Astron. Astrophys. 315, 1–10 (1996)

ASTRONOMY
AND
ASTROPHYSICS

Continuum millimetre observations of high-redshift radio-quiet QSOs

II. Five new detections at z>4

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Received 14 February 1996 / Accepted 2 May 1996

Abstract. We have performed a sensitive ($\sigma \sim 1.5$mJy) systematic study of the 1.25 mm emission of ~22 radio-quiet QSOs at z$\gtrsim$4, with the IRAM 30m telescope equipped with bolometer arrays. Five radio-quiet QSOs at z>4 have been detected at a 5-σ level in addition to the initial detection of the z=4.7 QSO BR1202−0725 reported in McMahon et al. (1994). The detected fluxes range from 2.5 to 10 mJy. All the reported detections were independently confirmed at the 3-σ level on at least three different nights. In addition 10 other QSOs from the Cambridge APM survey sample and 6 others QSOs from the literature were searched for millimetre emission but not detected with 2-σ upper limits of 3-4 mJy.

From this systematic study of about half of the known optically selected z>4 QSOs, some general trends of their millimetre emission can be inferred. All the QSOs we have detected pertain to the APM sample and are among those which have the largest UV rest-frame luminosities. The detection rate within the APM sample is 6 out of 16 observed, compared with zero in the remaining 6. Two of the four APM broad absorption line QSOs observed were detected and four of the seven weak lined APM QSOs were detected, whereas none of the five strong lined APM QSOs were detected. Thus there is evidence for enhanced millimetre emission from luminous QSOs with weak broad emission lines or broad absorption lines.

There is one clear case known of strong lensing amongst the six millimetre detected objects with z>4. In light of the fact that both previously known objects with confirmed strong millimetre emission at z>2 are gravitationally lensed, i.e. H1413+117 and IRAS F10214+4724, sensitive high resolution observations of these z>4 QSOs are required to determine whether gravitational lensing effects need to be taken into account.

Assuming that the millimetre wave continuum emission is due to dust emission, the very large amount of dust implied, $\sim 10^8\ h^{-2}\ M_\odot$, means that the host galaxies of these QSOs have undergone a substantial phase of star formation. If the gas-to-dust ratio in these galaxies is similar to that in lower redshift objects, the total gas mass would be $\sim 10^{11}\ M_\odot$.

We have begun to explore the 1.25 mm emission of bright radio-quiet QSOs in the redshift range 1.5 to 3.5, using criteria which seem to favor millimetre detections, established from our z>4 detections. One source was detected at z = 2.70. We have also observed three QSOs with z>3 that were previously studied at 1.25mm by Andreani et al. (1993) who reported detections at a level higher than 3σ. We have been unable to confirm any of these reported detections. In particular we have a 3σ upper limit of 3.2 mJy for the z=3.19 QSO PC2132+0126 for which Andreani et al. reported a flux of 11.5±1.7mJy. Either this source has substantially varied during the period between the two sets of observations or the single channel bolometer observations were affected by systematic errors.

Key words: quasars: general – galaxies: starburst – galaxies: ISM – infrared: galaxies – radio continuum: galaxies – cosmology: observations

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1. Introduction

The detection by IRAS of strong far infrared (FIR) emission from QSOs has revealed the presence of very large amounts of dust (Sanders et al. 1989, Heckman et al. 1992). Since it has been realised that, because of the very steep submillimetre emission spectrum in the QSO rest frame, (sub)millimetre astronomy could become a major tool to study sources at very large redshifts. The highest redshift QSOs are thus natural targets for millimetre observations.

We have already reported the success of our first search, with the detection of the bright z=4.7 QSO BR1202−0725 at 1.25 mm at IRAM (McMahon et al. 1994), and in the submillimetre range at JCMT (Isaak et al. 1994). The mass of dust inferred, $> 10^8 M_\odot$, is amongst the largest known.

We report here the results of the continuation of our program of a systematic search for 1.25 mm emission of QSOs at z>4. The new detections show that the case of BR1202−0725 is not an exception, and that the rate of millimetre detections among such sources is relatively high, especially with the sensitivity achievable with the IRAM 30m telescope equipped with the new bolometer array detectors.

It should be noted that the situation is also rapidly evolving in the parallel field of millimetre studies of high redshift hyperluminous galaxies. The strong gravitational lensing of IRAS F10214+4724 is now well established, with an amplification factor in the range 10-50 (Broadhurst & Lehar 1995; Graham & Liu 1995; Scoville et al. 1995; Downes et al. 1995; Serjeant et al. 1995; Close et al. 1995; Eisenhardt et al. 1996). This brings back this source to the normal range of luminosities and dust masses of the typical most hyperluminous IRAS galaxies. On the other hand, several radiogalaxies at the largest redshifts (up to z=4.26) have been detected at 0.8 or 1.25mm (Dunlop et al. 1994; Chini & Krügel 1994; Ivison 1995), showing that high redshift objects of both classes (QSOs and radiogalaxies) are currently detectable in the (sub)millimetre range.

A still open question is the relationship between the various classes of luminous FIR emitting objects. For instance, until recently, the most luminous IRAS galaxies (IRAS P09104+4109, F15307+3252 and F10214+4724) were considered to be Seyfert II like objects. However, broad emission lines have been detected in polarized light in all three objects (Hines & Wills 1993; Hines et al, 1995; Goodrich et al, 1996), supporting a picture that each harbours a QSO that is hidden from direct view and which can only be seen in scattered light.

2. Observations

We have carried out 1.25mm continuum observations with the IRAM 30m telescope equipped with the MPIfR 7 and 19 element bolometer arrays (Kreysa 1993). After our first observations in 1993 (McMahon et al. 1994), two winter-periods were needed to complete this programme because of the limited availability of the detectors at the telescope and of bad weather conditions during the April 1994 run. Most of the results reported here were obtained during a single run (2–8 February 1995) with the 7-channel MPIfR bolometer array, in about 45 hours of acceptable weather ($\tau_{1.25\mathrm{mm}} \sim$ 0.15-0.35 with reasonably stable atmospheric conditions).

The MPIfR 7-channel bolometer system consists of seven bolometers arranged at the corners and center of a closely packed hexagonal array with corner to corner spacing of 22". Each channel had a HPBW of ~12". The performances and observation modes for the telescope and the detector are essentially the same as those reported by McMahon et al. (1994). However, we found that the actual sensitivity could approach the nominal value of 40 mJy $s^{1/2}$ in very good weather conditions, and that the value quoted in McMahon et al. (1994), 70 mJy $s^{1/2}$, which included the average atmospheric noise, was rather conservative. For these observations, the chopping secondary mirror switched the beam $30''$ in azimuth at 2 Hz, and the telescope was switched by the same amount every 10s.

We had the opportunity to directly compare the efficiency of the array detector with the single channel bolometer (Thum et al. 1992) for the detection of weak sources. Although the sensitivities are comparable, there is an enormous gain, especially in non optimum weather conditions, when subtracting the remaining sky emission given by the average of the side channels. Such a procedure accurately determines the zero point and prevents fake detections. This is crucial for detecting weak sources $\sim$ 3 mJy. Consequently, no data of our two runs with the single channel bolometer (December 1993 and March 1994) are included in our final results. Observations of December 1993, made under very good weather conditions, were nevertheless useful for tentative detections, including that of BRI1335−0417. Subsequently we performed long integrations using the 7-channel detector which provided the firm detections reported in this paper.

We also report a few results that we obtained during a short run (31 March-2 April 1995) with the new 19-channel MPIfR detector. Its performances are quite similar to those of the 7-channel array. Indeed, for the detection of a point source there is practically no advantage from the additional 12 channels, and we systematically used the average signal of the 6 detectors of the first ring to subtract the remaining sky emission as with the 7-channel detector.

There is no elaborate data processing in the results reported here. Our adopted procedure probably overestimates the noise level, and the accuracy of the averages could be hopefully increased by an elaborate sky subtraction on short time scales comparable to those of the atmospheric fluctuations (Haslam & Zylka in preparation). We are considering to undertake such a complete reprocessing of the data in the future.

3. Results

The parameters of the observed sources are listed in Tables 1 and 2. The results are presented in Tables 3 and 4, where the detailed outcomes of independent observations of the same source are given together with the resulting averaged 1.25 mm flux density (in the last column). One can thus check the consistency of the observations, especially in the case of the weakest detected sources. It could be seen that each of them has been consistently detected at least at a 2 or 3σ level on several different days. Altogether, the combined observations warrants a 5σ level for the six new detections.

Table 1. Observed sources: general data for z>4 QSOs

Source	RA (1950.0)	Dec	z	m_{1450}†	M_B‡	Sp	references	
APM sample z>3.95		Detected sources						
BRI0952−0115	09 52 27.2	−01 15 53	4.43	18.7	−27.7	W	1	2
BR 1033−0327	10 33 51.5	−03 27 46	4.50	18.8	−27.6	W	1	2
BR 1117−1329	11 17 39.4	−13 30 00	3.96	18.1	−28.1	BAL	1	2
BR 1144−0723	11 44 02.5	−07 23 25	4.14	18.8	−27.5	BAL	1	2
BR 1202−0725	12 02 49.2	−07 25 50	4.70	18.0	−28.5	W	1	2
BRI1335−0417	13 35 27.5	−04 17 21	4.40	19.1	−27.3	W	1	2
		Upper limits σ < 1.5 mJy						
BRI0103+0032	01 03 45.2	+00 32 21	4.43	18.8	−27.6	S	1	2
BRI0151−0025	01 51 06.0	−00 25 49	4.20	18.9	−27.4	S	1	2
BR 0245−0608	02 45 27.4	−06 08 28	4.20	18.8	−27.5	W	1	2
BR 0951−0450	09 51 25.0	−04 50 08	4.35	19.2	−27.2	W	1	2
BR 1302−1404	13 02 46.8	−14 04 38	4.04	18.4	−27.8	BAL	1	2
BRI1328−0433	13 28 54.9	−04 33 26	4.20	19.1	−27.2	S	1	2
BRI1346−0322	13 46 41.1	−03 22 23	4.01	19.4	−26.8	S	1	2
BRI1500+0824	15 00 18.6	+08 24 49	3.96	19.1	−27.1	W	1	2
BRI2235−0301	22 35 47.4	−03 01 30	4.25	18.5	−27.8	BAL	1	2
BR 2237−0607	22 37 17.4	−06 07 59	4.55	18.3	−28.1	S	1	2
		Upper limits σ > 1.5 mJy						
BR 0019−1522	00 19 35.9	−15 22 18	4.52	18.8	−27.6	S	1	2
BRI0241−0146	02 41 29.4	−01 46 43	4.04	18.4	−27.8	W	1	2
BR 0351−1034	03 51 23.7	−10 34 08	4.36	18.6	−27.8	W	1	2
BRI1013+0035	10 13 15.0	+00 35 17	4.38		−27.4	W	1	2
BRI1050−0000	10 50 46.7	−00 00 51	4.29	19.4	−26.9	S	1	2
BRI1114−0822	11 14 55.2	−08 22 34	4.50	19.7	−26.7	W	1	2
BR 2212−1626	22 12 44.8	−16 26 30	4.00	18.6	−27.6	S	1	2
Other QSOs with z>3.6		Upper limits σ < 1.5 mJy						
Q0051−279	00 51 49.8	−27 58 24	4.43	19.2		BAL	5	4
PC0307+0222	03 07 15.4	02 22 00	4.38	19.9	−26.4	S	4	4
PC0344+0222	03 44 22.6	02 22 29	3.78	20.1	−25.9	S	6	6
PC0751+5623^{a}	07 51 41.9	56 23 04	4.28	19.6	−26.7	S	6	7
PC1247+3406	12 47 17.8	34 06 12	4.90	19.3	−27.2	S	10	10
PC1643+4631A	16 43 33.5	46 31 38	3.79	20.0	−26.1	S	6	6
		Upper limits σ > 1.5 mJy						
HM0000−26	00 00 49.5	−26 20 01	4.11	17.5	−28.8	W	3	4
PC0345+0130	03 45 27.0	01 30 08	3.64	19.5	−26.6	S	6	6
PC0910+5635	09 10 57.3	56 25 49	4.04	20.9	−25.4	S	6	6
PC1158+4635^{b}	11 58 02.9	46 35 29	4.73	19.6	−26.9	S	6	6
Q1208+1011	12 08 23.7	10 11 08	3.80			S	8	9
PC1643+4631B	16 43 52.4	46 31 02	3.83	20.4	−25.8	S	6	6
RXJ1759.4+6638	17 59 28.8	66 38 55	4.30			S	11	11
Q2203+29	22 03 47.0	29 15 24	4.40	19.3	−27.1	S	12	12
PC2331+0216	23 31 58.5	02 16 47	4.09	19.8	−26.4	S	6	6

Notes.-
† continuum magnitude at a rest wavelength of 1450Å unless noted otherwise.
‡ Absolute rest frame B magnitude computed assuming H_0 = 50, q_0 = 0.5 and a continuum spectral index of -0.5 where $f_\nu \propto \nu^\alpha$
W = Weak emission lines;
S = Strong emission lines;
BAL = Broad absorption lines.
References(1) QSO origin and positions used if different - References(2) Optical spectra: 1)Irwin, McMahon & Hazard in preparation; 2)Storrie-Lombardi et al. 1996; 3)Hazard & McMahon (unpublished); 4)Schneider et al. 1989; 5)Warren et al. 1987; 6)Schneider et al. 1991a; 7)Isaak et al. 1994; 8)Hazard et al. 1986b; 9)Sargent et al. 1986; 10)Schneider et al. 1991b; 11)Henry et al. 1994; 12)McCarthy et al. 1988.

Our main goal was a systematic study of the Cambridge APM sample of optically selected QSOs with z>4 (Irwin et al. 1991, 1996). We observed 16 of them, i.e. about half of the sample, with a rms $\sigma \lesssim$ 1.5 mJy (Table 3). In addition to the 5 new detections (plus BR1202−0725, McMahon et al. 1994), there are thus 10 non detections among this sample with a 3σ upper limit of $\sim$ 5 mJy (4 mJy for most of them).

In addition, we observed with a comparable sensitivity, and did not detect 6 non-APM radio-quiet QSOs at z>3.6 (Table 3) with lower optical luminosities (mainly those discovered by Schneider et al. 1991a). Three sources reported as detected in the millimetre range by Andreani et al. (1993) are among this additional sample. For most of the common sources our upper limits are inconsistent with the claimed $\sim 3\sigma$ level detections. Our flux limits differ from the Andreani et al.' fluxes at the 2-8σ level.

Table 2. Observed sources: general data for 1.5<z<3.5 QSOs

Source	RA (1950.0)	Dec	z	m[a]	Sp	references
		Detected source				
Q1230+1627	12 30 39.4	16 27 26	2.70	17.4	W	1
		Indications of detection				
Q0838+3555	08 38 07.6	35 55 42	1.77	16.	W	4
Q0842+3431	08 42 30.4	34 31 41	2.12	17.	W BAL	4
Q1017+1055	10 17 30.8	10 55 08	3.15	18.4	W	3
		Upper limits				
Q0114−0857	01 14 53.0	−08 57 20	3.16	20.5	W	3
Q0856+1713	08 56 29.6	17 14 60	2.32	19.0	BAL RW	2
Q0903+1734	09 03 49.9	17 34 28	2.77	18.0	BAL	8,5
Q0956+1217	09 56 11 1	12 17 07	3.30	17.6	W	3
Q1212+0854	12 12 34.9	08 54 57	2.35	18.0	W	7
Q1212+1445	12 12 07.5	14 45 39	1.64	17.9	BAL RW	7,5
Q1231+2924	12 31 27.0	29 24 20	2.01	16.	W	4,5
Q1235+0857	12 35 22.7	08 57 34	2.90	17.8	BAL RW	7,5
Q1246−0542	12 46 38.7	−05 42 58	2.21	16.7	BAL RW	9,5
Q1247+2647	12 47 39.0	26 47 27	2.04	15.6	S RW	6
Q1308−0214	13 08 40.2	−02 14 51	2.85	18.7	W	1
Q1308−0104	13 08 44.9	−01 04 36	2.55	18.1	W	1
Q1331−0108	13 31 53.6	−01 08 29	1.88	17.9	BAL RW	10,5
Q1426−0131	14 26 29.1	−01 31 57	3.42	17.8	W	11
PC2132+0126	21 32 37.9	01 26 05	3.19	19.8	S	12

Notes BAL = Broad absorption lines; W = Weak emission lines; RWλ = Radio weak.
[a] Reference for visible magnitudes: Véron-Cetty & Véron 1993.
References for spectra:
1) Foltz et al. (1989); 2) Hazard et al. (1986a); 3) Sargent et al. (1989); 4) Thompson et al. (1989); 5) Weyman et al. (1991); 6) Young et al. (1982); 7) Foltz et al. (1987); 8) Hazard et al. (1984); 9) Osmer & Smith (1977); 10) McAlpine & Williams (1981); 11) Mitchell et al. (1990); 12) Schneider et al. (1991a).

In the case of PC2132+0126 (z=3.19), the difference is quite striking since Andreani et al. reported 11.5 ± 1.7 mJy, while we measured 0.8 ± 0.8 mJy. Negative results were obtained also for this source in our two runs with the single channel detector. Of course variability is not excluded, but it would be surprising for dust emission in a radio-quiet QSO. It should be noted that Andreani et al. used a single channel bolometer which can be affected by systematic errors.

We have also started an exploratory programme to observe luminous radio-quiet QSOs at z$\sim$1-3.5, giving priority to objects suspected to be strong millimetre emitters given the experience gained from our previous detections (see discussion in Sects. 5 and 6). We have observed 17 sources with a rms $\sigma \lesssim 2.0$ mJy (Table 4), but only 7 sources with $\sigma \lesssim 1.5$ mJy. We have detected a strong source, Q1230+1627 at z=2.7, and there are also three 3σ tentative detections.

4. Dust mass

Submillimetre observations at JCMT are needed to determine the millimetre/submillimetre spectral index of the new detected sources. However, it is very likely that it is large, 3-4, and characteristic of dust emission, as found for BR1202−0725 (McMahon et al. 1994, Isaak et al. 1994), the lensed QSO H1413+117 (Barvainis et al. 1992, 1995), the lensed IR galaxy IRAS F10214+4724 (Clements et al. 1992; Downes et al. 1992) and the radiogalaxy 4C41.17 (Dunlop et al. 1994; Chini & Krügel 1994). The discussion on the dust content of BR1202−0725 (McMahon et al. 1994; Isaak et al. 1994) should thus apply to the new sources, and is summarized below.

The observed millimetre flux density $S_{1.25}$ (see Eq.(1) in McMahon et al. 1994) depends mainly on the dust mass M_D, and more weakly on the temperature and properties of dust, and on the redshift and the cosmological parameters. Assuming a usual dust emissivity law, a single dust temperature T_D=80K and no gravitational amplification, the relation between M_D and $S_{1.25}$ is approximately for $\Omega_0 = 1$ and $z \sim 4$ to 4.5

$$M_D/M_\odot \sim 10^7\, h^{-2}\, (80/T_D)\, S_{1.25} \quad (1)$$

where $h = H_0/100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $S_{1.25}$ is the 1.25 mm flux in mJy. For $\Omega_0 < 0.1$ or for $T_D \sim 40$ K, M_D is about three times larger (see Fig. 1 of McMahon et al. 1994). Hence, M_D is probably at least $\sim 10^8 M_\odot$ for all the detected sources in the absence of lensing. If the gas-to-dust ratio is similar to that of IRAS F10214+4724 and H1413+117, $\sim$ 500 (Downes et al. 1992; Barvainis et al. 1995), the total gas mass will approach $\sim 10^{11}\, M_\odot$. This is confirmed by the CO detection in BR1202−0725 (Omont et al. 1996). The presence of such a large quantity of dust in these z>4 quasars, and hence of heavy elements, suggests that a starburst phase is either present or has already taken place.

Since the two strongest millimetre sources at z $\sim$ 2-3, H1413+117 and IRAS F10214+4724, are strongly lensed (see e.g. Barvainis et al. 1995 and references therein and in Sect. 1), the question of lensing for our detected sources must be seriously addressed. Indeed, there is an obvious case, with multiple images for one millimetre detected source, BRI0952−0115 (McMahon et al., in preparation). Its dust mass is thus smaller than given by Eq.(1) by a yet unknown factor.

Mapping the emission of the strongest millimetre sources is just at the limit of the capabilities of the most sensitive millimetre interferometers presently operating at 1.3 mm, such as the IRAM one at Bure. The mapping of BR1202−0725 recently performed there by Omont et al. (1996) shows that its 1.3 mm emission presents an extension with a size of $\sim 4''$. This extension may result from a double lensed millimetre image rather than from an actual extension of the dust distribution. Another indication of the dust spatial distribution could be provided by the analysis of its temperature and heating. Because of the lack of observations at shorter wavelengths, there is no information on the dust temperature, except for BR1202−0725 where the measurements are limited to a part of the submillimetre range (Isaak et al. 1994). Similarly, the FIR luminosity which should vary approximately as T_D^5, is also quite uncertain. However, a dust temperature $\sim$ 80 K looks plausible, given the case of IRAS F10214+4724 (Downes et al. 1992) and of the most luminous QSOs detected by IRAS (Sanders et al. 1989). Even if dust at such a temperature dominates the FIR luminosity, contribution by dust at other temperatures could be important. For instance, in the case of IRAS F10214+4724, a substantial part of the FIR luminosity is provided by still warmer dust, maybe 30-40% (see e.g. Downes et al. 1992). On the other hand, there is no evidence

Table 3. Observed 1.25 mm flux densities

Source	z	I	II	III	IV (Fluxes in mJy)	V	VI	Total
				APM sample z>3.95				
BRI0952−0115	4.43		3.78±1.55		1.76±1.12	2.88±1.22	3.56±1.57	2.78±0.63
BR1033−0327	4.50				3.29±0.80	3.59±1.49	4.01±1.68	3.45±0.65
BR 1117−1329	3.96				4.45±1.29	2.85±1.28	5.89±1.84	4.09±0.81
BR 1144−0723	4.14	5.0±2.0	5.28±1.54			6.32±1.40		5.85±1.03
BR 1202−0725	4.70		12.59±2.28					12.59±2.28
BRI1335−0417	4.40	6.0±2.5	9.97±2.16			10.38±1.20		10.26±1.04
BRI0103+0032	4.43		−0.20±1.13					−0.20±1.13
BRI0151−0025	4.20			2.29±1.35				2.29±1.35
BR 0245−0608	4.20			3.96±3.41			0.11±1.23[a]	0.50±1.20
BR 0951−0450	4.35			1.41±2.69	1.34±1.07			1.34±1.07
BR 1302−1404	4.04			−2.85±2.92	0.98±1.15			0.98±1.15
BRI1328−0433	4.20			1.10±2.54	−1.36±1.08			−1.36±1.08
BRI1346−0322	4.01				−0.52±1.37			−0.52±1.37
BRI1500+0824	3.96		−0.30±1.32					−0.30±1.32
BRI2235−0301	4.25			−1.87±1.90		−0.02±1.03		−0.02±1.03
BR 2237−0607	4.55		-0.20±1.32					−0.20±1.32
BR 0019−1522	4.52			−4.12±4.33				−4.12±4.33
BRI0241−0146	4.04					0.69±2.15		0.69±2.15
BR 0351−1034	4.36			3.43±2.99				3.43±2.99
BR 1013+0035	4.38	0.5±2.5						0.50±2.50
BRI1050−0000	4.29			0.60±3.35				0.60±3.35
BRI1114−0822	4.50		1.65±1.63					1.65±1.63
BR 2212−1626	4.00			−0.28±2.23				−0.28±2.23
				Other QSOs with z>3.6				
Q0051−279	4.40			2.29±1.35				2.29±1.35
PC0307+0222	4.38		0.24±0.96					0.24±0.96[b]
6.6±1.7 PC0344+0222	3.78		0.41±1.29					0.41±1.29[c]
PC0751+5623	4.28		−0.67±1.23					−0.67±1.23
PC1247+3406	4.90					−0.14±0.89		−0.14±0.89
PC1643+4631A	3.80		3.03±2.01	−0.41±2.11	−1.74±1.42			0.29±1.06
HM0000−26	4.11			6.77±4.32		−1.45±3.22		2.6 ±2.6
PC0345+0130	3.64				1.22±1.79			1.22±1.79[d]
PC0910+5635	4.04			1.69±1.84				1.69±1.84
PC1158+4635	4.73	1.0 ±2.0						1.0 ±2.0
Q1208+1011	3.80					2.51±2.36		2.51±2.36
PC1643+4631B	3.83		0.79±2.52					0.79±2.52
RXJ1759.4+6638	4.30	−1.0±2.0						−1.0±2.0
Q2203+29	4.40			−2.02±3.03		1.63±1.50		−0.20±1.60
PC2331+0216	4.09					−0.34±1.51		−0.34±1.51

Notes.-
(I) Apr. 1994; (II) 02/03 Feb. 1995; (III) 03/04 Feb. 1995; (IV) 04/05 Feb. 1995; (V) 05/06 Feb. 1995; (VI) 07/08 Feb. 1995
[a] 15 March 1995
[b] 6.6±1.7 mJy in Andreani et al. (1993)
[c] 5.7±2.0 mJy in Andreani et al. (1993)
[d] 6.0±1.6 mJy in Andreani et al. (1993)

for large masses of colder dust in IRAS F10214+4724 and the luminous QSOs detected by IRAS (see Chini et al. 1989a,b).

The bulk of the warm dust should be concentrated within a radius ∼ 1kpc, as this distance is consistent with $T_D \sim$ 50-100 K and a direct exposure to the UV-X luminosity of bright QSOs (see Sanders et al. 1989). For such a direct heating of the dust by the QSO radiation field, a distribution of dust temperatures is expected, given the effects of shielding; the warp disk model proposed by Sanders et al. is rather constraining, although it remains the most likely way to achieve dust heating.

5. Statistics and correlations with other properties

5.1. Detection rate

Combining our present small number of detections with the relatively large number of significant non-detections allow us to infer a few general trends. For this discussion, we shall consider the 2σ upper limits derived from the σ values reported in Tables 3 and 4. We first consider the relatively complete sample of z > 4 sources, and will briefly discuss a sample extended to smaller redshifts in Sect. 6. Even for the z > 4 sample (∼ 45 radio-quiet QSOs at z>3.9, as known at the time of the observa-

Table 4. Observed 1.25 mm flux densities – continued

Source	z	I	II	VI	VII (Fluxes in mJy)	VIII	IX	Total
				QSOs with 1.5 < z < 3.5				
Q1230+1627	2.70			8.57±2.45	7.57±1.4	7.58±2.1	11.0±2.7	7.5±1.4[a]
Q0838+3555	1.77						4.50±1.5	4.50±1.5
Q0842+3431	2.12				2.93±2.0	6.02±2.6	3.41±1.9	4.14±1.3
Q1017+1055	3.15				3.08±1.4	4.16±1.8	5.01±2.8	3.7±1.2
Q0114−0857	3.16					3.34±2.0		3.34±2.0
Q0856+1713	2.32			−0.26±1.6				−0.26±1.6
Q1212+0854	2.35					2.92±1.9		2.92±1.9
Q1235+0857	2.90		−0.21±1.9	2.35±1.8				1.13±1.3
Q1246−0542	2.21			2.04±1.9				2.04±1.9
Q1247+2647	2.04			1.43±1.9				1.43±1.9
PC2132+0126	3.19	1.7±1.0	0.01±1.2					0.8 ±0.8[b]
Q0903+1734	2.77			−0.50±3.1				−0.50±3.1
Q0956+1217	3.30				0.78±2.2			0.78±2.2
Q1212+1445	1.64			−1.08±3.2				−1.08±3.2
Q1231+2924	2.01				2.08±2.1			2.08±2.1
Q1308−0214	2.85					1.13±2.1		1.13±2.1
Q1308−0104	2.55					3.04±2.3		3.04±2.3
Q1331−0108	1.88		0.61±2.3					0.61±2.3
Q1426−0131	3.42				2.63±2.2			2.63±2.2

Notes.-
(I) Apr. 1994; (II) 02/03 Feb. 1995; (VI) 07/08 Feb. 1995; (VII) 31Mar./01Apr. 1995; (VIII) 01/02 Apr. 1995; (IX) 02/03 Apr. 1995
[a] Uncertain calibration, see text
[b] 11.5±1.7 mJy in Andreani et al. (1993)

tions), our studies are somewhat biased towards higher redshifts and luminosities. Thus our study should only be complete for sources stronger than 5 mJy. Three are presently known, i.e. $\sim$ 10-15% of the APM color-selected sample. Such strong millimetre emitters are probably absent from the 14 other $z > 4$ sources known at the time of the observations, in particular those of the Palomar grism-selected sample (PC, Schneider et al. 1991a). Future detailed studies of the brighter sources with $S_{1.25} \sim$ 10 mJy (BR1202−0725 and BRI1335−0417) should be made to investigate whether they are just the tail of the distribution or have some exceptional property, lensing or more basic ones. The detection rate of 3 mJy sources is incomplete for the entire APM sample (31 QSOs at the time of the observations), although it should be nearly complete for the subsample observed at $\sigma < 1.5$ mJy (16 sources). The weighted average of the 10 undetected sources equals $\sim 0.3 \pm 0.4$ mJy, which suggests that no more than one 3 mJy source has been missed. It is possible that a few 3 mJy emitters are present in the sample of the other 15 sources not observed at high enough sensitivity. As the observed sample is biased towards sources whose characteristics seem to favor detection (see Sects. 5.4 and 5.5), the proportion of 3-4 mJy sources in the detected sample, 3/13, should be larger than for the unobserved sources. Consequently, no more than three 3 mJy sources should have been missed. The proportion of sources with flux > 3 mJy among the whole APM sample should then be in the range 20-30%. There is most probably no source with flux > 3 mJy among the 6 observed non-APM sources (mostly PC) at z>3.7. We note that the recently detected 2 mJy source (PC2047+0123 at z=3.80) by Ivison (1995) has the reddest spectrum of the PC sample ($\alpha \sim -1.61$).

5.2. UV luminosity

At smaller redshift, Sanders et al. (1989) have found a clear correlation between the rest-frame UV luminosity and the FIR luminosity inferred from the IRAS data. One thus expect some increase of $S_{1.25}$ with the rest-frame UV luminosity. To easily compare our luminosities with the absolute magnitudes of lower redshift quasars we have computed the absolute rest-frame magnitudes assuming a spectral index $\alpha = -0.5$ ($S_\nu \propto \nu^\alpha$) between the "observed" rest-frame flux at 1450Å and 4400Å the effective wavelength of the B band. These values, given in Table 1, are tabulated assuming $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and q_0=0.5. When observed fluxes at a rest-frame wavelength of 1450Å are not published, continuum fluxes have been calculated from the broad-band magnitudes.

The values of the detected 1.25 mm fluxes or their upper limits are plotted in Fig. 1 versus M_B. For clarity, we have only plotted upper limits where the rms errors were less than 2mJy. There is a clear trend for the detections to lie at the upper end of the luminosity distribution. This explains the large difference in detection rate between the APM and the PC samples, as the luminosities in the first sample are larger by one or two magnitudes. This result is insensitive to the assumed spectral index for the UV-to-optical continuum since the extrapolation is from the same rest-frame wavelength in all cases. However, the correlation is not tight within the APM sample since one of the smallest luminosity source, BRI1335−0417, is among the

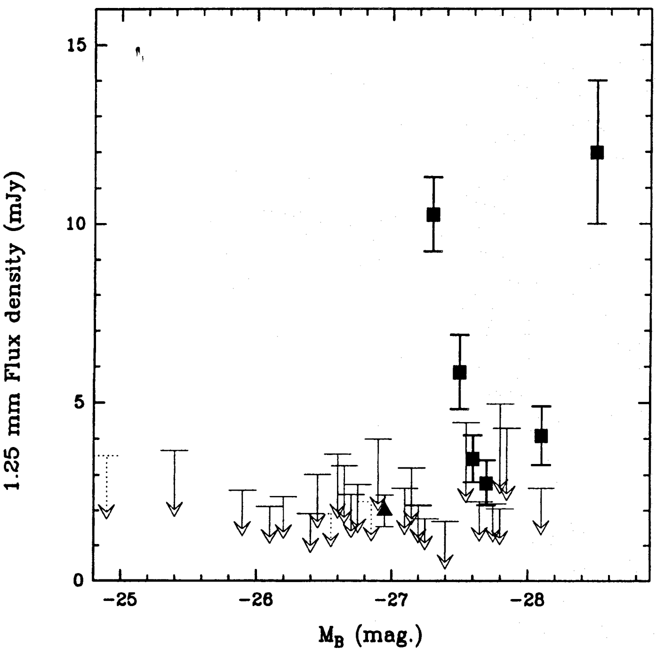

Fig. 1. Plot of the 1.25 mm flux density versus M_B, the optical absolute magnitude in the B rest-frame band (adopting H_0 = 50 km s^{-1} Mpc^{-1} and q_0 = 0.5), for the primary QSO sample at z>4 listed in Table 1 and the quasars observed by Ivison (1995). Upper limits are shown by arrows with lengths equal to the 2 σ value. Full lines and filled squares correspond to the data presented in this paper, whereas dashed lines and the triangle display the Ivison's data.

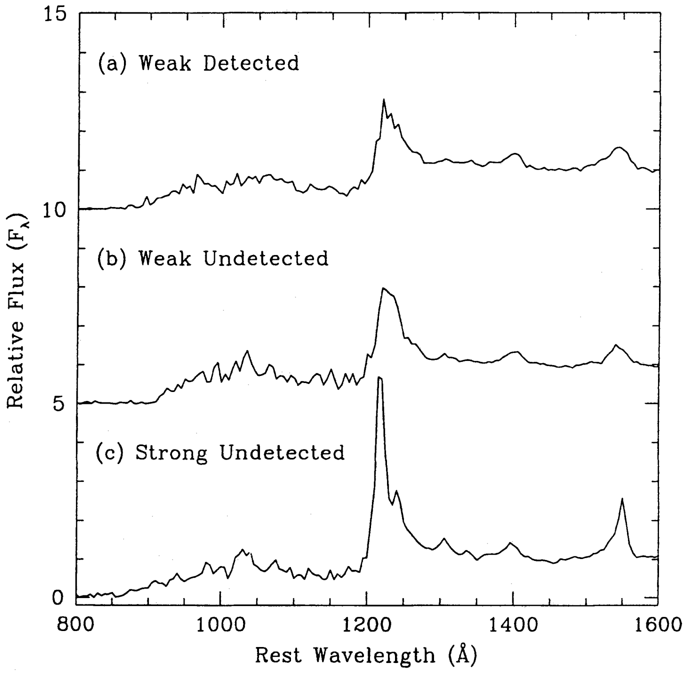

Fig. 2a–c. Combined spectra of the APM z>4 quasars discussed in this paper with the exception of the BAL quasars. All spectra have been normalized at 1500Å in the rest frame. **a** Averaged spectrum of APM weak line sources detected at 1.25 mm (1202−0725, 1335−0417, 1033−0327 and 0952−0115); **b** averaged spectrum of APM weak line sources undetected at 1.25 mm (0241−0146, 0245−0608, 0951−0450, 1114−08 and 1500+0824); **c** averaged spectrum of APM strong line sources undetected at 1.25 mm (0103+0032, 0151−0025, 1328−0433 and 1346−0322)

strongest millimetre emitters, and three of the most luminous optical sources are not detected. This result is insensitive to the assumed spectral index for the UV-to-have calculated optical continuum since the extrapolation is from the same rest-frame wavelength in all cases.

5.3. Reddening

In addition to millimetre emission, an obvious indicator of dust would be the reddening of the observed visible spectrum. There is no clear evidence of strong reddening in the optical spectra of the APM sample (Storrie-Lombardi et al. 1996) and the PC one, but for PC2047+0123.

The absence of strong reddening in objects with large amounts of dust, is somewhat puzzling. A similar paradox is encountered in explaining the strong FIR IRAS emission of the bright optical QSOs at small redshift (Sanders et al. 1989). This could be explained by either geometry and anisotropy of the dust distribution or a UV extinction law much flatter than the usual one by a selective destruction or absence of the smallest particles responsible for the UV reddening.

5.4. Emission lines

The visible spectra of the APM QSOs are given in Storrie-Lombardi et al. (1996). A few average spectra are reproduced in Fig. 2. Excluding the BAL QSOs discussed below, some similarities are apparent in the optical spectra of the millimetre detected sources: none show strong emission lines. On the contrary these lines are broad and relatively weak with respect to the continuum in all detected sources (see Fig. 2 and Table 1). BR1202−0725 and BRI13335−0417 are extreme members of this class, while BR1033−0327 and the lensed QSO BRI0952−0115 are of intermediate type.

This spectral characteristic of the detected sources is particularly striking with respect to the spectra of the many undetected sources, quoted as S in column 8 of Tables 1 and 2, which have sharp and strong emission lines. This is illustrated in Fig. 3 which displays histograms of the detected and undetected z > 4 QSOs as a function of their spectral type. It should be added that practically all the spectra of the PC sources, also undetected, are in this class (see Schneider et al. 1991a and references therein). However, there are other cases of non detection, with spectra quoted W in Table 1 and quite similar to those of BR1033−0327 or BRI0952−0115.

In conclusion, some correlation between the properties of the optical-UV emission lines and the intensity of the millimetre flux seems present. This property might be linked to the well-known correlation between a strong luminosity and the presence of weak and broad emission lines, often referred to as the Baldwin effect (Baldwin 1977; Osmer et al. 1994).

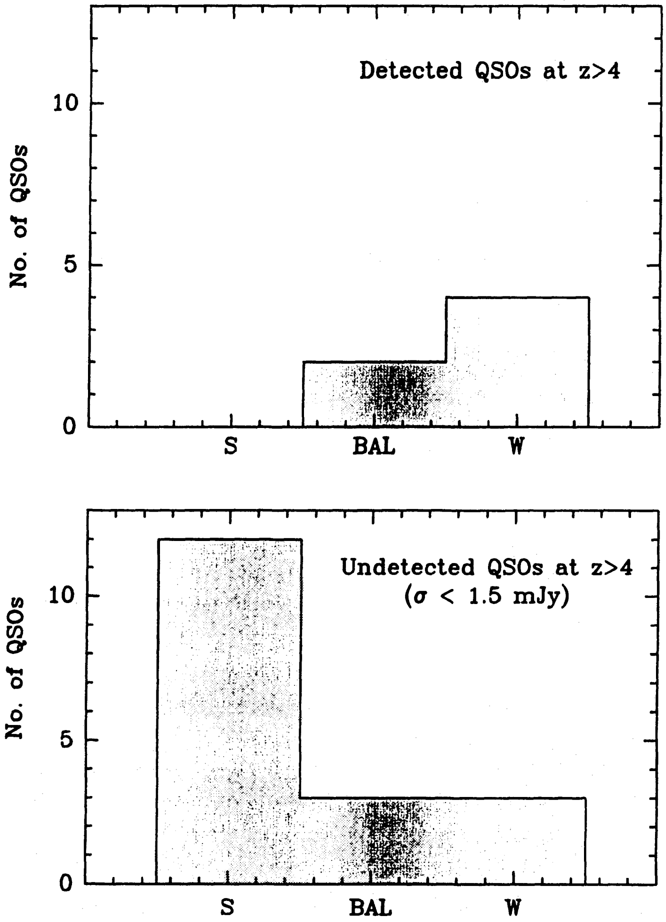

Fig. 3. Histograms of the distribution of the number of detected and undetected ($\sigma < 1.5$ mJy) QSOs at $z > 4$ as a function of their spectral types (given in Table 1).

5.5. Broad absorption lines QSOs

BAL QSOs are a class of quasars that exhibit strong resonance absorption from lines such as MgII, CIV, SiIV, NV and OVI. They also show evidence for strong optical [FeII] emission. Studies of IRAS selected QSOs by Low et al. (1989) have shown that 30% of them are BAL QSOs. However, only 2-5% of low redshift QSOs exhibit BAL characteristics, and this fraction reaches ~10% at high redshift. Lipari, Terlevich & Macchetto (1993) have proposed that BAL QSOs and [FeII] emitters are QSOs which are undergoing enhanced star formation. From the analysis of the reddening in BAL QSOs, evidence of dust in their nuclei has been found (Boroson & Mayer 1992, Sprayberry & Foltz 1992).

Five of the 31 QSOs of our APM sample display strong BALs (Storrie-Lombardi et al. 1996). Only one of those five BALs (BR0945−04) has not yet been observed. The millimetre detection rate is relatively high, 2 out of 4 observed. One should also note that the z = 2.5 radio-quiet QSO with the strongest millimetre flux (H1413+117, 18±2 mJy, Barvainis et al. 1995) is a typical BAL QSO, although it is strongly amplified by lensing by a factor ~ 5-10 (see e.g. Barvainis et al. 1994).

Consequently, we used the presence of BAL as a criterion for selecting our smaller redshift QSO sample. However, there is only one tentative detection among the observed 7 BAL QSOs in the redshift range 1.5-3.5 (Table 4). Although the presence of the BAL phenomenon seems rather a positive factor for millimetre detection, it is not a sufficient one.

6. Observations at smaller redshifts

It is important to extend millimetre continuum observations to smaller redshifts so as to infer information on evolutionary effects. We have thus started an exploratory programme on bright radio-quiet QSOs in the range z ~ 1.5-3.5. For a same source, the 1.25 mm flux is expected to vary little with z in the range z ~1-5, with however a non negligible increase at high redshift for a dense Universe ($\Omega_0 \sim 1$; see e.g. Fig. 1 of McMahon et al. 1994). Indeed, no radio-quiet QSO was previously detected in the (sub)millimetre range in this lower redshift interval, except the lensed QSO H1413+117 (The Clover Leaf). A special further aim is to discover new high redshift sources in which CO could be subsequently searched for. Given the previous small detection rate, we have used as selection criteria, in addition to a bright visible magnitude: the detection of mJy level radio emission, the presence of BALs (see Sect. 5.5), the presence of weak optical emission lines similar to those of the objects at z>4 with detected 1.25 mm emission.

There are indications of a correlation between weak mJy radio emission of radio-quiet QSOs at centimetre wavelengths and their far-IR emission (Sopp & Alexander 1991), similar to the well established relation in IRAS starburst galaxies (de Jong et al. 1985; Helou et al. 1985). We have thus initiated the 1.25 mm study of a complete sample of radio-weak QSOs with radio fluxes in the frequency range 1.4 GHz to 8.4 GHz between 0.20 and 2.0 mJy. Many of them are BAL QSOs. As reported in Table 4, we failed to detect any but, for many of them, our sensitivity was poor. The ratio $S_{1.25mm}/S_{6cm}$ is smaller in many of these sources than in H1413+117 and IRAS F10214+4724, and there is no tight correlation between the millimetre and centimetre fluxes. Consequently, radio-weak emission does not appear a very powerful criterion to discover new high redshift millimetre emitters with the present level of sensitivity of millimetre equipments.

As mentioned above, we have also used the presence of weak and broad emission lines as a criterion for a search of new millimetre sources at smaller redshift. The first results are given in Table 4. We observed a dozen of sources with $\sigma < 2$ mJy. We have definitely detected one object and there are tentative detections for three others. The detected source, Q1230+1627 at z=2.70, is strong and independently detected on four different days. Unfortunately, there were calibration problems for most of these observations, and there is still some uncertainty on the actual value of its 1.25mm flux, which is in the range 5-10 mJy. This source has the weakest optical emission lines (Foltz et al. 1989) found among over 500 sources of the LBQS survey (Foltz et al. 1987; 1989, Hewett et al. 1991; Chaffee et al. 1991). It also has a large luminosity and a relatively red spectral index (α ~1).

It was not detected at 8.4 GHz by Visnovsky et al. (1992) with a 3σ upper limit of 0.24 mJy.

7. Conclusion

Our new survey bring the number of firm 1.25 mm detections of radio-quiet QSOs at $z > 4$ from one to six, and for those at z >1 from two (i.e. BR1202−0725, H1413+117) to eight. For $z > 4$, our study is relatively systematic since we observed with a good sensitivity about half of the objects known at the time of our observations. Consequently, the general trends of the millimetre emission of optically known $z > 4$ QSOs can be inferred. Among color identified samples such as the APM one, the detection rate with rms $\sim$ 1-1.5 mJy, thus a detection limit $\sim$ 3-5 mJy, should be between 20% and 30%. Sources with $S_{1.25mm} > 10$ mJy or even > 5 mJy are rare, with detection rates $\sim$7% and 10-15%, respectively. It seems that, as expected, the detection is not easier at $z = 2$ than at $z = 4$; it could even be more difficult. Some correlations begin to emerge from the relations of the strength of millimetre emission with other characteristics of the sources. All the millimetre detected QSOs are among those which have the largest rest-frame UV luminosities. In addition they have weak and broad emission lines. The presence of broad absorption lines seems to increase the chance of a positive millimetre detection, but does not warrant it.

The occurence of a strong amplification by gravitational lensing of such objects remains a major issue. There is one known clear case of strong lensing among the six millimetre detected objects at $z > 4$, namely BR0952−0115. However, visible and near-IR deep imaging is needed to discard systematic effects of lensing in the other millimeter detected sources.

The mass of dust M_D is of order $10^8 M_\odot$ for most of the detected sources It is rather certain that such large amounts of dust imply giant starbursts at z >4, at least comparable to those found in the most hyperluminous IRAS galaxies at smaller redshift. We have ongoing programmes at JCMT to measure the submillimetre spectral indices, with the ISO satellite to detect the FIR emission of high redshift QSOs and infer their FIR luminosity, and with the IRAM interferometer to map the extension of the 1.3 mm emission and search for CO emission.

It is clear from the present results and prospects, that millimetre and submillimetre astronomy will contribute in an important way to understand the evolution of high-redshift QSOs, in particular the initial giant starburst phase of their host galaxies.

Acknowledgements. This work was carried out in the context of EARA, a European Association for Research in Astronomy. RGM thanks the Royal Society for support. We are grateful to A.W. Sievers and the IRAM staff at Pico Veleta for their efficient assistance, and to A. Greve for his participation to the observations with the single channel bolometer. We thank B. Fort for quite useful discussions on gravitational lensing and on his unpublished work. This research has made use of the Simbad database, operated at CDS, Strasbourg, France.

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