

LETTER TO THE EDITOR

## Molecular gas in QSO host galaxies at $z > 5$

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### ABSTRACT

We present observations with the IRAM Plateau de Bure Interferometer of three QSOs at  $z > 5$  aimed at detecting molecular gas in their host galaxies as traced by CO transitions. CO (5–4) is detected in SDSS J033829.31+002156.3 at  $z = 5.0267$ , placing it amongst the most distant sources detected in CO. The CO emission is unresolved with a beam size of  $\sim 1''$ , implying that the molecular gas is contained within a compact region, less than  $\sim 3$  kpc in radius. We infer an upper limit on the dynamical mass of the CO emitting region of  $\sim 3 \times 10^{10} M_{\odot} / \sin(i)^2$ . The comparison with the Black Hole mass inferred from near-IR data suggests that the BH-to-bulge mass ratio in this galaxy is significantly higher than in local galaxies. From the CO luminosity we infer a mass reservoir of molecular gas as high as  $M(\text{H}_2) = 2.2 \times 10^{10} M_{\odot}$ , implying that the molecular gas accounts for a significant fraction of the dynamical mass. When compared to the star formation rate derived from the far-IR luminosity, we infer a very short gas exhaustion timescale ( $\sim 10^7$  years), comparable to the dynamical timescale. CO is not detected in the other two QSOs (SDSS J083643.85+005453.3 and SDSS J163033.90+401209.6) and upper limits are given for their molecular gas content. When combined with CO observations of other type 1 AGNs, spanning a wide redshift range ( $0 < z < 6.4$ ), we find that the host galaxy CO luminosity (hence molecular gas content) and the AGN optical luminosity (hence BH accretion rate) are correlated, but the relation is not linear:  $L_{\text{CO}} \propto [\lambda L_{\lambda}(4400 \text{ \AA})]^{0.72}$ . Moreover, at high redshifts (and especially at  $z > 5$ ) the CO luminosity appears to saturate. We discuss the implications of these findings in terms of black hole-galaxy co-evolution.

**Key words.** galaxies: high-redshift – galaxies: ISM – galaxies: quasars: general – infrared: galaxies – submillimeter

### 1. Introduction

The detection of carbon monoxide (CO) emission in high redshift galaxies provides a crucial tool for investigating the early epochs of galaxy formation (see Solomon & Vanden Bout 2005, for a review). Indeed, CO emission is a proxy for the molecular gas content, the reservoir for star formation. The CO line profile also provides information on galaxy kinematics, from which constraints on the dynamical mass can be inferred.

Currently only 9 galaxies have been detected in CO at  $z > 4$ , only three of which are at  $z > 5$ , and all of them host powerful QSOs or radio galaxies Solomon & Vanden Bout (2005). With the exception of the radio-galaxy TN J0924-2201 (Klamer et al. 2005), all of these high- $z$  CO detections were obtained in galaxies pre-selected amongst luminous far-IR sources (as inferred from mm/submm continuum observations). However, such a selection criterion may prevent us from identifying evolutionary effects in terms of molecular gas and dust content in high- $z$  galaxies. Indeed, in local galaxies, CO and FIR luminosities are known to correlate (e.g. Young & Scoville 1991;

Solomon et al. 1997); hence strong far-IR emission may be a pre-requisite for CO detection. However, at  $z > 5$  the ISM is expected to undergo strong metallicity and dust evolution, which may cause high- $z$  galaxies to deviate from the local CO-FIR relation. Another caveat is that present mm/submm detections are close to the sensitivity limit of current cameras; hence even a small scatter in the CO/FIR ratio may lead to a non-detection in  $L_{\text{FIR}}$ .

An additional issue affecting the detection of CO in high- $z$  QSOs is the accuracy of the redshift. Indeed, at  $z > 4$  the emission lines typically observed in the optical band are either strongly blueshifted with respect to the systemic velocity of the host galaxy (such as CIV at 1549 Å and SiIV at 1400 Å, Richards et al. 2002) or, in the case of Ly $\alpha$ , strongly affected by intergalactic gas absorption (Ly $\alpha$  Forest). In these cases the redshift deviations from the systemic velocity can be as large as several thousand km s<sup>-1</sup>. Until recently, millimetre receivers had bandwidths of 0.5 GHz (covering 1500 km s<sup>-1</sup> at the best), limiting the efficiency of the search for CO in sources with such uncertain redshift estimates. This has changed very recently with the

**Table 1.** Summary of physical properties and of the CO observations for the QSOs in our sample.

Name	$z_{\text{MgII/CIII}}$	$S_{\nu}(850 \mu\text{m})$ mJy	$S_{\nu}(1.2 \text{ mm})$ mJy	$L_{\text{FIR}}$ $10^{13} L_{\odot}$	CO trans.	$I_{\text{CO}}$ Jy km s $^{-1}$	$z_{\text{CO}}$	$FWHM$ km s $^{-1}$	$L'_{\text{CO}}$ K km s $^{-1}$ pc $^2$	$M(\text{H}_2)$ $10^{10} M_{\odot}$
J033829.31+002156.3	5.027 <sup>a</sup>	$11.9 \pm 2.0^b$	$3.7 \pm 0.3^b$	1.5 <sup>b</sup>	(5–4)	$0.73 \pm 0.09$	5.0267	500	$2.7 \times 10^{10}$	$2.2 \times 10^{10}$
J083643.5+005453.3	5.774 <sup>c</sup>	$1.7 \pm 1.5^b$	$-0.4 \pm 1.0^g$	<0.4 <sup>b</sup>	(5–4)	<0.41	–	–	$<1.9 \times 10^{10}$	$<1.5 \times 10^{10}$
J163033.90+401209.6	6.065 <sup>d</sup>	$2.7 \pm 1.9^e$	$0.8 \pm 0.6^f$	<0.8 <sup>e</sup>	(6–5)	<0.30	–	–	$<1.0 \times 10^{10}$	$<0.8 \times 10^{10}$

Notes: upper limits are at  $3\sigma$ ; references for the redshift inferred from the low-ionization UV lines, for the  $850 \mu\text{m}$  flux and far-IR luminosity (corrected for our adopted cosmological constants) are: <sup>a</sup> Marinoni et al. (in prep.), <sup>b</sup> Priddey et al. (2003), <sup>c</sup> Stern et al. (2003), <sup>d</sup> Iwamuro et al. (2004), <sup>e</sup> Robson et al. (2004), <sup>f</sup> Bertoldi et al. (2003b), <sup>g</sup> Petric et al. (2003), <sup>h</sup> Carilli et al. (2001).

implementation of new receivers having a much wider bandwidth (e.g. the new receivers at the Plateau de Bure have a bandwidth of 4 GHz). Additionally, one can observe lower ionization lines, such as MgII at  $2798 \text{ \AA}$  and CIII] at  $1909 \text{ \AA}$ , which provide a better redshift estimate, since they are generally shifted by only a few hundred km s $^{-1}$  with respect to the systemic velocity of the host galaxy. At  $z > 4$  such low-ionization lines are shifted into the near-IR, and near-IR spectroscopic campaigns have recently provided accurate redshifts for a number of high- $z$  QSOs.

With the goal of increasing the number of CO detections at  $z > 5$ , and removing any bias towards FIR-luminous sources, we observed three high- $z$  QSOs with the Plateau de Bure Interferometer (PdBI). Here we report the detection of CO emission in one source, and upper limits for the other two. We adopt the following cosmological parameters:  $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_{\Lambda} = 0.73$  and  $\Omega_{\text{m}} = 0.27$  (Spergel et al. 2003).

## 2. Sample selection and observations

The three QSOs were selected from the SDSS catalog to be at  $z > 5$  and observable from the IRAM PdBI. For all, the redshift had been re-determined with MgII or CIII] near-IR spectroscopy, as listed in Table 1. These QSOs were selected regardless of their FIR luminosity, as inferred from previous submm/mm bolometric observations: two of the sources have not been detected in continuum at  $850 \mu\text{m}$  nor at 1.2 mm (Table 1), while J0338+0021 has a detection both at  $850 \mu\text{m}$  and at 1.2 mm, from which  $L_{\text{FIR}} = 1.5 \times 10^{13} L_{\odot}$  is inferred (Priddey et al. 2003). Finally, we note that J0836+0054 is a radio loud QSO (Petric et al. 2003).

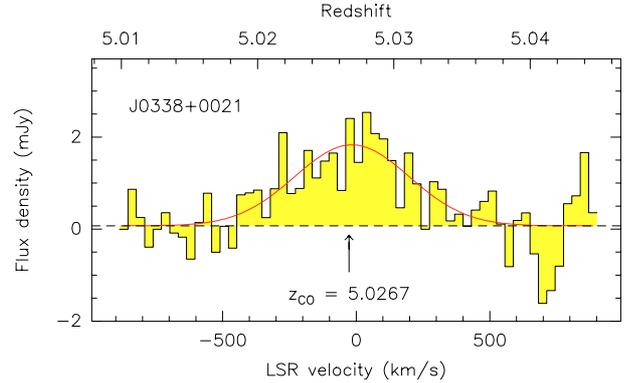
Observations in configuration D were performed between November 2005 and July 2006 with the IRAM PdBI six elements array. The old generation 3 mm receivers were tuned in single sideband to the frequency of the redshifted CO(5–4) or CO(6–5) line, depending on the specific redshift of each source (Table 1). The beam size in D configuration at such frequencies is typically  $\sim 5''$ . The on-source integration times were 11.2 h for J0338+0021, 10.5 h for J0836+0054 and 12.6 h for J1630+4012.

Following the CO detection in J0338+0021 (see next section), this source was also observed in configuration A (with the new PdBI receivers). Observations were obtained in January and February 2007, for a total of 5.9 h on source. The resulting synthesized beam size is  $1.59'' \times 0.76''$  (position angle:  $28^\circ$ ).

The resulting  $1\sigma$  sensitivities are 0.23, 0.34 and 0.26 mJy/beam in channels of  $400 \text{ km s}^{-1}$  for J0338+0021, J0836+0054 and J1630+4012, respectively.

## 3. Results

CO(5–4) is detected in J0338+0021 with a significance of  $8\sigma$ , at a frequency of 95.6191 GHz. This is amongst the most distant CO detections obtained so far, together with



**Fig. 1.** CO(5–4) spectrum of SDSSJ0338+0021 (sum of A and D conf.) rebinned to 10 MHz ( $31.4 \text{ km s}^{-1}$ ). The red line shows a single Gaussian fit to the line. Velocities are relative to the MgII redshift.

SDSS J114816.64+525150.3 at  $z = 6.4$ , TN J0924-2201 at  $z = 5.2$  and SDSS J092721.82+200123.7 at  $z = 5.77$  (Walter et al. 2003; Bertoldi et al. 2003a; Klamer et al. 2005; Carilli et al. 2007). Figure 1 shows the spectrum and Fig. 2 presents the integrated intensity map. The rms per channel of the spectrum in Fig. 1 is 0.55 mJy/beam. We note that the individual spectra taken in A and D configuration are consistent with each other. The redshift inferred from the CO line is  $z = 5.0267 \pm 0.0003$ , i.e. consistent with the MgII redshift (Table 1) within the uncertainty of  $\sim 20 \text{ km s}^{-1}$  on the line center. The absolute position of the CO source is at RA(J2000) = 03:38:29.32 and Dec(J2000) = 00:21:56.1 (accuracy  $< 0.1''$ ), which is consistent with the optical position. The source is spatially unresolved, implying a radius smaller than  $\sim 2.5 \text{ kpc}$  (along the beam minor axis).

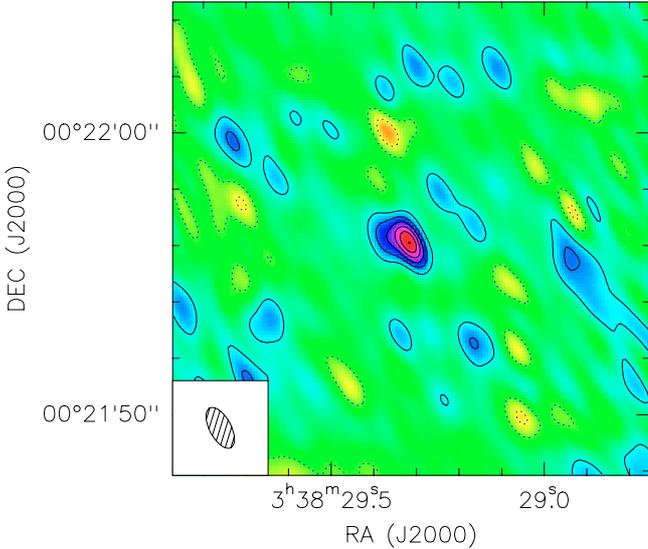
In Table 1 we also report the CO luminosity  $L'_{\text{CO}}$  defined as in Solomon et al. (1997). The millimetric continuum at the location of J0338+0021 is undetected ( $S_{\nu}[95.6 \text{ GHz}] = -18 \pm 85 \mu\text{Jy}$ ); the upper limit is consistent with the extrapolation of the detections at higher frequencies (using the grey body fitting curves with  $T \sim 50\text{--}65 \text{ K}$  in Priddey et al. 2003).

Both J0836+0054 and J1630+4012 (i.e. the two FIR-faint QSOs) were undetected in CO, and Table 1 gives the inferred upper limits on the CO intensity and luminosity (assuming a line width of  $400 \text{ km s}^{-1}$ ).

## 4. Discussion

### 4.1. Gas and dynamical mass

The CO luminosity can be used to infer the molecular gas content. Most authors adopt the conversion factor  $\alpha = 0.8 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$  between CO(1–0) line luminosity and  $M(\text{H}_2)$ , as inferred for nearby starbursts with moderate CO



**Fig. 2.** CO(5–4) cleaned map of SDSSJ0338+0021 (from both configurations A and D) obtained by integrating in velocity from  $-300$  to  $+230$   $\text{km s}^{-1}$  with contours in steps of and starting at  $1\sigma = 0.14$   $\text{Jy beam}^{-1} \text{km s}^{-1}$ .

excitation and in virial equilibrium (Downes & Solomon 1998; Solomon & Vanden Bout 2005). Such a conversion factor may not be appropriate for high- $z$  QSOs, which often show indications of high gas excitation (Bertoldi et al. 2003a; Weiß et al. 2007). We do not have information on the CO transitions lower than (5–4) in J0338+0021, and hence we cannot constrain the gas excitation. Given these uncertainties, we assume the same conversion factor as for local starbursts, and we also assume constant brightness temperature (the optically thick case) from  $J = 1$  to  $J = 5$ , i.e.  $L'_{\text{CO}}(1-0) = L'_{\text{CO}}(5-4)$ . Under these assumptions we infer a molecular gas mass of  $\sim 2.2 \times 10^{10} M_{\odot}$ . Note that this is probably a lower limit on the  $\text{H}_2$  mass, since the transition (5–4) is likely subthermal and the conversion factor probably higher, as inferred in other starburst galaxies and powerful sources (e.g. Bayet et al. 2006; Bradford et al. 2003; Weiß et al. 2007).

The line width and the upper limit on the CO size of J0338+0021 allow us to infer an upper limit on the dynamical mass. Following Tacconi et al. (2006) we derive  $v_c \sin(i)$  (where  $v_c$  is the circular velocity at the outer CO radius, and “ $i$ ” the inclination angle of the gaseous disk) by dividing the CO line  $FWHM$  by 2.4. We obtain  $M_{\text{dyn}} = Rv_c^2/G < 3.2 \times 10^{10} M_{\odot}/\sin^2(i)$ , where we have assumed an upper limit for the size of the CO source of  $1''$  ( $\sim$ average of our beam sizes), hence  $R < 3.2$  kpc. The main uncertainty of the dynamical mass upper limit is due to the unknown inclination angle “ $i$ ”. As discussed in Carilli & Wang (2006), type 1 AGNs may be biased against edge-on host disks, because in such cases the nucleus should be obscured. Such a bias is inferred from the finding that the CO emission in (type 1) QSOs is systematically narrower than in SMGs at similar redshifts. However, we note that in the specific case of J0338+0021 the CO  $FWHM$  is amongst the largest ever observed in QSOs (whose median  $FWHM$  is  $300 \text{ km s}^{-1}$ , Carilli & Wang 2006), and similar to the median  $FWHM$  observed in SMGs ( $500 \text{ km s}^{-1}$ ), suggesting that J0338+0021 is likely observed at high inclination.

Based on these results we conclude that the molecular gas mass accounts for a substantial fraction of the dynamical mass. More specifically, if the system is nearly edge-on ( $i \sim 90^\circ$ ) then

the molecular gas mass accounts for more than 70% of the dynamical mass. Even if the system has an inclination of  $i = 30^\circ$  the molecular gas mass still accounts for more than 20% of the dynamical mass. Such large fractions of molecular gas mass are also observed in local ULIRGs (Sanders & Mirabel 1996) as well as in distant SMGs (Tacconi et al. 2006), and indicate that the host galaxy of J0338+0021 is in an early evolutionary stage.

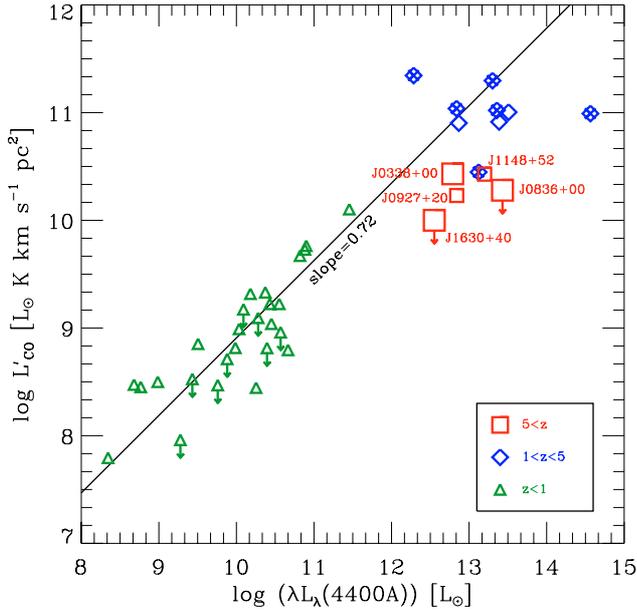
#### 4.2. The black hole-bulge mass ratio at $z \sim 5$

Based on the width of the MgII 2798 Å line and the continuum intensity at  $\lambda_{\text{rest}} = 3000$  Å (Marinoni et al., in prep.), and by following the prescription in McLure & Jarvis (2002), we estimate a black hole mass in this QSO of  $M_{\text{BH}} \approx 2.5 \times 10^8 M_{\odot}$ . We can infer an upper limit on the mass of a putative stellar bulge, by using the upper limit on the dynamical mass obtained above and subtracting the molecular gas mass (and assuming that the bulge is smaller than 3.5 kpc in radius). If the molecular gas disk is nearly edge-on, we derive  $M_{\text{BH}}/M_{\text{bulge}} > 2.5 \times 10^{-2}$ , which is substantially larger than the ratio observed locally, i.e.  $\sim 10^{-3}$  (Marconi & Hunt 2003)<sup>1</sup>. In order to have the lower limit on  $M_{\text{BH}}/M_{\text{bulge}}$  marginally consistent with the local value, the inclination of the gas disk in J0338+0021 must be about  $20^\circ$ , i.e. close to the average value found by Carilli & Wang (2006) for other QSOs with CO detection. However, as discussed above, the very broad CO emission of J0338+0021 relative to other QSOs suggests that the gaseous disk in the former is much more inclined. Moreover, one should keep in mind that the inferred  $M_{\text{BH}}/M_{\text{bulge}}$  is a *lower limit*. It is difficult to obtain more quantitative constraints without higher resolution and higher sensitivity data. However, the current observations suggest that the  $M_{\text{BH}}/M_{\text{bulge}}$  at high- $z$  is higher than observed locally. This result is in agreement with the  $M_{\text{BH}}/M_{\text{bulge}}$  ratio inferred for the most distant QSO J1148+5251 at  $z = 6.4$  by Walter et al. (2004). Other indications of a higher, with respect to local,  $M_{\text{BH}}/M_{\text{bulge}}$  mass ratio were found by Peng et al. (2006) and McLure et al. (2006) in  $z > 1$  AGNs. All of these results suggest that BH growth occurred on timescales shorter than bulge formation, and that the locally observed BH-bulge relation was achieved only at  $z < 1$ .

#### 4.3. Star formation efficiency

The far-IR emission is regarded as a tracer of the star formation rate (Kennicutt 1998). In QSOs the possible contamination by dust heated by the AGN has been a hotly debated issue; however recent observations have shown that at least in the *far-IR*, the emission is generally due to star formation even in the case of powerful QSOs (Schweitzer et al. 2006; Lutz et al. 2007; Wang et al. 2007). In J0338+0021 the observed  $L_{\text{FIR}} = 1.5 \times 10^{13} L_{\odot}$  implies a star formation rate of  $\sim 2500 M_{\odot} \text{ yr}^{-1}$ , if using the  $L_{\text{FIR}}$ -to-SFR conversion factor derived by Kennicutt (1998).  $L_{\text{FIR}}/L'_{\text{CO}}$  is considered a measure of the star formation efficiency, since it is related to the star formation rate per unit of molecular gas mass (Solomon & Vanden Bout 2005).  $L_{\text{FIR}}/L'_{\text{CO}}$  is found to steadily increase with luminosity (e.g. Solomon et al. 1997), which is interpreted as an increasing star formation efficiency in the most powerful starburst systems. J0338+0021 has a very high  $L_{\text{FIR}}/L'_{\text{CO}}$  ratio, implying very high star formation efficiency. More specifically, in J0338+0021, the whole molecular

<sup>1</sup> The value of  $M_{\text{BH}}/M_{\text{bulge}} \sim 0.002$  given in Marconi & Hunt (2003) has to be lowered by a factor of 5/3 to account for more recent estimates of the bulge virial masses (Marconi, priv. comm.).



**Fig. 3.**  $L'_{\text{CO}}$  versus (nuclear)  $\lambda L_{\lambda}(4400 \text{ \AA})$  for type 1 AGNs with CO measurements. Green triangles are sources at  $z < 1$ , blue diamonds are sources at  $1 < z < 5$ , red squares are sources at  $z > 5$ . Large squares indicate the new measurements at  $z > 5$  reported in this paper. Crosses mark strongly lensed QSOs, for which differential magnification of the nuclear optical emission and CO emission in the host galaxy may occur. The black solid line indicates a linear fit to the data at  $z < 1$ . Note the non-linearity of the relation and the likely flattening of the relationship at high redshift and high optical luminosities.

gas content is expected to be converted into stars on a time scale of only  $\sim 10^7$  yrs, i.e. a few times the dynamical timescale within the CO radius ( $t_{\text{dyn}} = R/v_c < 1.5 \times 10^7$  yr). Cases like J0338+0021 are rare but not unique; indeed similar “maximal starburst” systems are found among other hyper-luminous infrared galaxies at lower redshift, both QSOs and starbursts (e.g. Tacconi et al. 2006).

#### 4.4. Black hole accretion and molecular gas reservoir

If we focus on type 1 (unobscured) AGNs, it is interesting to compare the molecular gas content, as traced by  $L'_{\text{CO}}$ , with the optical luminosity, the latter being proportional to the Black Hole accretion rate. For type 1 AGNs with CO measurements (from Sanders et al. 1991; Evans et al. 2006; Solomon et al. 1997; Solomon & Vanden Bout 2005; Maiolino et al. 1997), we have derived the rest-frame optical luminosity ( $\lambda L_{\lambda}(4400 \text{ \AA})$ ) by using spectroscopic or photometric data available from the literature at the observed wavelength closest to  $(1+z)4400 \text{ \AA}$  (generally near-IR data for QSOs at high redshift). For nearby Sy1 we considered only objects with nuclear measurements of the optical flux, to minimize the stellar light contamination. Figure 3 shows  $L'_{\text{CO}}$  as a function of  $\lambda L_{\lambda}(4400 \text{ \AA})$ , where sources in different redshift ranges are identified by different symbols and colors. Objects marked by a cross are strongly lensed QSOs: in these cases differential magnification may occur between nuclear optical emission and CO emission in the host galaxy<sup>2</sup>. CO and optical luminosity clearly correlate, but the relation is non-linear.

<sup>2</sup> Note that high angular resolution observations rule out significant lensing for all of the QSOs at  $z > 5$  considered here (Richards et al. 2006, 2004; Frey et al. 2005; White et al. 2005), with exception of J1630+4012 for which no high angular resolution data are available.

More specifically, by fitting the low- $z$  data ( $z < 1$ ) alone, we obtain

$$\frac{L'_{\text{CO}}}{L_{\odot} \text{ K km s}^{-1} \text{ pc}^2} = 51.8 \times \left[ \frac{\lambda L_{\lambda}(4400 \text{ \AA})}{L_{\odot}} \right]^{0.72 \pm 0.08}. \quad (1)$$

High- $z$  QSOs show indications for further flattening of the relation at high luminosities. In particular, QSOs at  $z > 5$  hint at a possible saturation of the CO luminosity at a few times  $10^{10} L_{\odot} \text{ km s}^{-1} \text{ pc}^2$ .

The correlation between BH accretion rate ( $\lambda L_{\lambda}(4400 \text{ \AA})$ ) and molecular gas content in the host galaxy ( $L'_{\text{CO}}$ ) may be at the origin of the correlation between BH mass and stellar bulge mass observed in local galaxies (e.g. Ferrarese & Merritt 2000; Marconi & Hunt 2003). The non-linearity of the relation is probably a consequence of the fact that, while BH accretion can be arbitrarily high (limited only by the Eddington luminosity), the molecular gas content is limited by the galaxy evolutionary processes. In particular, the saturation of the CO luminosity in sources at  $z > 5$  may indicate that galaxy evolutionary mechanisms cannot assemble more than a few times  $10^{10} M_{\odot}$  of gas in such early evolutionary phases of galaxy formation. Such results are consistent with the finding of a saturation also in terms of star formation rate in high- $z$ , luminous QSOs (Maiolino et al. 2007).

Regardless of their interpretation, these results may explain the low galaxy-to-BH mass ratio observed in high- $z$  QSOs (especially at  $z = 6.4$ ), relative to local galaxies (Sect. 4.2).

#### 4.5. Low FIR/CO ratios are not common amongst high- $z$ , luminous sources

The detection of CO (5–4) and (1–0) in the far-IR weak (submm undetected) radio galaxy TNJ0924-2201 at  $z = 5.2$  by Klamer et al. (2005), suggested the possible existence of a significant population of high- $z$  sources with large reservoirs of molecular gas but with little dust emission. These could be cases where dust had little time to form, or whose average dust temperature is extremely cold. However, the non-detection of CO in the two far-IR faint QSOs in our sample does not provide additional support for the existence of a large population of such objects, and TNJ0924-2201 remains the only case of exceptionally low  $L_{\text{FIR}}/L_{\text{CO}}$  (about a factor of 5 lower than sources with similar CO luminosity). As a consequence, strong far-IR emission seems to generally be a prerequisite for CO detection at high redshift. Of course the statistics are still extremely poor, and more observations are required to investigate this. Moreover, we cannot rule out the possibility that in the two QSOs without CO detection the low-ionization UV lines provide a redshift which is offset by more than  $1000 \text{ km s}^{-1}$  (which would move the CO line out of the old 3 mm receiver band), although MgII has a velocity generally consistent with the systemic velocity within at most a few hundred  $\text{km s}^{-1}$  (Vanden Berk et al. 2001; Richards et al. 2002), and our result on J0338+0021 supports this scenario.

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