CO(1–0) line imaging of massive star-forming disk galaxies at $z = 1.5 - 2.2$

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ABSTRACT

We present detections of the CO($J = 1–0$) emission line in a sample of four massive star-forming galaxies at $z \sim 1.5 - 2.2$ obtained with the Karl G. Jansky Very Large Array (VLA). Combining these observations with previous CO(2–1) and CO(3–2) detections of these galaxies, we study the excitation properties of the molecular gas in our sample sources. We find an average line brightness temperature ratios of $R_{21} = 0.70 \pm 0.16$ and $R_{31} = 0.50 \pm 0.29$, based on measurements for three and two galaxies, respectively. These results provide additional support to previous indications of subthermal gas excitation for the CO(3–2) line with a typically assumed line ratio $R_{31} \sim 0.5$. For one of our targets, BzK-21000, we present spatially resolved CO line maps. At the resolution of $0.18''$ (1.5 kpc), most of the emission is resolved out except for some clumpy structure. From this, we attempt to identify molecular gas clumps in the data cube, finding 4 possible candidates. We estimate that $< 40\%$ of the molecular gas is confined to giant clumps ($\sim 1.5$ kpc in size), and thus most of the gas could be distributed in small fainter clouds or in fairly diffuse extended regions of lower brightness temperatures than our sensitivity limit.

Key words: galaxies: ISM – galaxies: high-redshift – galaxies: evolution

1 INTRODUCTION

The physical processes behind gas supply, and subsequent star formation, in early galaxies, remain key uncertainties in our understanding of galaxy formation. Study of the demographics and gas depletion timescales show that most star forming galaxies at $z > 1$ form a tight correlation between their star formation rates (SFR) and stellar masses. Such correlation, usually termed as the ‘main-sequence’ of galaxies, suggests that the star formation is typically a long-lived process, likely occurring over timescales of $\sim 0.7$ Gyr (e.g., Daddi et al. 2005, 2007). Major gas rich mergers, typically lying above such main-sequence, are unlikely to be the primary driving mechanism for such continuous star formation, since they would lead to short timescale, nuclear starbursts as it is seen in local Ultra Luminous IR Galaxies (ULIRGs; e.g., Solomon et al. 1997; Downes & Solomon 1998).

Two of the major challenges for understanding the mechanisms of gas accretion and stellar build up in these galaxies is to spatially and kinematically resolve the star formation and molecular gas components down to kpc scales (Shapiro et al. 2008), as well as targeting several molecular gas emission lines in order to characterize the physical state of the interstellar medium (ISM; Carilli & Walter 2013). High-resolution observations of the ionized gas (Hα) kinematics and the stellar component have shown that a majority of these galaxies are consistent with clumpy rotating disks with sizes of order 10 kpc (Genzel et al. 2006, 2008).
Förster Schreiber et al. [2009, 2011]. However, these observations do not directly trace the cold molecular gas from which stars are formed, and could be prone to obscuration within the host galaxy. Direct high resolution observations of the molecular gas are thus necessary.

Recently, observations of the molecular gas, through CO line emission, in optical/IR color-selected star-forming galaxies at $z = 1 - 3$ have revealed significant molecular gas reservoirs, comparable to their stellar component ($\sim 10^{10} \ M_\odot$) in systems which typically show SFRs in the range $50 - 400 \ M_\odot \ yr^{-1}$ (Daddi et al. 2008, 2010a; Tacconi et al. 2010, 2013). This indicated that these galaxies have low star formation efficiencies and long gas depletion timescales, compared to that seen in extreme starbursting submillimeter galaxies (SMGs) and quasars, and suggest their integrated properties may follow a different star-formation law (Daddi et al. 2010a; Genzel et al. 2010). Furthermore, their implied CO luminosity to gas mass conversion factors resemble local disk galaxies (Daddi et al. 2010a; Magdis et al. 2011, 2012; Magnelli et al. 2012).

These studies, however, focused on the observation of $J > 1$ CO line emission. One of the major assumptions encountered when observing $J > 1$ CO lines in main-sequence galaxies has been the adoption of an “average” constant ratio between the $J > 1$ CO line and CO(1-0). Determination of these ratios are required in order to convert the high-J CO line luminosities into CO(1-0) luminosities, for which the conversion factors of CO luminosity to gas mass have been calibrated (Bolatto et al. 2013). Thus, observations of the CO(1-0) line in statistical samples of star-forming galaxies at $z > 1$ are necessary for calibrating such line ratios.

As Bauermeister et al. point out, calibration of the line ratios is particularly important for the CO(3-2) line for two main reasons: (1) this line ($v_{\text{rest}} = 345.538 \ GHz$) is shifted to the 2mm and 3mm atmospheric windows at $z = 1 - 3$, being directly accessible with the most powerful (sub)millimeter facilities that can easily access these kind of galaxies, namely the Atacama Large Millimeter/submillimeter Array (ALMA) and the Plateau de Bure Interferometer (PdBI). Hence, observations of the CO(3-2) line will (and have) become routine and constitute the first direct attempt to characterize the molecular gas properties of these objects (e.g., Tacconi et al. 2010, 2013); (2) The cosmic time spanned by redshifts $z = 1 - 3$, 6 Gyr, corresponds to the important period when most of the stars in the Universe where created and where most of the galaxies were assembled.

To date, only a few main-sequence galaxies at cosmological distances ($z > 0.1$) have observations in two or more CO lines (Dannerbauer et al. 2009; Aravena et al. 2011; Bauermeister et al., 2013), and generally only a handful of these main-sequence galaxies have spatially resolved CO observations down to < 10 kpc scales (Tacconi et al. 2013; Genzel et al. 2013). Follow-up CO(1-0) observations of three representative $z \sim 1.5$ galaxies in the CO(1-0) line emission suggest that the molecular gas in these systems is already sub-thermally excited at the CO(3-2) transition similar to what is found in local disks (Dannerbauer et al. 2009; Aravena et al. 2011), with typical line brightness temperature ratios between both lines of $\sim 0.5$. This is also similar to what is found in SMGs (Harris et al. 2011; Ivison et al. 2011; Bothwell et al. 2013), but substantially different to high-redshift QSOs, which appear to have highly excited gas with line temperature ratios close to unity (Riechers et al. 2006; Weiß et al. 2007; Ao et al. 2008; Riechers et al. 2011a; Ivison et al. 2012, e.g.). Recent observations of $z \sim 0.3$ disk galaxies support these findings, indicating that the molecular gas content, as traced by CO(1-0), is two times larger than expected from $J > 3$ CO measurements, comparable to $z > 2$ SMGs (Papadopoulos & Ivison 2002, Harris et al. 2010; Ivison et al. 2011; Riechers et al. 2011d).

In this paper, we present observations of the CO(1-0) emission line in four main-sequence star forming galaxies at $z \sim 1.5 - 2.2$ obtained with the Karl G. Jansky Very Large Array (VLA). The angular resolution of our observations for one of these sources, 0.18”, allows us to spatially resolve the distribution of the molecular gas. The new correlator system at the VLA permits us to expand the bandwidth and velocity resolution of the previous CO(1-0) detections in three of our targets, and to detect the CO emission in a new object at $z = 2.2$. We adopt a standard ΛCDM cosmology throughout (Komatsu et al. 2011).

2 OBSERVATIONS

2.1 BzK-21000

Observations of the $^{12}$CO($J=1$–$1$) emission line ($v_{\text{rest}} = 115.2712 \ GHz$) of this galaxy were made simultaneously while observing the CO(2–1) emission line in the bright $z = 4.05$ SMG, GN20 (VLA project: AC974). Description of these observations are presented in detail in Hodge et al. (2012). In summary, observations were carried out in D and B array configuration during 2010 March-April (D-configuration) and 2011 February-April (B-configuration). At the redshift of BzK-21000, $z_{\text{CO}} = 1.5213$ (Daddi et al. 2010a), the CO(1-0) line is shifted to 45.7184 GHz. The WIDAR correlator was configured with two spectral windows (SPWs) of 64 channels and 2 MHz per channel resolution. The SPWs were centered at 45.592 and 45.720 GHz for a total bandwidth of 246 MHz. The difference in total bandwidth with respect to 2 CO line is $2.1 \text{BzK-21000}$ obtained with the Karl G. Jansky Very Large Array (VLA). The angular resolution of our observations for one of these sources, 0.18”, allows us to spatially resolve the distribution of the molecular gas. The new correlator system at the VLA permits us to expand the bandwidth and velocity resolution of the previous CO(1-0) detections in three of our targets, and to detect the CO emission in a new object at $z = 2.2$. We adopt a standard ΛCDM cosmology throughout (Komatsu et al. 2011).

Similarly, the pointing center was selected to cover all 4 galaxies, such that the flux scaling multiplicative factor needed for primary beam correction at the location of BzK-21000 was 1.33.

The nearby quasar J1302+5748 was used for gain and pointing calibration and the source J1331+0300 (3C286) served as flux and bandpass calibrator. The data was calibrated using the Astronomical Image Processing System (AIPS; Greisen 2003) and the Common Astronomy Software Application (CASA) package (McMullin et al. 2007). Time ranges with poor visibilities as well as edge channels where the bandpass deteriorated (at each edge) were flagged. The data was imaged using the CLEAN algorithm in CASA. All images were accordingly primary beam corrected. We used a briggs weighting scheme, cleaning down to 2σ in a tight box ($\sim 2.5''$ in size) around our target and setting the
trying several weighting schemes, we chose Briggs weighting with a robust parameter of 1.0. This approach minimized negative noise peaks in the image when averaging channels across the CO line, while retaining good sensitivity. In the case of BzK-4171, we applied a further taper of 1.7′′ to increase the sensitivity toward extended sources (although the actual rms of the map is higher). We used a box around the source of ∼5′′ in size, cleaning down to 2σ. The obtained sensitivities and beam sizes are summarized in Table 1.

### 2.3 BX610

Observations of the CO(1–0) emission line in BX610 were performed from October 2011 to November 2011 in D-array...
Table 2. Observed properties of the high-redshift star-forming galaxies

| Source     | $z_{\text{CO}}$ | $v_{\text{FWHM}}$ | $I_{\text{CO}}$ | $L_{\text{CO}}$ | $M_{\text{gas}}$ | SFR | SFE | $R_{21}$ | $R_{31}$ |
|------------|-----------------|-------------------|-----------------|-----------------|-----------------|-----|-----|---------|---------|
| BzK-21000  | 1.5204 (3)      | 435 ± 98          | 0.20 ± 0.05     | 2.39 ± 0.60     | 0.86 ± 0.21     | 210 | 88  | 0.80 ± 0.27 | 0.39 ± 0.24 |
| BzK-4171   | 1.464 (3)       | 410 ± 200         | 0.22 ± 0.07     | 2.45 ± 0.78     | 0.88 ± 0.28     | 95  | 38  | 0.77 ± 0.35 | 0.47 ± 0.35 |
| BzK-16000  | 1.524 (2)       | 217 ± 80          | 0.20 ± 0.06     | 2.40 ± 0.72     | 0.86 ± 0.26     | 74  | 30  | 0.58 ± 0.25 | 0.38 ± 0.25 |
| BX610      | 2.2105 (3)      | 240 ± 70          | 0.18 ± 0.04     | 4.28 ± 1.08     | 1.54 ± 0.39     | 212 | 50  | –       | 0.58 ± 0.21 |

Notes: $^a$ CO(1–0) redshift. The parenthesis corresponds to the uncertainty associated to the last digit in this measurement; $^b$ Measured CO line full-width at half maximum (FWHM); $^c$ Spatially and velocity integrated CO line flux $I_{\text{CO}} = S_{\text{CO}} v$; $^d$ CO luminosity in units $L_\odot = 10^{10}$ K km s$^{-1}$ pc$^2$; $^e$ Gas mass obtained using $\alpha_{\text{CO}} = 3.6$ (K km s$^{-1}$ pc$^2$)$^{-1}$, in units $m_\odot = 10^{12}(\alpha_{\text{CO}}/3.6)$ M$\odot$; $^f$ Star formation rates (SFRs) derived from Herschel IR observations (Magdis et al. 2012), and UV/24µm measurements for BX610 (Tacconi et al. 2013). The associated uncertainties amount to $\sim$30%. We assume a conversion SFR = $10^{-10}$L$_{\text{IR}}$ and a Chabrier (2003) Initial Mass function. $^g$ Star formation efficiency derived from the CO(1–0) observations, defined as SFE = $L_{\text{IR}}/L_{\text{CO}}$ in units of $L_\odot = L_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$; $^h$ Observed brightness temperature line ratios between the CO(3–2) and CO(2–1) with respect to the CO(1–0) line, where $R_{21} = T_{21}/T_{10} = I_{21}/I_{10} \times (v_{10}/v_{21})^2$ and similarly for $R_{31}$.

Figure 2. VLA CO(1–0) maps averaged over 500, 200 and 300 km s$^{-1}$ for BzK-4171, BzK-16000 and BX-610. Contour levels are given in steps of $\pm 1 \sigma$, starting at $\pm 2 \sigma$, with $\sigma \approx 76, 100$ and 39 µJy beam$^{-1}$ for each galaxy, respectively. The + symbols indicate the VLA 1.4 GHz position for the BzK galaxies (Morrison et al. 2010), and the optical position for BX610 (Erb et al. 2006; Förster Schreiber et al. 2009). The $\times$ symbol shows the CO(3–2) position for BX610 (Tacconi et al. 2013).

3 RESULTS AND ANALYSIS

CO(1–0) line emission is detected in all galaxies in the sample. Figures 1, 2 and 3 show the obtained CO maps and respective spectra. Table 2 summarizes the results.
with the exception of BzK-21000, where the difference is at the 1.4σ level \cite{Aravena2010}. This suggests that such offsets have only a minor effect in the final CO intensities. Also, as shown in Fig. 2, the CO(1–0) peak position is in agreement with the CO(3–2) position for BX610.

Figure 3 shows the CO(1–0) spectra obtained for all sources. In the case of BzK-21000, where the emission is clearly resolved into more than a single component, we plot the spatially integrated spectrum. Since we are not resolving the CO emission in the other objects at the significance of the detections, we show the spectra at the peak position for these cases. By fitting a single Gaussian to the spectra we find the CO redshifts and line-widths listed in Table 2. The latter compares well with the line profiles shown by \cite{Daddi2010a} and \cite{Tacconi2013}, however, any difference should not significantly affect our estimate of the CO integrated intensity, as it corresponds to the integral along the spectra from the moment-0 map.

### 3.1 CO luminosities and gas masses

We derive CO luminosities through $L'_\text{CO} = 3.25 \times 10^7 (1 + z)^{-3} \nu_{\text{obs}} D_\text{L} I_{\text{CO}}$, where $D_\text{L}$ is the luminosity distance at redshift $z$, in Mpc, $\nu_{\text{obs}}$ is the observing frequency, in GHz, and $I_{\text{CO}}$ is the line intensity in Jy km s$^{-1}$ \cite{Solomon1997}. Using the measured CO line intensities, we obtain the CO luminosities listed in Table 2.

To estimate the gas masses from CO measurements, a conversion factor between CO luminosity and gas mass, $\alpha_{\text{CO}}$ is commonly used (in units $M_\odot [\text{K km s}^{-1} \text{pc}^2]^{-1}$) such that $M_{\text{gas}} = \alpha_{\text{CO}} L'_\text{CO}$. Local Ultra-Luminous Infrared Galaxies (ULIRGs) were found to be consistent with $\alpha_{\text{CO}} = 0.8$ \cite{Downes1998}, however, in the Milky Way this factor was found to be 4.36 (e.g., \cite{Bolatto2013}). The latter is consistent with recent findings that suggest $\alpha_{\text{CO}} = 3.6$ in $z \sim 1.5$ disk galaxies \cite{Daddi2010a}, however its actual value appears to be dependent on metallicity and highly uncertain (e.g., \cite{Genzel2012}). Individual values of $\alpha_{\text{CO}}$ for the BzK galaxies range from $\sim 2.5$ to $4.0$ with typical uncertainties of $\pm 1.4$ \cite{Daddi2010a}.

Since most of our targets correspond to the ones used by Daddi et al. to derive this conversion factor, we adopt $\alpha_{\text{CO}} = 3.6$ throughout. The molecular gas masses obtained thereby are listed in Table 2.

### 3.2 Line ratios

Assuming the CO lines can be approximated in the Rayleigh-Jeans (RJ) limit, we can estimate the ratio between the CO(2–1) and CO(1–0) as $R_{21} = T_{21}/T_{10} = I_{21}/I_{10} \times (\nu_{10}/\nu_{21})^2$, where $T_{21}$ and $T_{10}$ are the brightness temperatures of the CO(2–1) and CO(1–0) lines, $I$ correspond to the CO line intensities, and $\nu_{21}$ and $\nu_{10}$ are the rest-frame CO line frequencies. Similarly, for the ratio between CO(3–2) and CO(1–0) we have $R_{31} = T_{32}/T_{10} = I_{32}/I_{10} \times (\nu_{10}/\nu_{32})^2$. The corresponding line ratios thereby obtained are listed in Table 2.

For local thermodynamic equilibrium (LTE) of the molecular gas, we would expect $R_{11} = 1$. However, in all cases we find that the ratios $R_{21}$ and $R_{31}$ are below unity, indicating that the gas is already sub-thermally excited at the CO(2–1) line. In the cases of BzK-4171 and BzK-16000, the new observations confirm within the uncertainties the previously derived values for $R_{21}$ \cite{Dannerbauer2000, Aravena2010}. In the case of BzK-21000, the larger CO(1–0) intensity measured, compared to the previous measurements \cite{Aravena2010}, imply a lower $R_{21}$ value yet still consistent with both lines being close to LTE. From these, we find a noise weighted average ratio between the 3 galaxies $R_{21} = 0.70 \pm 0.16$. For the two galaxies with CO(3–2) measurements, we derive a noise weighted average $R_{31} = 0.50 \pm 0.29$, where the quoted uncertainty includes the errors in the line ratio measurements ($\delta = +0.16$) and the scatter around the average ratio ($\delta = +0.13$).

### 3.3 Star-formation efficiencies

The SFR per unit mass of molecular gas, or the inverse of the gas depletion timescale, is usually taken as a measure of the star formation efficiency, $\text{SFE} = \text{SFR}/M_{\text{gas}}$. Given the large uncertainties in the calibrations when obtaining SFRs from IR luminosities and molecular gas masses from CO luminosities (the $\alpha_{\text{CO}}$ factor), a proxy for the SFE has also been defined as the ratio between the IR luminosity and the CO(1–0) luminosity, with $\text{SFE} = L_{\text{IR}}/L'_\text{CO}$ in units of $L_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$. The SFEs for our sample are listed in Table 2. As an effect of the revision in the line ratios in the previous section, the SFEs appear to be slightly lower than previously reported for these galaxies, yet well within the range found for local spiral galaxies with SFEs ranging...
from 10 to 100 $L_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$ (e.g., Lescow et al. 2008). SFE values for ULIRGs and distant SMGs typically exceed 100 $L_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$ (e.g., Yao et al. 2003; Neri et al. 2003; Greve et al. 2003; Bouché et al. 2007).

4 DISCUSSION

4.1 Gas excitation

Even though we only have two sources with $R_{31}$ values measured, and clearly more measurements are needed, our results support the typically assumed line ratio $R_{31} = 0.5$. However, this also suggests that individual ratios can span a significant range from $\sim 0.4$ to $0.6$, and possibly larger given the uncertainties. Thus, while it is valid in a statistical sense to assume a constant value for this ratio, such an assumption may not necessarily be applicable to individual cases. This uncertainty can be considered to be relevant and at the same level of other involved sources of uncertainty such as low significance of CO detections, the $\alpha_{\text{CO}}$ conversion factor, etc.

Our average $R_{31}$ value compares well with the average ratio $R_{31} = 0.46 \pm 0.07$ found for three disk galaxies at $z \sim 0.3$ (Bauermeister et al. 2013), which have SFRs of 40–60 $M_\odot$ yr$^{-1}$. Such low gas excitation has also been found in some SMGs at $z \sim 2$, with an average value of $R_{31} \sim 0.5 - 0.6$ (Harris et al. 2011; Ivison et al. 2011; Riechers et al. 2011a; Danielson et al. 2011; Bothwell et al. 2011; Spilker et al. 2011). However, these line ratios might be the result of CO$(1-0)$ being more spatially extended than higher-J CO lines with the line ratios being considerably higher in their centers. Distant quasar host galaxies (and radio galaxies) appear to be mostly thermalized at the CO$(3-2)$ line (e.g., Riechers et al. 2011a; Ivison et al. 2008, 2012), highlighting the role of AGN in molecular gas excitation in the host galaxy. This suggest that in disks and SMGs the gas excitation, and thus $R_{31}$, might be more influenced by star formation activity that it is in quasar host galaxies where the powerful AGN may play a more important role in gas heating.

4.2 Finding clumps in CO data: BzK-21000

The high resolution achieved in the observations of BzK-21000 enables us to look for bright compact CO clumps. While the map tapered to 1.1” resolution only reaches a significance of $\sim 4.5\sigma$ for the integrated CO emission of the galaxy, compact clumps with larger brightness temperatures ($T_B$) might be identified in the high resolution CO data cube.

We searched for clumps using the AIPS task SERCH, which carries out a matched-filter analysis using a Gaussian kernel to convolve the data cube along the frequency axis with an expected input line width, and thereby searches for regions with a significance over a specified limit. This method has been used for source finding in a number of studies (e.g., Hodge et al. 2012). The expected size of the molecular clumps range from 0.3–1.0 kpc based on the size of star forming and stellar clumps from observations (e.g., Swinbank et al. 2010; Jones et al. 2010; Förster Schreiber et al. 2011) and numerical simulations (e.g., Bournaud et al. 2007; Elmegreen et al. 2008; Dekel et al. 2009). We thus use a data cube in the native angular resolution of 0.18”, or 1.5 kpc at $z = 1.52$ (slightly larger than the expected clump size) and channel width of 52 km s$^{-1}$. We searched for clumps within a region of 3.0” $\times$ 3.0” centered at the VLA radio position of BzK-21000 (Morrison et al. 2010), utilizing Gaussian kernels in the range $\sim 50$ to 200 km s$^{-1}$ in steps of 2 channels ($\sim$ 50 km s$^{-1}$) with a signal-to-noise cut at $S/N = 4$. As a cross check, we independently inspected the data cube and manually searched for bright knots. We find that 4 line candidates can be identified in this way. Based on the number of negative peaks in the cube, however, we expect that 2 of these candidate clumps are false detections.

Figure 4 shows the spatial location of each of the identified CO knots in the cube compared to the optical and average CO images of BzK-21000. Figure 5 shows the CO profiles for each of these candidates. Only one of the iden-
CO(1–0) in star-forming galaxies at $z \sim 2$

5 CONCLUSIONS

We have presented detections of the CO(1–0) line emission in four massive star-forming galaxies in the redshift range $z = 1.5 - 2.2$. Our observations allow us to confirm previous measurements of the brightness temperature line ratio between the CO(2–1) to CO(1–0) lines in three BzK galaxies. We measure average line ratios of $R_{21} = 0.70 \pm 0.16$ (based on the 3 BzK galaxies) and $R_{31} = 0.50 \pm 0.29$ (based on two objects). These findings indicate that the molecular gas is, on-average, likely sub-thermally excited already in the CO(2–1). We find that the gas is sub-thermal in both cases at the CO(3–2) line, and support the widely assumed line ratio $R_{31} = 0.5$ (Tacconi et al. 2010, 2013; Genzel et al. 2013). Since $R_{31}$ ranges from $0.4$ to $0.6$, we note that care must be exercised in assuming the average line ratio for individual cases.

Finally, we took advantage of the high angular resolution achieved for BzK-21000, and searched for gas clumps in the CO data cube. We found 4 clump candidates with estimated gas masses that can account for up to 40% of the total molecular gas mass of this system.

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