The SCUBA Bright Quasar Survey (SBQS): 850micron observations of the z>4 sample

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ABSTRACT
We present initial results of a new, systematic search for massive star-formation in the host galaxies of the most luminous and probably most massive z>4 radio-quiet quasars (M_B ≤ −27.5; νL_ν(1450Å) > 10^{13} L_⊙). The survey, undertaken at 850μm using SCUBA at the James Clerk Maxwell Telescope (JCMT), has a target sensitivity limit of 3σ ~ 10mJy, set to identify sources suitable for detailed follow-up e.g. continuum mapping and molecular line diagnostics. A total of 38 z>4 radio-quiet quasars have been observed at 850μm, of which 8 were detected (>3σ) with S_{850μm} > 10mJy (submillimetre-loud). The new detections almost triple the number of optically selected, submillimetre-loud z>4 radio-quiet quasars known to date. We include a detailed description of how our quasar sample is defined in terms of radio and optical properties. As a by-product of our selection procedure we have identified 17 radio-loud quasars with z>4.

There is no strong evidence for trends in either detectability or 850μm flux with absolute magnitude, M_B. We find that the weighted mean flux of the undetected sources is 2.0 ± 0.6mJy, consistent with an earlier estimate of ~ 3mJy based on more sensitive observations of a sample z>4 radio-quiet quasars (McMahon et al.,1999). This corresponds to an inferred starformation rate of ~1000 M_⊙ yr^{-1}, similar to Arp220. The typical starformation timescale for the submillimetre-bright sources is ~ 1 Gyr, 10 times longer than the typical accretion-driven e-folding timescale of ~ 5 x 10^7 years. Our 850μm detection of the z = 4.4 quasar PSS J1048+4407 when analysed in conjunction with 1.2mm single-dish and interferometric observations suggests that this source is resolved on angular scales of 1-2″ (6-12 kpc). In addition, we present a new optical spectrum of this source, identifying it as a broad absorption line (BAL) quasar. The new redshift is outside that covered in a recent CO line search by Guilhouette et al., (1999), highlighting the need for accurate redshifts for the observation and interpretation of high-redshift line studies.

Key words: high-redshift star-formation ; radio-quiet quasars; quasar host galaxies

1 INTRODUCTION

It is becoming increasingly clear that star-formation with its complementary photometric and spectroscopic signatures provides observers with a range of probes with which to study formation and evolution of galaxies in the early Universe. Particularly important to such studies are the millimetre-/submillimetre-/far-infrared- wavebands, a wavelength range in which clear fingerprints of both warm dust, heated by UV starlight from massive young stars, as well as atomic and molecular line emission, excited in regions of on-going starformation, can be seen. Recent work by Wright & Reese (2000) has further illustrated the importance of this waveband, demonstrating that roughly half the radiation produced by starlight in galaxies is absorbed by dust and reradiated in the far-infrared/submillimetre-waveband. Likewise, COBE observations have shown that the cosmological starformation rates inferred from UV- and optical studies (eg. Madau et al., (1998)) are more than a factor of two lower than those required to produce the observed
Figure 1. A plot of the 850 $\mu$m flux vs. redshift for high-z objects with observed 850 $\mu$m fluxes and accurately determined redshifts. Stars denote detections of $z \sim 4$ radio-quiet quasars, with solid stars representing detections presented in this paper, and open stars sources taken from previous work. Squares denote detections of radio galaxies – unfilled taken from Archibald et al, 2000, and filled from the literature. Solid circles denote a selection of other high-z objects. Objects for which CO observations exist are ringed: solid rings – CO detections; dashed rings – CO non-detections. Lensing corrections are indicated by vertical dotted lines. The two curves trace the estimated flux that an Arp220-like object (based on a fit to observed FIR fluxes of Arp220) would have at different redshifts ($\Omega_M = 1; \Omega_\Lambda = 0$; dashed line: $\Omega_M = 0.3; \Omega_\Lambda = 0.7$) and the horizontal $3\sigma$ limit of this survey.

far-infrared background, suggesting that there exists a population of star-forming galaxies that are hidden at optical wavelengths.

How can one use the (sub)millimetre-waveband to study starformation, both qualitatively and quantitatively, in the high-redshift Universe? Photometric measurements of the (sub)millimetre-wave emission constrain the rest-frame spectral energy distribution – with more than one (sub)millimetre flux it is possible to evaluate a (sub)millimetre spectral index, thus confirming or refuting a thermal origin of the emission (eg. Hughes et al. (1993), Isaak et al. (1994)). With sufficient data, one can also determine a best-fit dust temperature, from which a bolometric (sub)millimetre-/far-infrared luminosity can be derived. Establishing the original energy source responsible for this reprocessed emission is considerably more difficult (eg. Sanders et al. (1984)), as the continuum spectral signatures of dust-obscured AGN and massive starbursts are very similar, indeed, with current telescopes indistinguishable at (sub)millimetre-wavelengths. If one assumes that some fraction of the (sub)millimetre/far-infrared luminosity arises from reprocessed UV-light from massive stars, then it is possible to infer starformation rates also. The presence and detection of the molecular gas tracer CO, found ubiquitously in nearby starburst galaxies, points to future starformation potential. In addition spectral line measurements provide important kinematic and dynamic information. Whilst thermal emission from dust out to high redshift can now be detected with relative ease due to the new generation of sensitive multi-pixel millimetre (Kreysa et al. 1998) and submillimetre-wave arrays (Holland et al. 1999), detecting CO is more difficult, requiring a very accurate measure of the source redshift because of the limited bandwidth ($\Delta \nu \sim 1$ GHz), and thus small fractional bandwidth at 100-200 GHz (< 1%), of the current generation of millimetre-wave receivers.

2 SURVEY DESIGN

2.1 Choice of targets

Recent attempts to study starformation in the high-redshift Universe have focused on identifying target objects in two quite distinct ways. The first of these – deep, unbiased surveys of blank sky – only recently became possible with the introduction of sensitive, multi-pixel (sub)millimetre-wave bolometer arrays. Surveys undertaken using SCUBA (Submillimetre Continuum Bolometer Array (Holland et al. 1999)) at the James Clerk Maxwell Telescope (eg. Hughes et al. (1996), Barger et al. (1997), Smail et al. (1997), Eales...
et al. (1999) have been particularly successful, identifying some tens of submillimetre-selected sources with 850 \( \mu m \) fluxes \( S_{850} > 5 \) mJy. Classifying these sources, in particular assigning redshifts, is complicated by (i) the limited accuracy with which one can determine the source positions using a single-dish telescope (ii) the large number of potential, though very faint, optical counterparts revealed in deep observations of the submillimetre-wave source fields. As a result it has been possible to begin to derive the star-formation properties of only handful of submillimetre-selected sources (eg. Frayer et al. 1999, 2000).

In contrast, objects with known redshift provide a very convenient starting point from which to base searches for and studies of star-formation at high-redshift. The first submillimetre-wave observations of high redshift objects were made in the early 1990s (Clements et al. 1992, Barvainis, Antonucci and Coleman 1992). Following on from the successful detection both of the (sub)millimetre continuum (by Clements et al. 1992) and CO emission (by Brown & VandenBout 1993), and subsequently Solomon, Radford and Downes (1993) from the ultra-luminous infrared galaxy IRAS F10214+4724 at \( z \sim 2.3 \), (sub)millimetre studies of the continuum and CO line at high redshift of a small sample of radio-quiet quasars taken from the Cambridge APM BR/BRI \( z \sim 4 \) QSO survey (Irwin, McMahon & Hazard 1991, Storrie-Lombardi et al. 1999, Storrie-Lombardi et al. 2001) were made. At the time, these quasars were amongst the most distant known. With the combination of the 800 \( \mu m / 1100 \mu m \) measured with UKT14 (Duncan et al. 1993) on the JCMT (Saak et al. 1994) and the 1300 \( \mu m \) fluxes measured at IRAM-30m (McMahon et al. 1994), it was possible to show that the (sub)millimetre continuum spectral indices were consistent with thermal emission. The (sub)millimetre emission thus indicates the presence of massive quantities of warm dust \( T_d \sim 50 \) K at redshifts of \( z \sim 4 \), synthesized, and possibly heated, by bursts of star-formation in the host galaxies. Large quantities of molecular gas, \( M_H2 > 10^{10} M_\odot \) as traced by CO (eg. Ohta et al. 1994, Mont et al. 1996a, Guilloteau et al. 1999), were also detected in the host galaxies of a handful of quasars at \( z > 4 \). The detected gas masses are comparable to the total dynamical mass of the galaxy, a situation seen in galaxies undergoing their first bouts of star-formation (eg. Downes & Solomon 1998).

2.2 Survey definition

The number of objects from which both dust and CO emission have been detected is small, and so it is currently not possible to differentiate between observed/derived properties that are representative of objects at high redshift, and those that are extreme. An efficient way by which to increase the number of massive star-forming galaxies that can be readily studied needs to be identified. Shown in Figure 2 is a plot of the observed 850 \( \mu m \) flux vs. redshift for a selection of high-redshift objects with accurately determined redshifts. Looking at \( z > 4 \): each source from which CO emission has been detected at greater than 5\( \sigma \) (see Guilloteau et al., 1999 and references therein) has \( S_{850} > 10 \) mJy, and conversely CO emission has been detected from 4 of the 5 objects with \( S_{500} > 10 \) mJy. This suggests an observationally imposed cutoff for successful CO detections of \( S_{850} \sim 10 \) mJy. If we assume that by \( z \sim 5 \) (0.9(1.2) Gyr after recombination, using an Einstein De Sitter cosmology, \( H_0 = 50 \) km s\(^{-1}\) Mpc\(^{-1}\) and a \( \Lambda \) cosmology, \( \Omega_M = 0.3 \), \( \Omega_\Lambda = 0.7 \), \( H_0 = 65 \) km s\(^{-1}\) Mpc\(^{-1}\) respectively) at least one massive burst of star-formation has already taken place, producing dust, then it is clear that it is more efficient with the current generation of radio telescopes to search first for the continuum dust emission from an object, following up secure detections with searches for CO.

A 3\( \sigma \) detection of a source with \( S_{850} \sim 10 \) mJy takes approximately 25 minutes (excluding pointing and calibration overheads) using SCUBA/JCMT under observing conditions for which the sky transparency is c. 65%. Such conditions occur \sim 25% of the time (Figure 2) and thus a survey for submillimetre-loud object at high redshift can slot well into periods during which the sky transmission is not high enough to undertake the high-priority projects requiring the highest possible sky transmission. Indeed, under the very best observing conditions, when the zenith transparency at

\* CO has not been detected in BR B1117–11329, which has \( S(850 \mu m) = 13 \pm 1 \) mJy, Buffey et al., in prep.)
850µm can be as high as 90%, the required sensitivity can be reached in an elapsed time of around 12 minutes. Such observations become an inefficient use of telescope time since they become dominated by slew time and pointing checks. In contrast, the detection of associated molecular gas for a 10mJy source would currently take some tens of hours using the PdB Interferometer and the Owens Valley Millimeter Interferometer.

Samples of statistically significant size over a wide range of redshifts are crucial not only to studies of star formation and AGN activity at different epochs, but also to the determination of the role of star formation activity and black-hole accretion in the evolution of the Universe.

In this paper we report on the first results of an 850µm program to search for massive star-bursts in the host galaxies of the most optically bright radio-quiet quasars at z ∼ 4 using SCUBA at the JCMT. The aim of the survey is to identify a sample of ~10 submillimetre-bright sources, from which it should in principle be possible to detect molecular gas emission using the current generation of millimetre interferometers. Based on extrapolations to 850µm of observations of radio-quiet quasars at z ∼ 4 by Omont et al. (1996b), we might expect to detect ~0.3 submillimetre-bright sources per hour (S850µm ≥ 10mJy) under modest submillimetre-observing conditions (sky transparency of c. 65% at 850µm). We note that this detection rate is based on the simplifying assumption that the sample of Omont et al. (1996b) has the same distribution of source properties as any sample that we might define for the purposes of these observations. Such newly identified submillimetre-bright sources, together with the 4 z ∼ 4 well-studied objects from which CO has already been detected, and those for which upper limits to a gas mass have been obtained, will provide a sample of statistically significant size (N > 3√N), with which it will be possible to begin to draw conclusions about massive star formation and its role in the high redshift universe.

We present here the interim results of our survey for a subset of 38 sources and discuss the implications of these current and future observations on studies of star formation at high-redshift. In a companion paper, Omont et al. (2001) present 1.2mm observations of the same parent sample of z ∼ 4 quasars. In a future paper (Priddey et al., in prep.) we present detailed results of both the CO observations and the submillimetre observations.
will present an analysis of the combined sample of more than 100 z \geq 4 quasars, including observations by others of different samples, which have now been observed at either 850\mu m or 1.2mm.

We have adopted an Einstein de Sitter cosmology of \( H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega = 0 \) and, where useful, include a comparison with parameters derived using a \( \Lambda \)-cosmology with \( H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_M = 0.3 \); \( \Omega \Lambda = 0.7 \).

3 SAMPLE DEFINITION

3.1 Optical properties

The parent observational sample has been selected to include the most luminous (rest-frame UV) z \geq 4 radio-quiet quasars known as of January, 2000. The quasar sample was primarily drawn from the APM multicolour photographic surveys based on APM scans of UKST plates by Irwin, McMahon & Hazard (1991), Storrie-Lombardi et al. (1996, 2001) and the Caltech DPOSS based on STSCI scans of POSS-II plates by Kennicutt et al. (1995). The first step in the sample definition was to calculate the absolute magnitude in a consistent manner for all (\( \sim 200 \)) known z \geq 4 quasars in order to select a sample on the basis of their rest-frame absolute B band magnitudes (see Figure 3).

Absolute B band magnitudes (\( M_B \)) were evaluated using observed R band magnitudes for all the quasars, assuming a spectral index \( \alpha = -0.5 \) and using the relationship

\[ M_B = R - dm(z) + 2.5 \log(1 + z) + k_R(z) - 0.5, \]

where \( R \) is the observed R-band(\( \lambda \sim 6500\AA \)) magnitude and \( dm(z) \) is the distance modulus, evaluated at the source redshift. R band magnitudes were determined from APM scans of UKST OR (5900–6900\AA) or of POSS-I E (6200–6800\AA) plates from APMCAT (www.ast.cam.ac.uk/~apmcat; McMahon & Irwin (1992)). Errors on these magnitudes are estimated to be \( \sigma_R \sim 0.3 \). At \( z \sim 4 \), the R band starts to sample the rest-frame spectrum near the prominent Lyman \( \alpha \) emission line; and at higher redshifts, the band suffers from the strong intergalactic absorption shortwards of Lyman-\( \alpha \). To compensate for both of these effects, a redshift- and filter-dependent correction factor (\( K_R(z) \)) is invoked. Initially, for the purposes of sample selection, we adopted the empirical correction of Kennefick, Djorgovski & Meylan (1996). However, for the subsequent analysis, we derived our own correction, based on the mean LBQS quasar spectrum (Francis et al. 1991), combined with the model of the hydrogen opacity of the intergalactic medium of Madau (1995), to obtain an average correction for each filter as a function of redshift. The correction was compared with empirical values derived from all \( z > 4 \) quasars for which we possess accurately flux-calibrated spectra (see Storrie-Lombardi et al., 1996, and Peroux et al., 2001), and is found to follow the trend of the data well. The scatter superimposed on this trend is large, however, leading to an overall uncertainty in the magnitude \( \sigma_M \sim 0.5 \). This scatter reflects not only the idiosyncratic variations in the effects of emission and absorption features, but also an intrinsic dispersion in the slope of the quasar continuum. For some of the quasars in the sample, a more direct measure of the continuum luminosity is available either through optical spectroscopy or through photometry in the K band, which, at \( z = 4 \), samples the rest-frame B band directly. However, for consistency and for the purposes of comparison, we use the uniformly available R magnitudes to derive a homogeneous measure of luminosity. Issues pertaining to the derivation of accurate source magnitudes will be addressed more completely in a following paper.

Objects already observed to a sensitivity equivalent or better than that of the survey as parts of other (sub)millimetre programmes were excluded from the target list (eg. the 5 quasars observed by McMahon et al., 1999; BR B0019–1522, PSS J0134+3307, PSS J0747+4434, BR B1600+0729, BR B2237–0607), as were sources with transit elevations of less than 60 degrees. An exception to this was PSS J1048+4407, previously observed and detected at 1.25mm at the IRAM 30-m (Maoli et al., in prep), but not confirmed with 1.35mm observations at the Plateau de Bure interferometer (Guilloteau et al. 1999).

3.2 Radio properties

The final source selection criterion was that of radio flux. We have used the NRAO VLA Survey (NVSS) to measure or place upper limits on the radio emission from all z \geq 4 quasars that were potentially in our sample. The NVSS survey (Condon et al. 1998) is a sensitive radio survey that was carried out with the VLA at 20cm in B-array, with a 5\sigma sensitivity of \( \sim 2.5\text{ mJy/beam} \). To determine which of the optically selected quasars are radio-loud, we cross-correlated the optical positions of our parent sample with sources in the NVSS catalogue. To assess the probability of a radio source being matched to one of the optically selected quasars by chance, the background source density was determined by counting the density of radio sources in the annulus with radius 10″ to 100″, resulting in a value of 50 deg⁻². The rms positional error of the NVSS catalogue is given as \( \sigma \) and thus, if one assumes that any radio source within 21″ is a potential match, one expects 0.005 chance associations per source, or a probability of 1 in 200 of incorrectly attributing radio emission to an optically selected quasar. Even if this radio emission were not to be from the quasar itself, a fraction of the emission would still be picked up by JCMT/IRAM main and error beams.

Listed in Table 1 are all optically-selected z \geq 4 quasars for which we find an NVSS source within a 30″ radius — a total of 17 objects — along with their derived parameters. A detailed discussion of the radio properties of the sample is beyond the scope of this paper and will be presented elsewhere. All sources with \( S_{1.4GHz} > 2.5\text{ mJy} \) were excluded from the final SBQS target list. Based on a flux extrapolation of \( S \propto \nu^{-\alpha} \), and a canonical spectral index of \( \alpha = 0.7 \), we therefore expect the maximum synchrotron contamination at 850\mu m to be less than 0.1mJy. Thus, it is reasonable to assume that the emission for any source that is detected at 850\mu m is likely to be thermal in origin.

Our final target list comprised 76 sources with \( M_B < -27.5 \), augmented by 22 sources with \( -27.0 < M_B < -27.5 \) which were included to improve sky coverage: 15 quasars were taken from the APM B/R and B/R/I survey (BR and BR sources: Irwin, McMahon & Hazard, 1991; Storrie-Lombardi et al. 1996; Storrie-Lombardi et al. 2001), 70 from the Palomar Sky Survey (PSS sources: Djorgovski 2000).
Table 1. Optically and X-ray selected \( z \gtrsim 4 \) quasars with 1.4GHz associations in NVSS. (Assuming a cosmology \( H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_0 = 0.5 \), and a spectral index for both radio and optical \( \alpha = -0.5 \))

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<th>Quasar name</th>
<th>RA (J2000)</th>
<th>Dec (J2000)</th>
<th>( z )</th>
<th>( d )</th>
<th>( \log P(r) )</th>
<th>( S_{1.4} )</th>
<th>( S_{850\mu m} )</th>
<th>( M_B )</th>
<th>( \log L_{1.4} )</th>
<th>( \log R_{1.4} )</th>
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<td>0.31</td>
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</tr>
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</table>

For completeness all quasars in our parent sample for which potential radio counterparts were found are listed in the table. Those marked with A and B have already been found by Stern et al. (2001) and Fan et al. (2000) to have NVSS counterparts, whilst the source labelled C has a radio-counterpart as found in the FIRST survey (Becker, White and Helfand, 1993).

\( a \) Separation between optical and nearest radio source positions

\( b \) Logarithm of the probability that the optically selected quasar has been falsely associated with a radio source from the NVSS catalogue, separated by distance \( r \)

\( c \) Extrapolated contribution by synchrotron emission to any observed 850\( \mu m \) flux, based on a spectral index, \( \alpha \), of 0.7, \( S_\nu \propto \nu^{-\alpha} \)

\( d \) \( L_{1.4} = \text{ergs}^{-1}\text{Hz}^{-1} \)

\( e \) Ratio of radio (1.4 GHz) to optical (rest-frame B-band) luminosities

from the Palomar Survey (PC sources: [Schneider, Schmidt & Gunn, 1991; Schneider 1991]), 1 from the VLA (VLA source: [Stern et al. 2000]) and 9 from the Sloan Digital Sky Survey (SDSSp sources: [Fan et al. 1999; 2000]).

4 OBSERVATIONS AND DATA REDUCTION

4.1 Observations

Observations were made using the wide-band 850\( \mu m \) filter on SCUBA, during periods when the zenith sky transparency was \( \sim 60 - 75\% \) (\( \tau_{850\mu m} \sim 0.08 - 0.12 \), referred to as grade 3 weather in JCMT parlance). Sources were observed by the “displaced observer” with priority set by source availability and luminosity. The standard 850\( \mu m \) photometry observing mode was used – a 9-position jiggle superposed onto a 7 Hz/60′′ chop throw of the secondary mirror in the azimuthal direction, implemented to remove sky emission offsets. Gradients in sky emission were taken out by “nodding” the telescope – a physical movement of the telescope to the off-position every 18s. A typical observation consisted of sets of c. 30–50 18-second integrations, with the total number of integrations chosen to achieve a sensitivity of \( S_{850\mu m}(1\sigma) \sim 3.3\text{mJy} \). Pointing was checked regularly, and found to be accurate to better than a few arc-seconds. Astronomical seeing was monitored using the 5GHz CfA phase interferometer – the phase monitor was not in continual use however, when working, the data suggested that the seeing was not worse than \( 3'' \). Sky transparency was monitored using regular 850\( \mu m \) sky-dips and data taken by the 225 GHz Caltech Submillimetre-Observatory (CSO) tau-meter. Flux calibration was achieved using the primary calibrators Mars and Uranus, as well as the secondary calibrators HLTau, IRC10216 \( \ddagger \), OH231 and 16293. \( \ddagger \) Absolute fluxes for the planets were derived using the Starlink package, FLUXES. The average time to complete the observation of a single source, including pointing, calibration, sky-dip and slewing overheads, was over 1 hour. This is quite a bit longer than

\( \ddagger \) We note that in the worst case, the combined pointing and seeing errors of 3'' would result in a loss of point-source coupling of 40%, assuming a Gaussian beam profile with a FWHM of 14''

\( \ddagger \) IRC10216 was adopted as calibrator on one occasion only, due to its periodic variability. When used as a calibrator, the output flux of IRC10216 was at a maximum

\( \ddagger \) See the JCMT web-page for the most recent calibrator fluxes
would be the case for a contiguous set of observations, reflecting the start/stop nature of a back-up program.

Here, we discuss observations of a subset of the target list: sources observed during the period February – July, 2000.

4.2 Data reduction

Data were reduced using the Starlink SURF reduction package (Fennness & Lightfoot 2000), using the automated ORACDR pipeline (Fennness & Economou 2000) as well as a basic SURF-based pipeline written in-house prior to the release of ORACDR. Two different schemes were implemented to determine an appropriate measure of the background sky-noise, the first using the mean of the inner ring of six pixels surrounding the central on-source bolometer to define the temporal sky variations, and the second the median of all bolometers. In general, only small differences in the final fluxes and rms noise determinations were seen between the two methods for observations in which detections were made. There were, however, more significant differences in rms values determined for non-detections. In particular, the sky-noise correction derived from the inner-ring mean resulted in a non-zero offset in the distribution of the signal/noise ratios for all off-source bolometers, indicating incomplete sky-removal. This was in contrast to the median-derived sky correction which we chose to adopt in the final analysis. All quasar data were clipped at the 20σ level prior to applying the sky-subtraction in order to eliminate transient spikes. Corrections for atmospheric extinction were prior to applying the sky-subtraction in order to eliminate sky-dips. In-...
Table 2. Observational parameters of the observed z>4 sample

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<th>MB</th>
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<th>integ. time (s)</th>
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</table>

− Errors are estimated to be $\sigma_R$, $\sigma_2$, where redshifts have been taken from Peroux et al. (2000), with the exception of sources marked *, where redshifts have been taken from Peroux et al. and Storrie-Lombardi et al.

$R$ magnitudes determined from APM scans of the UKST OR (5900-6900 Å) or POSS-1 E (6200-6800 Å) plates. Errors are estimated to be $\sigma_R = 0.3$

d See text for an explanation of the method used to evaluate the absolute source magnitudes

e Integration times have been calculated based on no. integrations x 18s/integration x 1.5, where both chopping and a 50% observational SCUBA overhead has been allowed for. This does not include any overhead for calibration or pointing.

f Where a 3σ detection was not achieved, the tabulated flux is given as the on-source signal only

g The position reported here is that taken from the Djorgovski web page. A check of the position using the APM catalogue after the JCMT SCUBA observations had been made revealed that the published position is out by 2σ.

h The correct position is: (J2000) 10 48 46.64 +44 07 10.9

i The flux reported is the weighted sum of 4 sets of integrations that differed considerably in statistical significance, ranging from 3σ and better detections to a near-zero on-source flux.

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a BR/BRI source positions taken from the APM catalogue; PSS source parameters have been taken from the Palomar Sky Survey (Djorgovski 2000). SDSSp source positions have been taken from the Sloan Digital Sky Survey (Fan et al. 1999, Fan et al. 2000).

b Palomar Sky Survey redshifts have been taken from Djorgovski (2000), with the exception of sources marked *, where redshifts have been taken from Peroux et al. and Storrie-Lombardi et al.

c R magnitudes determined from APM scans of the UKST OR (5900-6900 Å) or POSS-1 E (6200-6800 Å) plates. Errors are estimated to be $\sigma_R = 0.3$
fluxes are more than a factor of 100 in excess of what might be expected based on the NVSS radio limits. Thus, the single submillimetre flux measurements, combined with the a-priori radio limit of our parent sample, suggest strongly that we are detecting submillimetre emission from these sources that is thermal in origin.

How do the fluxes reported here compare with those measured for other z > 4 radio-quiet quasars? The brightest radio-quiet quasar z > 4 host galaxy observed both at submillimetre and millimetre wavelengths remains BR B1202-0725 (Isaak et al. 1994, McMahon et al. 1993, Buffey et al., in prep.) – with an 850µm flux of almost greater than twice that of the brightest sources detected in this survey, PSS J0808+5215, PSS J1057+4555 and PSS J2322+1944. Are-second resolution (c. 1-2") imaging with the Plateau de Bure interferometer (PdB) by Omont et al. (1996b) have shown BR B1202-0725 to be a composite source, made up of two comparable gas-rich and possibly interacting galaxies. If we assume that the 850µm flux distribution is similar to that of the 1.25mm flux, split equally between the two objects, then BR B1202-0725 is no longer such an exceptional object, and has a flux comparable to that of the brightest sources present here. With the further assumption that PSS J0808+5215, PSS J1057+4555 and PSS J2322+1944 are all single sources, there is a suggestion of a maximum observed flux of S_{max}^{850} ∼ 20 mJy. The origin of such a maximum is intriguing. A possibility is that the starformation is self-regulated, with the large number of supernovae events in the massive star-burst disrupting the local ISM and blocking star-formation. We are currently obtaining both deep radio observations with the VLA and millimetre observations with PdB, with which we will be able to establish the degree of extension of the sources.

We note that the sources we detect here are as bright, if not brighter than those detected in blank-sky and cluster-lensing surveys. Interestingly, the two brightest sources detected in the cluster lensing surveys (Ivison et al. 1998, Knudsen et al. 2000) have 850µm fluxes of just over S(850µm) ∼ 20mJy, and are both AGN at z ∼ 2. For comparison, the measured fluxes of the brightest and median source in the Canada-UK-Deep-Sky-Survey are ∼ 8mJy and ∼ 4.5mJy respectively (eg. Eales et al. 1999). The 200-square arcminute survey "8mJy survey" (3σ <8mJy (Dunlop 2000, Scott et al., in prep.) has yielded 24 sources, detected at statistically significant levels, with 10 brighter than 10mJy, and the brightest with a flux of 15mJy. We note here that others have also started similar surveys to our own at 1.25mm using the IRAM-30m (Carilli et al. 2001a), but leave a comparison between surveys to a companion paper.

6.2 PSS J1048+4407

In addition to identifying new submillimetre-bright sources, we detected PSS J1048+4407, a source for which observations at ∼ 1.3 mm with IRAM-PdB and the IRAM-30m were in conflict.

by Omont et al. (1996b). In evaluating our detection rate we have excluded BR B1500+0824 and BR B1302−1404 because of the common non-detection to the IRAM-30m sample.
shift of $z = 4.360$, correcting for the systemic shift from rest for the line as derived by Tytler & Fan (1992).

Given the discrepancy between the observed and newly derived redshift we suggest that the failure to detect CO emission is due to incorrect redshift, rather than an anomalous gas-to-dust ratio. This serves as a note of caution – given the limited bandwidth of the current generation of millimetre and submillimetre telescopes, the non-detection of any spectral line emission should be considered both in an astronomical context and, as important, in terms of a possible error in redshift.

### 6.3 Inferred astrophysical properties

Shown in Table 2 are physical properties of the detected sources derived from the optical luminosities and submillimetre fluxes reported here. We have assumed that the measured submillimetre flux arises from thermal emission from warm dust, and that the dust is heated solely by the UV flux from massive star-formation. The former can be justified, at least in part, by the radio-selection criterion that we used to define the parent sample. In addition, we will be able to combine the 850$\mu$m fluxes measured here with 1.25mm fluxes that have been measured in a parallel 1.25mm MAMBO survey (Omont et al. 2001) running at the IRAM-30m. The latter assumption is more difficult to justify, as it is possible that a fraction of the rest-frame UV absorbed by the dust comes from the central AGN. The size of the AGN contribution is difficult to estimate as it depends on the source geometry (eg. Sanders et al. (1989)), about which we have little knowledge. Observations of local, ultra-luminous infrared galaxies (ULIRGs, with $L_{FIR} > 10^{12}L_{\odot}$), arguably the most likely low-redshift counterparts of the quasar host galaxies, have been interpreted as being suggestive that between 70-80% of ULIRGS are powered predominantly by star-burst activity, with at least half the sources observed probably have simultaneous star-burst and AGN activity on the physical size scales of a few kpcs (eg. Genzel et al., 1998)). An additional unknown at this point is the extent of gravitational lensing and thus source magnification. The incidence of gravitational lensing amongst high luminosity quasars is around 1% for samples of bright quasars (Kochanek 1993). Studies of previous samples have, however, a median redshift of only $z \sim 2$. At $z \sim 4$ the probability of a quasar being lensed by a foreground galaxy is a factor of $\sim 2$ higher due to the larger optical depth to lensing (Turner et al. 1984; Fukugita et al. 1992). This qualitative argument is in rough agreement with the empirical result that only one of the 49 $z > 4$ APM BRI quasars, the $z = 4.43$ APM quasar BRI B0952–0115 with $S_{850\mu m} = 14$mJy (Buffey et al., in prep.) is known to be gravitationally lensed. It therefore seems un-

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**Figure 5.** An optical spectrum of PSS J1048+4408, taken at a resolution of 5Á using the ISIS spectrograph on the WHT by Peroux et al. On the basis of this spectrum, we classify this quasar as a BAL, not possible with previous spectra because of the limited spectral coverage. The presence of broad absorption lines makes an accurate determination of the host galaxy redshift difficult, however we derive redshifts of: $z = 4.422$ ($\text{Ly}\alpha$ (1216Á)), $z = 4.367$ ($\text{Si}+\text{O}$ (1400Á)) and $z = 4.354$ ($\text{CIV}$ (1539Á)). From an average of these three lines we derive a source redshift of $z = 4.38$, in contrast to $z = 4.45$ as first derived by Kennefick et al. We note that even this redshift estimate could be biased high, as explained in the text.
likely that a large number of the submillimetre-bright source detections reported here are lensed. High resolution optical imaging of the whole sample would be needed to confirm this. At present we have no evidence to support or refute the possibility of magnification, and thus assume that there is none.

6.3.1 Astrophysical properties inferred from the optical AGN luminosity

An advantage of targeting quasars for a study of high-redshift (sub)millimetre sources is that we are able to use the optical luminosity of the AGN to constrain the mass of the black hole powering the AGN, from which we can estimate the mass of the surrounding host galaxy. If we assume a bolometric correction from the B band of $L_{bol}/L_B = 12$ (Elvis et al. 1994), and that the black hole is accreting at the Eddington rate, then there exists a simple relation between black hole mass, $M_B$, and its bolometric luminosity, $L_{bol}$:

$$L_{bol} = \frac{4\pi G m_p c M_{bh}}{\sigma_T} \approx 3 \times 10^{13} \frac{M_{bh}}{10^9 M_\odot} L_\odot, \quad (2)$$

where $\sigma_T$ is the Thomson scattering cross-section and $m_p$ the proton mass.

The accretion rate can be written in terms of the luminosity and an efficiency parameter $\epsilon$, for which a conservative estimate is $\epsilon_{0.1} \equiv \epsilon \approx 0.1$ (Rees 1984):

$$\dot{M}_{\text{acc}} = \frac{L}{\epsilon c^2} = \frac{22}{\epsilon_{0.1}} \frac{M_{BH}}{10^9 M_\odot} M_\odot \text{yr}^{-1}. \quad (3)$$

While Equation 3 holds, the growth of black hole mass and luminosity is exponential, with an $e$-folding time-scale $\tau_{\text{acc}} = M_{BH}/\dot{M}_{\text{acc}} = \epsilon_{0.1} \times 4.5 \times 10^7$ yr. Studies in the local Universe (Magorrian et al. 1998; Gebhardt et al. 2000) have shown that there exists a linear relation between the mass of non-active black holes and the stellar mass of the surrounding galactic bulge at the current epoch. If we assume that there is some imprint of this relationship at early epochs (however, see Omont et al. [2001] and Priddey et al. (in prep)), then we can obtain a measure of the mass of the final (ie. $z = 0$) quasar host galaxy (Column 7 of Table 3) using a value of $M_{BH} \approx 0.005 M_{ph}$ from Gebhardt et al. [2000]. It is clearly possible that at $z = 4$, the ratio of the black hole to spheroid mass is different from the local value. For example Kauffmann & Haehnelt (2000) predict that the host masses will less massive by a factor of between 5-10 at $z = 2$ as compared to $z = 0$. Work by Rix et al. (1999) on the magnitudes of lensed host galaxies of lensed quasars also suggests that the masses of quasar hosts are low at high redshift however although this is based on the observed rest-frame B band magnitudes, these observations could be affected by dust obscuration, and hence the inferred masses may be underestimated. In the long term, one would hope that it will be possible to determine the dynamical masses of quasar hosts at high redshifts so that the issue can be studied more directly.

These estimates represent lower limits to the mass of the central engine, as we observe the quasars while they are still accreting. It seems unlikely for a number of reasons, however, that the masses grow much larger than this. Firstly, the inferred masses are large, comparable to the most massive non-active black holes ($\lesssim 10^9 M_\odot$) at the cores of nearby galactic bulges (Gebhardt et al. 2000). Secondly, the accretion rates required to sustain these luminosities (Table 3, Column 6) are extreme—and encroaching upon ($\sim 10\%$) of the star-formation rates inferred from the far-infrared luminosity (Column 11). Thus, the gas supplies in the galaxy are being rapidly diminished, at a rate too high to sustain either processes for much longer than 1 Gyr – indeed Priddey & McMahon determine a median gas consumption timescale of 0.1 Gyr (Priddey & McMahon 2001). Although we have no knowledge of the precise accretion history of the AGN, we can derive a time taken to assemble the inferred black masses of around $0.5 - 1$ Gyr if we assume that the accretion rate is Eddington-limited throughout the growth of the black hole and that the seeds from which the black

### Table 3. Derived properties of the detected (submillimetre-loud) z$\gtrsim$4 radio-quiet quasars sources – see Section 6.3 for the definitions used in deriving source properties

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<th>Source name</th>
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<th>$M_B$</th>
<th>$\nu L_B$</th>
<th>$M_{BH}$</th>
<th>$\dot{M}_{\text{acc}}$</th>
<th>$M_{ph}$</th>
<th>$S_{850}$</th>
<th>$M_D$</th>
<th>$L_{FIR}$</th>
<th>SFR</th>
<th>$\tau_\star$</th>
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median z$\gtrsim$4 SBQS

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<th>$\dot{M}_{\text{acc}}$</th>
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<th>$S_{850}$</th>
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holes form are $M \sim 10^{3-6} M_\odot$ (Haehnelt, Natarajan & Rees, 1998).

### 6.3.2 Astrophysical properties inferred from the submillimetre fluxes

Turning to the host galaxy properties derived from submillimetre flux observed at frequency $\nu_0 = \nu_{\text{rest}}/(1 + z)$, the dust mass given in Column 9 of Table 3 is determined using

$$M_D = \frac{S(\nu_0)D_L^2}{(1+z)\kappa_D(\nu)B_\nu(\nu, T_D)},$$

where we assume that the emissivity $\kappa$ is a power-law function of frequency, and we adopt the normalisation of Hildebrand (1983):

$$\kappa_D(\nu) = \kappa_0 \left(\frac{\nu}{2.4 \text{ THz}}\right)^\beta,$$

where $\kappa_0 = 18.75 \text{ cm}^2 \text{ g}^{-1}$ is the value determined at $\lambda = 125 \mu\text{m}$. For the dust temperature and emissivity index, we use $T_D = 40\text{K}$ and $\beta = 2.0$, derived by Priddey & McMahon (2001) from a composite submillimetre spectrum of $z\geq4$ quasars. The far-infrared luminosity is calculated by integrating under the thermal, grey-body spectral energy distribution,

$$L_{\text{FIR}} = 2\pi h c^2 \left(\frac{kT}{hc}\right)^{4+\beta} \Gamma(4 + \beta) \zeta(4 + \beta),$$

where again we assume $T = 40\text{K}$, $\beta = 2.0$, $\Gamma$ is the Gamma-function and $\zeta$ is the Riemann-Zeta function. If we assume that all the energy re-radiated by the dust originates from stars, then the far-infrared luminosity can be used to estimate the current star-formation rate:

$$M_* = \Psi \frac{L_{\text{FIR}}}{10^{10} L_\odot} M_\odot \text{ yr}^{-1}.$$

The exact value of $\Psi$ depends sensitively upon the star-formation history of the host galaxy, the stellar Initial Mass Function (IMF) and the fraction of starlight absorbed by the dust cloud. We adopt the simplifying assumptions that the star-formation rate is constant and that the cloud-covering factor is unity. Then, for a Salpeter IMF with upper and lower mass cut-offs of 100 $M_\odot$ and 0.3 $M_\odot$ respectively, $\Psi \approx 1$ and is approximately constant for ages $\gtrsim 10^8 \text{yr}$. The total time required to form the final stellar mass (Column 7) inferred from the black hole mass is given in Column 12 of Table 3, and is roughly 1 Gyr. The star-formation history derived from the chemical/dynamical model of elliptical galaxy evolution developed by Freiça & Terlevich (1993) has just such a form—a constant star formation rate lasting for around 1 Gyr. Observational support for long periods of sustained high star-formation rates is reported in Abraham et al. (1998) (see Figure 6). For an alternative interpretation, however, see Omont et al. (2001) who argue for shorter burst timescales.

We have two time-scales describing the fate of gas in the evolving host galaxy: a time-scale for the conversion of gas into stars, $\sim 1 \text{ Gyr}$, or gas accretion onto a super-massive central black hole with an accretion time of the same order. This may be suggestive of a possible synchrony between formation of the AGN and its host galaxy, however we leave a more detailed and speculative discussion of the inferred quasar and host galaxy properties to a future paper.

![Figure 6](image-url) Cumulative distribution of the fraction of detections (heavy solid line), non-detections (dashed line) and observations (light solid line) as a function of absolute magnitude. There is some indication of a difference in the cumulative distribution, however using the K-S test, it can be shown that the null hypothesis that the magnitudes of the detected sources and the non-detected sources are similarly distributed cannot be rejected at the 90% level.

Throughout, we have assumed that the dominant heating source is star-formation in the quasar host galaxy. At present, however, it is not possible to determine conclusively whether this is indeed the case. If instead, we were to that assume the AGN contribution to the dust heating cannot be neglected, then (a) for a fixed dust temperature the inferred star-formation rate would fall, with a corresponding increase in the formation time for the massive spheroid (b) a hotter dust component heated directly by the AGN would contribute significantly to the overall far-infrared luminosity, and thus in addition, smaller dust masses as well as lower star-formation rates and longer timescales would be inferred. Observations of samples, such as this SBQS sample, at shorter wavelengths using SIRTF will reveal any warmer dust component.

### 6.4 Optical/submillimetre correlations

With a sample of 38 observed sources, it becomes meaningful to start to make both qualitative and quantitative assessments of the trends in the detection rates with source redshift and magnitude. Shown in Figures 1 and 2 are the cumulative magnitude and redshift distributions for the observed, detected and non-detected subsamples. To assess quantitatively the degree of similarity between the distributions we use the Kolmogorov-Smirnov (K-S) test (eg. Barlow 1998). In Figure 3 we note that there is some indication of a difference between the detected and non-detected cumulative magnitude distributions however, formally, the difference is not statistically significant, and so we cannot reject the null hypothesis that the two samples are drawn from the same population. The magnitude and redshift distribution of the two samples are shown in a slightly different way in Figures 4 and 5.

Plotted in Figure 6 are the 850 $\mu\text{m}$ fluxes and absolute
magnitudes for the detections presented in this paper, as well as upper limits (1.65σ (90% confidence level) + “on-source signal”) for non-detections. Error bars for both detections and non detections are 1σ. It is difficult to make a quantitative assessment of the significance of the optical/submillimetre magnitude correlation, given the significant fraction of upper limits in the sample. There are two competing physical processes that would produce a statistically significant correlation between detected submillimetre flux and absolute quasar luminosity. Firstly, the most luminous quasars reside in the most massive host galaxies, in which there is likely to be ongoing star-formation – the larger the host galaxy, the greater the potential for massive bursts of star-formation, and thus more dust and more UV photon flux with which to heat the dust. More quantitatively, using Equations 2, 3 and 7,

$$L_{FIR} \approx 0.1 \frac{M_*}{\Psi_{0.1} M_{acc}}$$

If we observe these objects just before the end of their accretion lifetime, when the accretion rate encroaches upon the star formation rate, $M_{acc} \sim M_*$ $\Rightarrow L_{FIR} \sim \nu L_B$ (Priddey & McMahon 2001). Secondly, the more luminous the central quasar, the greater its UV-output, and thus the larger the power that may be absorbed by dust, and re-emitted in the rest-frame far-infrared.

A plot of the source magnitude vs. redshift for detections and non-detections also fails to reveal a preferential range of redshifts/magnitudes for which the number of detections is high. It must be cautioned, however, that the number of sources in any one bin is small, so the overall statistical significance of this result is low.

In addition, a potential systematic bias arises from the fact that the absolute $B$-band magnitudes have been derived from the measured $R$-band APM magnitudes. As discussed in Section 3.1, calculating an optical luminosity from an $R$ magnitude is complicated for sources at $z \gtrsim 4$ because the band is contaminated by redshifted Lyman-$\alpha$ emission, and at higher redshifts, intergalactic absorption. We introduced a correction to account these effects, and found that it worked well on average, but that the scatter about the average was $\sigma_M \sim 0.5$. Obtaining optical spectra and/or $K$-band photometry for all the targets may ultimately help to alleviate this.

6.5 Non-detections – an assessment of the contribution of the $z \sim 4$ population to the submillimetre-wave background

Shown in Figure 11 is the signal-to-noise distribution of the non-detections (solid line) – this has a clear non-zero mean. More quantitatively, the weighted mean of fluxes of the observed non-detections is $2.0 \pm 0.6mJy$, a quantity that we can evaluate because our survey has a sensitivity that is consistent between sources to within a factor of $\sim 2$. The mean
Figure 10. A plot of 850\mu m flux vs. \(M_B\). Filled circles denote source detections reported in this paper, while crosses denote upper limits to non-detections (where plotted flux = “signal” + 1.645\sigma (90% confidence)). The flux error bars denote 1\sigma errors, as given in Table 2, whilst magnitude error bars, \(\sigma_{MB} \pm 0.5\), are a measure of the combined systematic and random error in the measurement and derivation of the absolute magnitudes.

Figure 11. Histogram of the S/N ratios of all non-detections in the current sample: heavy-lined histogram denotes S/N ratios evaluated for the on-source pixel. Superposed (light-line) is the outline of the S/N distribution for all functional off-source pixels, over which is plotted a Gaussian approximation to the off-source distribution. Note that the mean of the off-source distribution is zero, and the distribution itself very nearly Gaussian. This suggests that the sky-offsets are being removed correctly.

7 FOLLOWUP WORK

Whilst useful for identifying the most submillimetre-bright sources, the detection of objects at a single wavelength clearly provides only limited insight into the detailed physical properties of the individual sources. Given the strong dependence of the inferred far-infrared luminosity on dust temperature, and that star-formation rates are derived from the far-infrared luminosity, it is important to determine the far-infrared spectral energy distributions for individual objects if we are to obtain independent measures of the star-formation properties and potential of the quasar host galaxies. We have started followup programs at several wavelengths: (a) a parallel program at 1.25\text{mm} using the IRAM-30m which, when combined with (b) 450\mu m measurements using SCUBA at the JCMT will be used to constrain the spectral energy distributions and thus dust temperatures and far-infrared luminosities (c) CO observations using millimetre interferometers to measure the gas mass, simultaneously setting upper limits to the physical extents of the high-z host galaxies, are also in progress along with (d) VLA observations to search for the signatures of starformation or weak radio-sources (Carilli et al. 2001).

Our approach to targeting starformation at high-redshift has been to preselect candidates that are likely to have massive molecular gas reservoirs, as inferred from the presence of dust. At some redshift, however, it may become more efficient to search directly for the gas reservoir itself, as the presence of significant quantities of dust preselects for objects in which at least one massive starburst of star-formation must already have taken place.

A second selection effect arises from the original definition of our sample. By basing our sample on the most optically-bright quasars, we tacitly assume that the quasar and the host galaxy are coeval. Using arguments based on timescales given in Section 6.3 above, we have shown that this may be the case. The evidence, however, is not conclusive, and indeed depends on a number of assumptions, not least of which being that the rest-frame far-infrared luminosity is powered solely by star-formation, and that there is no gravitational lensing of the quasar and its host galaxy. With the combination of measurements of the CO, dust and optical properties, the physical parameters that we can derive from these measurements and a sample of statistically significant size, we will be able to investigate in a more quantitative manner.

We are currently undertaking a parallel search for submillimetre-bright quasar host galaxies at redshifts \(z \sim 2\). The elapsed time interval between \(z \sim 4\) and \(z \sim 2\) is around 1.5 Gyr, corresponding to a doubling of the age of the Universe at \(z \sim 4\). Given the gas masses observed in these radio-quiet quasar host galaxies, and the high star-formation rates that we infer from the FIR luminosity (Table 3), one might expect that if the formation redshift of quasar host galaxies is high, a sizeable fraction of any molecular gas reservoir would be used up between \(z \gtrsim 4\) and \(z \sim 2\). The submillimetre-wave properties of the two sam-

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8 SUMMARY

We have observed a total of 38 $z \gtrsim 4$ radio-quiet quasars at 850μm using the JCMT. We have identified a total of 8 new submillimetre-bright sources with $S_{850\mu m} > 10$ mJy including a previously ambiguous detection made at the IRAM-30m at 1.25 mm. The observations were carried out under modest observing conditions (sky transmission $\sim 65\%$), but even so the integration time per target was around 0.5 hour, giving an overall detection efficiency of 0.5 sources per hour of integration. This method, observing preselected targets in photometry mode, thus compares favourably with the complementary strategy of blank-field mapping. These observations triple the number of known $z \gtrsim 4$ objects for which CO observations should be possible in a finite amount of observing time to $N > 10$. As such, we now have a submillimetre-bright sample of statistically significant size, for which we possess accurate identifications and spectroscopic redshifts, for which we can now start to study the star-formation properties in detail. We analysed a new optical spectrum of the BAL PSS J1048+4407, one of the sources detected, and find that the redshift is quite different from that used for CO observations of Guilloteau et al. ([1999]), which may explain the observed lack of CO from this object. The strong 850μm emission in contrast to the lack of 1.35mm emission detected in PdB observations suggests strongly that the much higher angular resolution obtained with the interferometer is causing significant fraction of the emission to be resolved out – the (sub)millimetre-source is extended.

Of the remaining 30 objects observed, 27 were observed down to a sensitivity of 3σ $< 12$ mJy and not detected. Based on this sample, we find that our detection rate is comparable to that measured by Omont et al. ([1996]) at 1.25 mm using 30-m, scaled to match the appropriate flux limits. At present, the sample (detections and non-detections) is too small to determine formally whether there is a range of absolute magnitudes and redshifts for which the rate of detection is high, however there may be some indication that the magnitude distribution of the detections and non-detections differ. We determined a fiducial flux of 2.0 $\pm 0.6$ mJy for the non-detections, which we believe to be a statistical measure of the submillimetre flux of the more submillimetre-faint quasar host population.

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