\(^{-2}\). Finally, if one allows for the observed ratio of Seyferts II to Seyferts I at low redshift \(2.3 \pm 0.7\) (Huchra & Burg, 1992), even neglecting any contribution from totally optically obscured AGN, it is feasible that that a major part \((15–100\%\) per cent) of the SCUBA source population could possess AGN.

Further evidence for such high space densities of AGN comes from the deepest X-ray surveys which reach source densities of \(\sim 1000\) deg\(^{-2}\) (Hasinger et al. 1998). Whilst the nature of the faintest sources is still controversial, an AGN origin for the energy source is widely considered as the most plausible explanation \((e.g.\ Hasinger et al. 1998)\). Furthermore, estimates of the local space density of massive dark objects within galaxies (Magorrian et al. 1998) exceed the density of the optically-selected quasars, of which these objects are presumed to be the dull remnants (Jacholkaitis, Nataraajan & Rees 1994; Trehantham et al. 1998): there may exist a significant population of AGN which are either obscured by dust or accrete in low-efficiency modes.

Lower limits on the contribution of AGN to the submm source counts comes from studies of local ultraluminous infrared galaxies. These limit the fraction of ULIRGs in which AGN activity is the primary energy source to 20–30 percent,

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although these observations do not exclude the possibility that the remaining starburst-dominated cases contain AGN as well [Genzel et al. 1998].

An alternative estimate of the contribution of broad line AGN to the submm source counts can be derived by assuming that $L_{FIR}$ is linearly correlated with $L_{UV}$ as shown in Figure 3. Above 3 mJy at 850 μm, the source density ranges between 4 and 9 deg$^{-2}$ for a thermal spectrum with temperature of 70K and 30K respectively. This is essentially because only AGN with $M_B < -25$ would have detectable flux at 850 μm. It is thus important that observations of quasars with $M_B < -25$ are carried out at 850 μm to distinguish between the range of models.

If AGN are present in a significant fraction of the SCUBA sources, this has important implications for studies which use the SCUBA source counts to infer star formation rates from the from a 850 μm flux. The tacit assumption in Equation 3 is that this locally-derived relation between $L_{FIR}$ and the star formation rate, based on galaxies such as M51 in which $L_{FIR} \sim 10^{10} L_\odot$, can be applied within the extreme environments of high redshift AGN and massive starbursts, in which FIR luminosities are 100–1000 times larger. For example, the intense UV flux from any starburst or AGN could suppress the formation of low mass stars which dominate the total mass. Thus, even if the dust is not heated by a more energy-efficient AGN, the AGN’s presence may affect the underlying IMF which is used to deduce the total star formation rate.

5 CONCLUSIONS

We have observed a small but statistically-complete sample of luminous high redshift ($z > 4$) quasars with SCUBA at 850 and 450 μm, and have found that the typical FIR luminosity of these quasars is less than or comparable with that of the archetypal local ultraluminous IRAS galaxy Arp220. Using a simple model for the contribution of AGN to the submm source population, we find that ~15 per cent of the sources in the deep SCUBA surveys at the $S_{850} \sim 3$ mJy level, may contain active nuclei. Hence, both the contribution of AGN to the FIR luminosity, and its effect upon the underlying IMF (should starburst be the dominant power source), need to be considered.

Further submm studies of lower redshift and lower luminosity quasars are required in order to determine directly the far infrared luminosity function for quasars. In addition sensitive X-ray observations with AXAF and XMM may determine the fraction of the SCUBA sources which harbour AGN.

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