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Dust and CO lines in high redshift quasars

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Abstract. We report the results of a systematic search for redshifted rotational lines of CO and dust emission towards a sample of 9 high redshift radio quiet quasars using the IRAM Plateau de Bure interferometer. Dust emission at ~ 1.35 mm has been found in 5 out of the 9 objects. These results confirm the corresponding previous detections with the MPIfR bolometer at the 30-m. No 3 mm continuum was detected in any source. The flux densities measured at 1.35 mm with the interferometer are systematically smaller by $\sim 30\%$ from the broad-band bolometer fluxes, consistent with an average spectral index of ~ 3.5 within the calibration uncertainty.

In parallel, searches for CO in significant redshift ranges were performed for 8 of the above sources. 6 sources were not detected. Assuming a line width of $\leq 450\,\mathrm{km\,s^{-1}}$, we obtain typical upper limits of ~ 0.4–$0.5\,\mathrm{Jy\,km\,s^{-1}}$ at the 3σ level in the frequency (redshift) range searched. We report a tentative (3σ) detection of the J=3-2 line of CO in Q 1230+1627B, and a unambigous detection of the J=5-4 CO line in the gravitationally lensed radio quiet quasar BRI 0952$-$0115 at a redshift of $z = 4.43$. After BR 1202$-$0725 at $z = 4.69$ (Otha et al. 1996, Omont et al. 1996a), and BRI 1335$-$0417 at $z = 4.41$ (Guilloteau et al. 1997), this is the third detection of CO at $z > 4$. The velocity-integrated CO(5-4) line flux is $0.91 \pm 0.11\,\mathrm{Jy\,km\,s^{-1}}$, with a linewidth of $230 \pm 30\,\mathrm{km\,s^{-1}}$. The 1.35 mm (250 μm rest wavelength) dust continuum flux density is 2.23±0.51 mJy, in agreement with previous measurements at 1.25 mm at the 30-m IRAM telescope. The ratio of the CO to 1.35 mm continuum flux is comparable to that of BRI 1335$-$0417 and 2-3 times larger than for BR 1202$-$0725. The angular resolution of the observation is not high enough to give evidence of any extension of the 1.35 mm continuum and 3 mm CO emission.

Key words: galaxies: formation – galaxies: quasars: emission lines – galaxies: quasars: individual: BRI 0952-0115 – galaxies: quasars: individual: Q 1230+1627B – cosmology: observations – cosmology: early Universe

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1. Introduction

Galaxy formation is one of the major outstanding problems of astronomy and understanding when and how galaxies form is one of the primary objectives in both observational and theoretical astrophysics. The mere fact, that active galaxies, such as radio galaxies and quasars, and more recently normal emission line galaxies, are observed up to redshifts of 5.6 (Weymann et al. 1998, Hu et al. 1998), less than one billion years after recombination, implies that galactic scale, gravitationally bound structures exist at this epoch. The study of the masses and dynamical state of these young systems is a direct constraint on the growth of large scale structure since the epoch of recombination (cf Efstathiou & Rees 1988, Peacock et al. 1998, Haehnelt et al. 1998)

The observation and detailed study of the astrophysical conditions that exist in galaxies at high redshift is of fundamental importance. Understanding and characterizing star formation there and its consequence on early galaxy evolution is a major goal, since it is one of the most difficult problems in modelling galaxy formation. The study of star forming molecular material in galaxies at the furthest reaches of the Universe and earliest observable epochs has recently been shown to be possible with spectacular results mostly with the IRAM interferometer. It is well known that such high z detections are possible because of the steep submillimeter dust spectrum ("inverse k-correction") and, for CO, because higher lines in the rotational ladder which emanate from dense warm gas are redshifted into the 3mm band. Further, for unresolved sources the observed brightness temperature does not decline with redshift for $z < 1$ due to the effect of angular size distance on the beam size (in parsecs) (Solomon et al. 1992a,b). However, the number of firm CO detections remains small, namely: two radio quiet quasars with $z > 4$, BR 1202$-$0725 at $z = 4.69$ (Omont et al. 1996a, Ohta et al. 1996) and BRI 1335$-$0417 at $z = 4.41$ (Guilloteau et al., 1997), two gravitationally lensed AGN, H 1413+117 (the Cloverleaf) at $z = 2.54$ (Barvainis et al. 1994) and FIRAS 10214+47 at $z = 2.28$ (Brown & Vanden Bout 1992), the gravitationally lensed quasar MG 0414+0534 at $z = 2.64$ (Barvainis et al. 1998), the SCUBA submillimeter AGN SMM 02399$-$0136 at $z = 2.8$ (Frayer et al. 1998) and the quasar APM 08279+5255 at $z = 3.91$ (Downes et al. 1998).

The derivation of dust, gas and virial masses via the CO lines has opened a new window on the properties of galaxies at high redshift. It is obvious that for the subject to develop further more objects with reliable CO detections are needed at high redshift. Rather than carry out an indiscriminate search of high redshift objects, we have focused our CO search on objects that have previous millimeter detections of dust emission. Over the last few years, we have pioneered the study of very high quasars and their hosts in the millimeter/submillimeter regime. This program has involved detailed millimeter and submillimeter continuum studies of about 20 $z > 4$ quasars (McMahon et al. 1994; Isaak et al. 1994; Omont et al. 1996b; Benford et al. 1999). More recently the work has been extended to molecular line work and we have detected and mapped two $z > 4$ radio quiet quasars in the CO line. Remarkably, we have detected extended CO in the case of the $z = 4.69$ QSO BR 1202−0725 (Omont et al. 1996a) and more recently the detection of spatially unresolved CO in the $z = 4.41$ QSO BRI 1335−0417 (Guilloteau et al. 1997). This work has shown that galactic scale objects exist at a very early epoch in the evolution of the Universe with inferred total warm molecular gas masses of up to several $10^{10} M_{\odot}$.

We present here further results of a systematic study, with the IRAM interferometer, of the quasars where 1.25 mm dust continuum emission has been detected at the IRAM 30-m telescope (Omont et al. 1996b). In this study, CO has been searched with various sensitivity in nine new high redshift quasars. One of these objects has been detected, BRI 0952−0115 at $z = 4.43$, representing the third 3 mm detection of CO at $z > 4$ after BR 1202−0725 and BRI 1335−0417. A tentative (3σ) CO detection is reported for Q 1230+1627B at $z = 2.74$. Since at least half of the high redshift sources, where CO has been detected, are lensed, the possible amplification by gravitational lensing is a key issue for their actual far-infrared luminosity and their molecular gas mass. The fact that the newly detected quasar, BRI 0952−0115, has a spectacularly lensed optical image (Mc Mahon et al. 1992) may have some relevance for this discussion.

2. Observations

Observations were made with the IRAM interferometer between October 1996 and April 1998, with four or five antennas. We used the standard CD configuration, which gives typical synthesized beam of $\sim 3'' \times 2''$ at PA $\sim 40°$ at 1.35 mm (depending on source declination) and $\sim 6'' \times 5''$ at 3 mm. Dual frequency receivers were used to search simultaneously for emission in one CO line at 3 mm and dust emission at 1.35 mm. The simultaneous observation of the continuum in the 3 mm and 1.3 mm bands allows independent checks of the 1.3 mm 30-m detections and their calibration.

Because of the uncertainty in the redshifts and in order to provide wide velocity coverage, two different tunings, separated by 450 MHz, were sometimes used at 3 mm. The 3 mm receivers were tuned in single sideband and the 1.35 mm receivers in double sideband (at 223 GHz LSB and 226 GHz USB). Typical SSB system temperature were $\simeq 150$ K at 3 mm and $\simeq 350$ K at 1.35 mm. Flux density scale is accurate to better than 15%.

Table 1. Positions and redshifts of observed sources

Source	z	RA (J2000.0)	Dec (J2000.0)	Ref.
BRI 0952−0115	4.434	09 55 00.1	−01 30 07.1	7
BR 1033−0327	4.509	10 36 23.7	−03 43 20.7	1
BR 1117−1329	3.958	11 20 10.2	−13 46 26.1	1
BR 1144−0723	4.147	11 46 35.6	−07 40 05.2	1
Q 1230+1627B	2.735	12 33 10.5	+16 10 54.0	2
Q 0100+1300	2.681	01 03 11.3	+13 16 17.0	3
Q 0842+3431	2.126	08 45 38.7	+34 20 43.0	4
PSS 1048+4407	4.45	10 48 46.5	+44 07 13.0	5
PSS 1721+3256	4.03	17 21 06.7	+32 56 36.0	6

References: 1. Storrie-Lombardi et al. (1996); 2. Hewett et al. (1995); 3. Young et al. (1982); 4. Thompson et al. (1989); 5. Kennefick et al. (1995); 6. S.G. Djorgovski priv. comm.; 7. Central frequency of detected CO line

Phase noise was generally below 40° on all baselines even at 1.35 mm.

The name, redshift and position of the sources which were observed are listed in Table 1. Table 2 gives for each source the observation parameters, in particular the redshift range observed for the CO search, and the results: the 3 mm CO line intensity and the flux densities at 3 and 1.35 mm as measured with the interferometer in one beam at the central position. Table 2 also reproduces previous results obtained at 1.25 mm at the IRAM 30-m telescope: those reported by Omont et al. (1996b) and the subsequent tentative detections of Q 0100+1301 (PHL 957), PSS 1048+4423 and PSS 1721+3256.

3. Results from the survey for continuum emission

Fig. 1 presents images in the continuum at 1.35 mm of the sources listed in Table 1 together with the previously detected objects BR 1202−0725 and BRI 1335−0417. Except for BR 1202−0725, no spatial extension was detected in any of the sources in the conditions of the observations.

As compared to the previous measurements done at the 30-m, the present data confirm at the 4σ or better level the detections (or tentative detections) of BRI 0952−0115, Q 1230+1627B, Q 0100+1300, Q 0842+3431, and at the 3σ level that of BR 1033−0327. On the other hand, we do not detect any emission, down to very low levels, from either BR 1144−0723 (an apparently safe result from the 30-m), nor from PSS 1721+3256 for which a marginal result was obtained at the 30-m. This conclusion persists even taking into account the mean ratio between the fluxes measured with the interferometer and the 30-m (see below). However, the detection of BR 1144−0723 has been confirmed at 3–4 σ both at 850 μm by Buffey et al. (in preparation, quoted by McMahon et al. 1999) and at 1.25 mm by Maoli et al. (in preparation), but with a smaller flux than in Omont et al. (1996b), corresponding to a 1.35 mm flux of ~2–3mJy compatible with the interferometer data. In the two remaining sources (PSS 1048+4407, BR 1117−1329), the Plateau de Bure sensitivity is insufficient to conclude, although the detection of

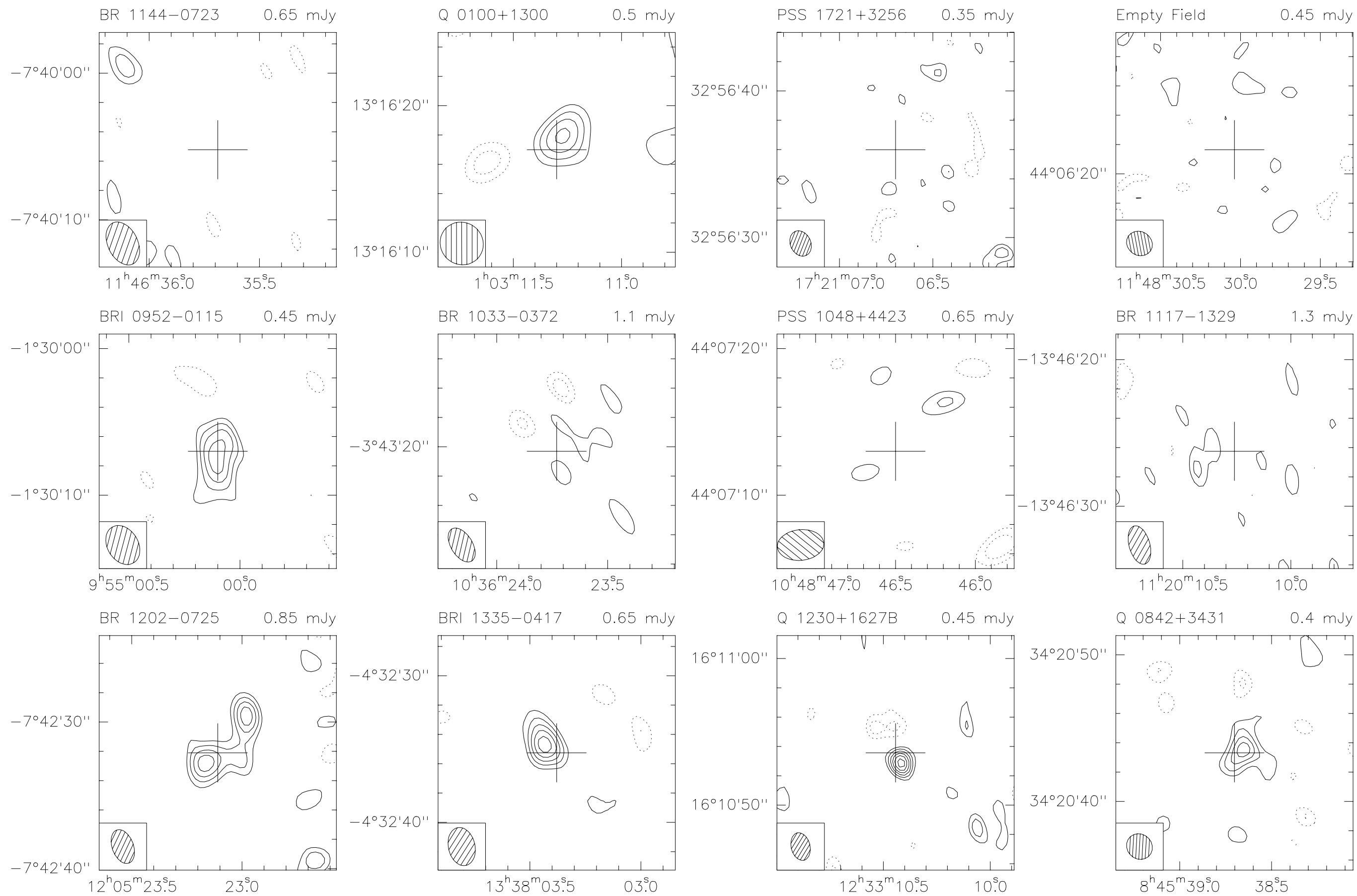

Fig. 1. 1.35 mm continuum maps of the observed fields. Contour levels are −3, −2, 2 to 7 σ by 1 σ. The clean beam is indicated in the lower left corner, and the noise level (1 σ) in the upper right corner. The cross indicates the optical position. All coordinates are J2000.0

BR 1117−1329 has been confirmed at 850 μm by Buffey et al. and that of PSS 1048+4407 is tentatively confirmed at 1.25 mm by Maoli et al. The reliability of our interferometer results are assessed by observations of two empty fields down to similar sensitivities. No significant bias is seen in any of these two fields, confirming the inherently stable nature of the instrument.

With the exception of BR 1202−0725, the 30-m fluxes are systematically higher than the 1.35 mm interferometer fluxes. The weighted mean ratio is 1.40. A possible explanation is that the sources are spatially extended, since the interferometer could not detect any source extension greater than $\sim 2''$. However, except for the exceptional case of BR 1202−0725 (Omont et al. 1996a), there is no direct indication for such extensions, even for the second strongest source, BRI 1335−0417 (Guilloteau et al. 1997). The discrepancy is more easily ascribed to the spectral index of the emission. The difference in effective frequency, 225 GHz at Bure, ∼240 GHz at the 30-m, with the very steep dust spectrum, may explain a flux ratio of ~ 1.25, assuming a spectral index of 3.5. The remaining 15% is within the calibration uncertainty.

On the contrary, the spatial extent of BR 1202−0725 can explain why the 30-m flux is apparently lower than the interferometer flux. The 30-m observations, which were pointed on the optical position, have likely missed part of the flux from the second source, which is not far from the half power half beamwidth of the telescope (5.5″). The amount of missed flux is critically dependent on even small pointing errors during the observation. We note that the new 1.25 mm flux measured by Maoli et al. (in preparation) at the 30-m is $\sim 30\%$ larger than the value of Omont et al. (1996b) and more in agreement with the Bure result.

Finally, we did not detect any 3 mm continuum from any of the sources. Based on the measured 225 GHz fluxes, and using a dust spectral index of 3.5, the expected 3 mm continuum value is about 0.2 mJy. This is too low to be detectable on any individual sources, since the typical 1σ level is 0.20–0.25 mJy.

4. Results of the survey for CO emission. Discussion of BRI 0952−0115

The search for redshifted CO has been less successful. Out of the 9 sources observed in a relevant redshift range (the 3 mm observing frequency for Q 0100+1300 does not include the appropriate redshift), we detected CO(5-4) in BRI 0952−0115 at the 9σ level (Fig. 2), and have a tentative detection (3σ at the appropriate position) of CO(3-2) for Q 1230+1627B. The latter result, if real, indicates a CO redshift in the range (2.739–2.742) or even higher, since we cannot exclude that the (tentative) sig-

Table 2. Observation parameters and results

Source	z	CO line	$\nu_{3\,\mathrm{mm}}$ MHz	z range	Line Flux Jy km s^{-1}	1.35 mm mJy	1.25 mm (30-m) mJy
BR 1202−0725[a]	4.693[c]	5-4	101224[c]	[4.679–4.707]	2.4 ± 0.3	16 ±2	12.6±2.28
BRI 1335−0417[b]	4.407[c]	5-4	106570[c]	[4.392–4.423]	2.8 ± 0.3	5.6±1.1	10.3±1.04
BRI 0952−0115	4.434[c]	5-4	106052[c]	[4.419–4.449]	0.91 ± 0.11	2.23±0.51	2.78±0.63
BR 1033−0327	4.509	5-4	104605	[4.497–4.521]	< 0.55	4.16±1.36	3.45±0.65
BR 1117−1329	3.958	4-3	92989	[3.948–3.970]	< 0.60	−0.64±1.47	4.09±0.81
BR 1144−0723	4.147	5-4	111962	[4.137–4.157]	< 0.55	0.54±0.78	5.85±1.03
Q 1230+1627B	2.709	3-2	93232	[2.701–2.718]	< 0.51	3.33±0.52	7.5 ±1.4
	2.741[d]	3-2	92434[d]	[2.728–2.746]	(0.80 ± 0.26)[d]		
Q 0100+1300	2.681	3-2	(93940)			2.80±0.59	$\sim 4 \pm 1$
	2.776	3-2	91658	[2.763–2.782]	< 0.48		
Q 0842+3431	2.126	3-2	110619	[2.120–2.132]	< 0.55	2.32±0.45	4.14±1.3
PSS 1048+4407	4.450	5-4	105737	[4.438–4.462]	< 0.42	0.25±0.68	$\sim 3 \pm 1$
PSS 1721+3256	4.030	4-3	91658	[4.017–4.042]	< 0.33	0.17±0.41	$\sim 3 \pm 1$
Empty field 1						−1.43±0.90	
Empty field 2						−0.06±0.51	

Notes. Upper limits on the CO line flux are derived assuming a total line width of 450 km s^{-1}, and are given at the 3σ level.
[a] Data from Omont et al. (1996a)
[b] Data from Guilloteau et al. (1997)
[c] Central frequency of the detected CO line
[d] Frequency and redshift of the tentative detection

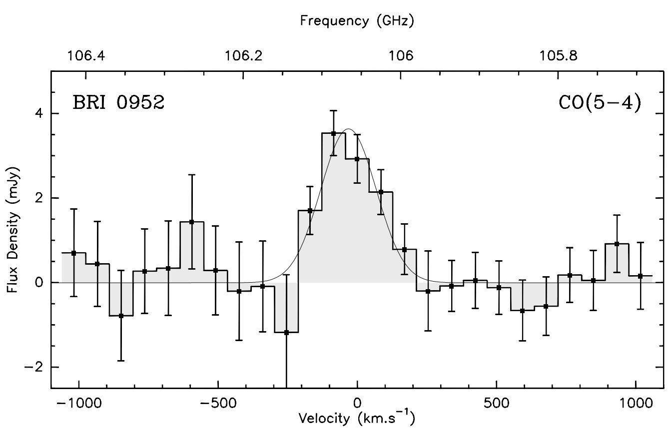

Fig. 2. Spectrum of the CO J=5-4 line towards BRI 0952−0115, superimposed with the best Gaussian profile. Error bars are $\pm 1\sigma$. The velocity scale corresponds to a frequency of 106.055 GHz corresponding to a redshift $z = 4.4337$.

nal is the edge of the line. This is close to the expected redshift of 2.735, with the CO redshift higher than the optical redshift, as found for similar objects. In all other sources, assuming a total line width of ≤ 450 km s^{-1}, we obtain typical upper limits of ~ 0.4–0.5 Jy km s^{-1} at the 3σ level (see Table 2).

The only new clear CO detection is in BRI 0952−0115, the highest redshift quasar known to be clearly gravitationally lensed from its optical image (McMahon et al. 1992, McMahon et al. in preparation). The I image is well resolved in two peaks which are separated by 0.95″ and differ in brightness by 1.35 magnitudes. The total amplification, estimated from a rough modelling of the double optical image, could reach a factor ~ 4. Its visible spectrum was analysed by Storrie-Lombardi et al. (1996). The emission lines are weak and heavily absorbed. The average redshift of emission lines (excluding Lyα) is 4.426±0.020. There is a strong damped Lyα absorption at $z = 4.01$.

In the continuum at 1.3 mm, BRI 0952−0115 is amongst the weakest sources detected at the 30-m telescope (Omont et al. 1996b). The flux density measured with the interferometer is 2.23±0.51 mJy, in excellent agreement with the 30-m value (Table 2). The continuum source position is offset by $(0.11 \pm 0.22''$, $-0.32 \pm 0.27'')$ from the optical position (RA $09^h55^m00.10^s$ Dec $-01°30'07.1''$ J2000.0), well within the astrometric uncertainty of both measurements. With the present angular resolution ($2.6'' \times 1.8''$) there is no evidence of any extension in the continuum emission as in the case of BR 1202−0725 (Omont et al. 1996a) – see Fig. 1.

The search of the CO(5-4) line ($\nu_{rest} = 576.2677$ GHz) was initiated from the emission line redshift ($z = 4.426$), with the centre of the first frequency setting shifted down by 225 MHz ($\nu = 105.980$ GHz), with the idea to explore two different tunings, separated by 450 MHz (see Sect. 2). Since a 3σ line was apparent at 106.055 GHz after one transit, the observation was continued with a setting centered at this frequency. The detection was thus confirmed at the 9σ level on the line intensity at the position of the continuum emission. The CO(5-4) line is found at a frequency of 106.055 ± 0.010 GHz, corresponding to a redshift of 4.4337 ± 0.0006. The spectrum is displayed in Fig. 2, and maps over 135 MHz wide channels are shown in Fig. 3. The integrated line flux is 0.91 ± 0.11 Jy km s^{-1} with a line width of 230 ± 30 km s^{-1}.

There is no doubt about the reality of the CO detection in BRI 0952−0115: the signal-to-noise is high, especially on the integrated intensity, and the profile, as well as the baseline, are

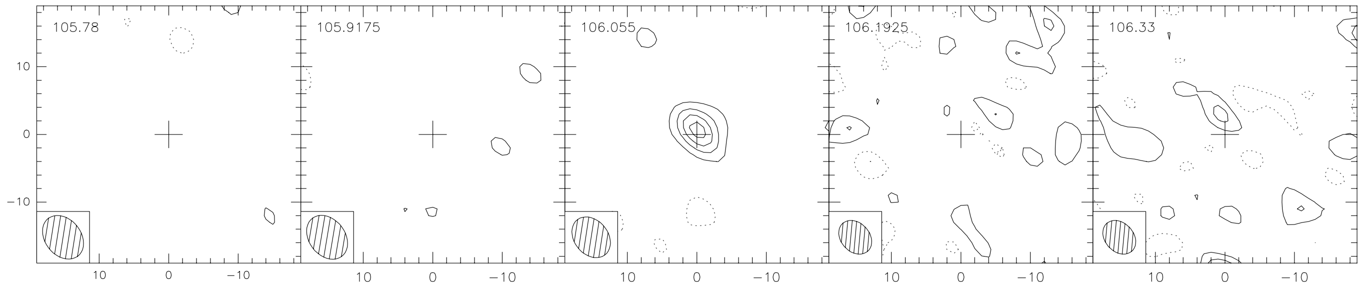

Fig. 3. Images the CO J=5-4 line towards BRI 0952−0115, in 137 MHz wide channels. The frequency (in GHz) is indicated in the upper left corner. The contour step is 0.5 mJy. Because of the two frequency settings used in the observations, the noise levels (and beam shapes) differ from channel to channel: from left to right 1σ is 0.30 mJy, 0.30 mJy, 0.25 mJy, 0.50 mJy, 0.50 mJy respectively.

well behaved. The coincidence with the QSO position and the absence of signal elsewhere (Fig. 3) further strengthens this conclusion. The lack of pure continuum emission when all the 3-mm broad band measurements, except in the line frequency range, are included, indicates that the detected 3 mm emission comes from a spectral line. The width of 230 km s^{-1} is in the range of the values observed for BR 1202−0725 (Omont et al. 1996a) and BRI 1335−0417 (Guilloteau et al. 1997) and the other high z sources referred therein. The derived redshift for the molecular gas is just in the redshift range derived from optical emission lines, in the upper part as expected, close to the low ionisation lines.

With this third detection of CO at redshift larger than 4, it is interesting to compare the three sources and try to infer some conclusions about the nature of the ultraluminous infrared galaxy host of BRI 0952−0115. The latter is much weaker than both BR 1202−0725 and BRI 1335−0417 in the 1.35 mm continuum by factors ∼6 and ∼2, respectively. With its amplification factor $A \sim 4$, it is likely that its luminosity is also substantially less than the two other sources, since a large gravitational amplification is unlikely for BR 1335−0417 and unproven for BRI 1202−0725.

The non-detection of BRI 0952−0115 at 350 μm, i.e. 8±22 mJy, (Benford et al. 1999) indicates a temperature of order 40–50 K which is similar to the values derived for BR 1202−0725 and BRI 1335−0417 (Benford et al. 1999). Assuming $T_{\rm D} = 50$ K, $\Omega_0 = 1$, $h = 0.7$ where $h = H_{\rm o}/100$ km s^{-1} Mpc^{-1}, and $A = 4$, Eq(1) of Omont et al. (1996) yields a mass of dust $\sim 3\ 10^7\ {\rm M}_\odot$. With the same assumptions, from the values derived by Benford et al. (1999) for BR 1202−0725 and BRI 1335−0417, one infers a far-infrared luminosity, $L_{\rm FIR}$, of about $10^{12}\ {\rm L}_\odot$ for BRI 0952−0115. Although this value is more uncertain because of the $T_{\rm D}^5$ dependence of $L_{\rm FIR}$, it is not unlikely that BRI 0952−0115 is comparable to the standard IRAS ultralumimous infrared galaxies (ULIRGs) such as Arp 220.

A similar conclusion can be reached from the intensity of the CO emission. The latter is about 2.5 times smaller than in BR 1202−0725 and BRI 1335−0417. The ratio of the CO intensity to the 1.3 mm continuum flux is thus comparable to BRI 1335−0725, but ∼3 times larger than in BR 1202−0725. The reasons for such differences is not understood.

It is now well appreciated that the derivation of the mass of molecular gas from the CO intensity in such objects is not at all straightforward. Indeed, the CO intensity depends much on the optical thickness of the CO lines and on the excitation conditions of such high J levels. Using the same conversion factor as in Omont et al. (1996a) for the mass of molecular hydrogen from the (5-4) line luminosity (see Solomon et al. 1992a), one obtains $M({\rm H}_2) = 2 \times 10^{10} h^{-2} A^{-1} {\rm M}_\odot$ However, this is certainly an overestimate; the H_2 mass derived this way for ULIRGs with similar CO luminosities (Solomon et al. 1997, Downes et al. 1993, Downes et al. 1998) is too high by about a factor of ∼3. Assuming $h = 0.7$ and $A = 4$, a possible value for the molecular mass of BRI 0952−0115 is thus rather $M({\rm H}_2) \sim$ 2–3 $\times 10^9$ ${\rm M}_\odot$, comparable to the molecular gas mass derived by Downes & Solomon (1998) in ULIRGs, including Arp 220.

5. Conclusion

The detection of BRI 0952−0115 further examplifies that CO is detectable in ULIRGs up to the largest redshifts even with modest gravitational amplifications. One should stress that a source twice fainter than BRI 0952−0115 should be easily detectable with the IRAM interferometer, especially when a sixth antenna is in operation in late 1999. The extreme limit of sensitivity of this instrument will thus practically reach the intensity of unlensed ULIRGs at any redshift.

This detection also strengthens the fact that there is a relatively constant ratio (within a factor ∼3) between the 3mm CO intensity and the 1.3 mm continuum flux of high z sources. It shows that CO can be detected at Bure in the weakest sources currently detectable at 1.3 mm with the IRAM 30-m telescope ($S_{1.3\,{\rm mm}} \sim 3\,{\rm mJy}$). Even a large fraction of the sources currently detected in SCUBA surveys at 0.85 mm, with an equivalent sensitivity at 1.3 mm ∼1 mJy, should be detectable in CO at Bure.

The search of CO in most of the sources detected at 1.3 mm at the 30-m telescope that we observed without success (Table 2), should be addressed again. There is a very good chance that several of them are detectable with reasonably long integrations and better estimates of the redshift. The fact that the CO redshift was found very close to the optical redshift of low ionisation optical lines shows that there is good chance to detect other sources when such correct redshifts are available. It is clear that Q 1230+1627B remains a priority in view of the tentative detection of CO in this source.

Despite the extraordinary progress of molecular detection at the highest redshifts where galaxies are known, the diagnosis of the properties and distribution of the gas and the star formation remains marginal in the absence of strong lensing amplification. The very large improvement of the next generation of millimeter-submillimeter interferometers ALMA will be crucial to really trace molecular gas and star formation in various galaxy contexts at very high redshift, combining observational techniques such as multi-line and multi-species studies, mapping at high spatial resolution and surveys.

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