Are $^{12}$CO lines good indicators of the star formation rate in galaxies?

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ABSTRACT

In this paper, we investigate the relevance of using the $^{12}$CO line emissions as indicators of star formation rates (SFR). For the first time, we present this study for a relatively large number of $^{12}$CO transitions (12) as well as over a large interval in redshift (from $z\approx 0$ to $z\approx 6$). For the nearby sources ($D\leq 10$ Mpc), we have used homogeneous sample of $^{12}$CO data provided by Bayet et al. (2004, 2006), mixing observational and modelled line intensities. For higher-z sources ($z \geq 1$), we have collected $^{12}$CO observations from various papers and have completed the data set of line intensities with model predictions which we also present in this paper. Finally, for increasing the statistics, we have included recent $^{12}$CO(1-0) and $^{12}$CO(3-2) observations of intermediate-z sources. Linear regressions have been calculated for identifying the tightest SFR-$^{12}$CO line luminosity relationships. We show that the total $^{12}$CO, the $^{12}$CO(5-4), the $^{12}$CO(6-5) and the $^{12}$CO(7-6) luminosities are the best indicators of SFR (as measured by the far-infrared luminosity). Comparisons with theoretical approaches from Krumholz and Thompson (2007) and Narayanan et al. (2008) are also performed in this paper. Although in general agreement, the predictions made by these authors and the observational results we present here show small and interesting discrepancies. In particular, the slope of the linear regressions, for $J_{\text{upper}} \geq 4$ $^{12}$CO lines are not similar between theoretical studies and observations. On one hand, a larger high-J $^{12}$CO data set of observations might help to better agree with models, increasing the statistics. On the other hand, theoretical studies extended to high redshift sources might also reduce such discrepancies.

Key words: Galaxies: starburst-nuclei-ISM – Submillimeter – ISM: molecules – infrared:galaxies

1 INTRODUCTION

Fifty years ago, it has been showed that the star formation rate (hereafter SFR) is intimately linked with the reservoir of the gas from which stars are forming (Schmidt 1959). The Kennicutt-Schmidt power law parameterized on local galaxies by Kennicutt (1998a,b); Kennicutt et al. (2007) has led to an SFR index of $N=1.4\pm 0.15$. Since late 90s, researchers have converted the Kennicutt-Schmidt law into a more interesting relationship connecting the SFR (traced by the infrared luminosity - hereafter $L_{\text{IR}}$) to the mass of molecular gas, investigating various molecular tracers. Firstly, Sanders et al. (1991); Sanders & Mirabel (1996) have shown that the SFR is roughly proportional to the $^{12}$CO($J=1$-0) line (hereafter CO(1-0)) luminosity (slope of 1.4-1.6, consistent with the Kennicutt-Schmidt law index). This SFR-CO(1-0) relationship has been broadly interpreted as an increase of star formation efficiency as a function of molecular gas mass (and density). More recent analysis focussing on tracers of dense molecular gas such as the HCN(1-0) line (Gao & Solomon 2004a,b; Wu et al. 2005), the HCN(3-2) line (Bussmann et al. 2008) or the CO(3-2) line (Yao et al. 2003; Narayanan et al. 2005), have shown that these transitions are likely to be better indicators of star formation rate than the total H$_2$ content (traced by the CO(1-0) luminosity). Indeed, the CO(1-0) line can be excited at rather low densities ($\sim 10^2$ – $10^3$ cm$^{-3}$) and low temperature ($\sim$ 5K above ground) whereas the higher-J CO transitions and the HCN lines trace denser and warmer gas, more closely connected
with the stars in formation. However, recent modelling work (Krumholz & Thompson 2007; Narayanan et al. 2008) show that this situation is more complex than it appears, involving in particular the values of the molecular line critical densities as compared with the mean gas density of the observed regions.

So far, none of observational or modelling work investigate the relationship between the SFR and molecular gas tracers both for several transitions (>2) of the same molecule (here CO) and over several factors of redshift (here \( z \approx 0-6 \)). In this paper, the influence of the high-J CO lines is especially studied. This is motivated by the fact that, in addition to obtain much more accurate estimation of the CO line luminosities when adding the high-J transitions (see Bayet et al. 2004, 2006), more subtle effect may be revealed by these lines, when considering their respective critical densities.

The knowledge of the global star formation history, and for individual galaxies, of their actual and past star formation rate, is a key item for understanding galaxy evolution, and for comparing with state-of-the-art models. Statistical relations linking star formation properties with other galaxy global characteristics established by observing nearby galaxies, have been already used to understand the processes ruling the large scale star forming activities (e.g. Malhotra et al. 2001; Boselli et al. 2002). Such trends can afterwards be used in the large scale cosmological models, which lack the spatial and temporal resolution to describe the local details of star formation in individual galaxies.

In this paper, we have thus compared the CO line emissions (from J=1-0 to J=12-11 transitions) with the infrared emission, for the nearby galaxies we have surveyed using the Caltech Submillimeter Observatory (CSO) (see Bayet et al. 2004, 2006). We extended this comparison to higher redshifted sources (\( z = 1.4-6.4 \)) for which CO line emissions have been previously observed (Cox et al. 2002; Bertoldi et al. 2003; Pety et al. 2004; Walter et al. 2004; Greve et al. 2005; Solomon & Vanden Bont 2005; Tacconi et al. 2006; Weiß et al. 2007). For these distant objects, we derived the total and the individual CO line emissions (from J=1-0 to J=12-11) by the same approach as the one presented in Bayet et al. (2004, 2006). In order to strengthen the results in a more statistical point of view, we finally have included additional literature CO(1-0) and CO(3-2) data from Gao & Solomon (2004a, b); Yao et al. (2003) and Narayanan et al. (2005), respectively.

The paper is divided straightforwardly as followed: Sect. 2 presents the data sample while Sect. 3 lists the results we have obtained, focussing especially on the comparison with the model predictions from Krumholz & Thompson (2007) and Narayanan et al. (2008). Finally, we conclude in Sect. 4.

## 2 SAMPLE SELECTION

It has been crucial to determine, or find in the literature, the total CO line emission as well as the individual line emissions of the CO transitions from J=1-0 to J=12-11. The total infrared luminosity (from 8 to 1000 \( \mu \)m) for both the nearby and the high-z sources has also been crucial to determine. Here, we have converted all the gathered data, for the first time, into a coherent and homogeneous sample we have corrected for various effects, as described below. In Table 1 and Fig. 1, the observed CO data for nearby and distant sources are presented, respectively. Model predictions go up to the J=15-14 transition of CO, consistently to the work of Bayet et al. (2004, 2006). However, we have restricted our study to only the first 12 CO transitions, higher-J CO lines having very weak intensity (see Bayet et al. 2004, 2006 and Fig. 1). In the rest of the paper, the total CO will thus refer to the sum of only the first 12 CO transitions.

### 2.1 Nearby sources

The CO data we are using in this study for the nearby sources are from the observational and modelling work of Bayet et al. (2004, 2006). They already provided a consistent line intensity sample for 8 nearby (<10 Mpc) galaxies: NGC 253, IC 10, IC 342, NGC 6946, M 83, Henize 2-10 and the Antennae (NGC 4038 and Overlap) from CO(1-0) to CO(15-14). We converted the first twelve CO integrated line intensities into luminosities (in Kkm\(^{-1}\)pc\(^2\)) using the formulae in Solomon & Vanden Bont (2005):

\[
L_{CO}^* = 3.25 \times 10^7 \times S_{CO} \Delta v \times v_{obs}^2 \times (1 + z)^{-3} \times D_L^2
\]

where \( z \) is the redshift\(^1\), \( \nu_{obs} \) is the observed frequency\(^2\) (in GHz) of the CO line, \( S_{CO} \Delta v \) is the CO integrated line intensities (in Jykms\(^{-1}\)) and \( D_L \) is the luminosity distance.

\(^{1}\) For nearby sources we used the NED database values of \( z \).

\(^{2}\) The observed frequency is equal to the rest frequency \( \nu_{rest} \) divided by (1+z).

### Table 1. List of the detected CO lines for nearby galaxies included in this study. These CO lines detections are from Bayet et al. (2004, 2006). Similar information for distant sources is found in Fig. 1 (observations represented by black bullets). When the line is not detected, we have used its corresponding predicted emission from modelling work (see Subsects. 2.1 and 2.2). For the Antennae sources (NGC 4038 and Overlap), the \( 12^{12}CO(4-3) \) and \( 12^{12}CO(7-6) \) lines have been observed by Bayet et al. (2006) but they suffer from large uncertainties. Therefore, we used for these two objects and two transitions, rather the corresponding best model predictions.

| Nearby sources | Distance detected \( 12^{12}CO \) lines |
|----------------|----------------------------------|
| IC 10          | 1.0\(^1\) 1-0, 2-1, 3-2, 4-3, 5-6, 7-6 |
| NGC 253        | 2.5\(^2\) 1-0, 2-1, 3-2, 4-3, 5-6, 7-6 |
| IC 342         | 1.8\(^3\) 1-0, 2-1, 3-2, 4-3, 5-6, 7-6 |
| He 2-10        | 9.0\(^4\) 1-0, 2-1, 3-2, 4-3, 5-6, 7-6 |
| NGC 4038       | 13.8\(^5\) 1-0, 2-1, 3-2, 4-3, 5-6, 7-6 |
| Overlap\(^6\)  | 13.8\(^5\) 1-0, 2-1, 3-2, 4-3, 5-6, 7-6 |
| M 83           | 3.5\(^6\) 1-0, 2-1, 3-2, 4-3, 5-6 |
| NGC 6946       | 5.5\(^7\) 1-0, 2-1, 3-2, 4-3, 5-6 |

\(^{1}\) : Malhotra et al. (2001); \(^{2}\) : Massey & Armandroff (1995); \(^{3}\) : Adopted value from Mauersberger et al. (1996); \(^{4}\) : McCall (1989); \(^{5}\) : Kobulnicky & Johnson (1999); \(^{6}\) : Saviane et al. (2004); \(^{7}\) : Thim et al. (2003) and Tully (1988).
(in Mpc), the total CO luminosity has been obtained by summing the individual CO line luminosities converted previously from Eq. 1 into solar luminosity units (L⊙) to avoid any frequency bias in the SFR-total CO relationship. Table 2 summarizes the results obtained.

The infrared data used for the nearby sources and, more generally in the whole paper, are from Sanders et al. (2003). For consistency with the additional literature data described in Subsect. 2.3, we chose to use the total infrared luminosity from 8 µm to 1000 µm (LIRs−1000µm), thereby including the continuum emission shorter than 60 µm affected by the contribution from very small grains. This total infrared luminosity is known to be contaminated by a possible AGN contribution (see also Graciá-Carpio et al. 2008). In particular, the AGN yield can be fairly large in the MIR range (e.g. Rowan-Robinson & Crawford 1989) in active galaxies such as LIRGs and ULIRGs. However, for the sample of the nearby sources we are studying here, this AGN contamination is considered as negligible since none of the 8 sources (IC 10, NGC 253, IC 342, Henize 2-10, NGC 4038, Overlap, M 83 and NGC 6946) is known for hosting an AGN (see e.g. Leroy et al. 2006; Martín et al. 2006; Usero et al. 2006; Wilson et al. 2000; Kramer et al. 2005; Israel & Baas 2001, respectively).

A more important aspect for nearby sources is that the CO measurements (both observations and model predictions) referred to an aperture of 22″, as described by Bayet et al. (2004, 2006), while the infrared data from Sanders et al. (2003) showed a higher aperture (80″). Thus, in Fig. 2 where we present various SFR-CO luminosity relationships (see Sect. 3), we compare, for nearby sources, two emitting regions which are not spatially identical. Indeed, the region which emits the infrared luminosity is larger than the region where CO is detected. It is the same case for the intermediate-z data (Subsect. 2.3) but this problem does not appear in the case of higher-z sources since they are seen as point-like sources in both the sub-mm/mm and infrared wavelengths. To correct this effect on nearby and intermediate-z sources, we have estimated a factor between the CO and the infrared luminosities resolution via the dust emission traced by SCUBA maps at 850 µm. We have derived from these maps the luminosity (removing the background contribution) of the 850 µm emission at a spatial resolution of 22″ and 80″, for the sources available in the SCUBA archive. We have then calculated the ratio between the emissions observed at 22″ and 80″ that we have applied to the infrared data. We have obtained ratios varying from 2.3 to 6.5, depending on the source. Rather than the 450 µm SCUBA maps, we have chosen the 850 µm SCUBA maps because they show a better signal-to-noise ratio. Nevertheless, we checked that the factors obtained at 850 µm were in agreement with the ones at 450 µm (difference obtained being less than 2%). After having applied such correction to the infrared data of the galaxies in common to this paper and the SCUBA archive, we have however obtained similar results to those listed in Table 3 and presented in Fig. 2 which show non-aperture corrected data. The slopes did not show changes greater than 5% in their values, depending on the SFR-total CO line luminosity relationship studied. Due to the fact that all the data could not be corrected consistently for this effect since the galaxies presented here have not been all observed by SCUBA (e.g IC 342), we thus have decided to keep non-corrected infrared data in Fig. 2, increasing however the error bars on the slope values by 5% in Table 3.

Both the (non-aperture corrected) infrared and the CO luminosities used in the Fig. 2 are listed in Table 2.

2.2 High-z sources

So far, a complete observed CO SED does not exist for J=1-0 to J=12-11 neither for nearby nor high-z sources.

At high redshift, various CO transitions have been however already detected (e.g. Cox et al. 2002; Bertoldi et al. 2003; Pety et al. 2004; Walter et al. 2004; Greve et al. 2005; Solomon & Vanden Bout 2005; Tacconi et al. 2006; Weiß et al. 2007). Most of these data are summarized in Solomon & Vanden Bout (2005). In our study, we restricted the number of studied sources presented in Solomon & Vanden Bout (2005) to ten objects: 4C60.07, 0PM 082794, Cloverleaf QSO, SMM J14011, VCV J1409, PSSJ2322, TN J0924, SDSS J1148, IRAS F10214 and HR 10, keeping only those which show at least two CO line detections. Indeed, to correctly constrain the models which estimate the missing line emissions (LVG models, see Appendix A) and derive relevant predicted CO line intensities, it is crucial to have as many CO line detections as possible. This is why we have rejected from our study high-z sources presented in Solomon & Vanden Bout (2005) with only one CO line observed.

To estimate the total CO luminosity as well as the individual missing molecular CO line luminosities in these sources, we have used a single-component Large Velocity Gradient (LVG) model as done in Bayet et al. (2004, 2006). The obtained line intensity predictions (see Fig. 1) correspond to a beam size of 22″, consistently with other data sets. The goal of the paper is to investigate the SFR-molecular CO line luminosity relationships. Thus, we will not discuss further the physical properties of the molecular gas we have obtained using the LVG model. Nonetheless, we present them in Appendix A.

In Fig. 1, we have superimposed on the CO observations (black bullets with error bars), the predicted emissions of both the observed and the missing CO lines (grey filled triangles). Similarly to the nearby sources case, the total CO luminosity has been obtained by summing the individual CO line luminosities converted previously from Eq. 1 into solar luminosity units (L⊙) to avoid any frequency bias in the SFR-total CO relationship. More precisely, we have used the observed velocity-integrated CO line fluxes (ScoΔv in Jy km s^−1) when detected and the predicted values when not. The redshift values used in Eq. 1 are those presented in Solomon & Vanden Bout (2005).

We did not need to correct the CO line luminosities for any beam dilution effect since the high-z galaxies are

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3 For all the sources, we obtained the luminosity distance using the web site calculator of http://www.astro.ucla.edu/~wright/CosmoCalc.html, within a cosmology of H₀ = 77 kms^{-1}Mpc^{-1}, Ω_M =0.27 and Ω_V =0.73.

4 For this source, we rather used more recent CO data from Weiß et al. (2007)
point-like sources within telescope beams and show unresolved emissions whatever these wavelengths. However, some of these distant objects are lensed. Thus, we have applied the factor of lens magnification listed in Solomon & Vanden Bout (2005) to all the CO line luminosities. The underlying assumption of such a correction is that the gravitational lens magnifies similarly the emission from compact and warm regions usually traced by high-J CO lines such as the CO(7-6) line and the regions more extended normally traced by typical low-J lines such as the CO(1-0) transition. In principle, this is a relevant assumption since the properties of the lens does not depend on the magnified source but only on the properties of the galaxies separated the observer from the studied source.

For the infrared luminosity, we used the integrated values (“L$_{\text{IR (int.)}}$”) listed in Table 1 of Solomon & Vanden Bout (2005), corresponding to infrared emission corrected for lens magnification. After having checked several references in this table, it appears that the “L$_{\text{IR (int.)}}$” values are similar to the L$_{\text{IR 8-1000\mu m}}$ presented in Sanders et al. (2003) (see the example of HR 10 for which Dey et al. 1999 derived the infrared luminosity by fitting the dust SED on a rest wavelength range from 10 $\mu$m to 2 cm).

For these distant sources, we also present in Table 2, both the infrared and the CO luminosities we have used in Fig. 2.

### 2.3 Intermediate-z data from the literature

We have included in our study CO data from observations at intermediate redshift (within similar beam sizes) to better constrain the SFR-molecular CO line luminosity relationships, and especially increase the statistics. These data are either from Gao & Solomon (2004a,b) (CO(1-0) transitions, and especially increase the statistics. These data term constrain the SFR-molecular CO line luminosity relations at intermediate redshift (within similar beam sizes) to between the CO and infrared luminosities over a large range of redshift (galaxies from z approx. 0 up to z approx. 6 sources). This characteristic has been previously seen (Sanders et al. 1991; Sanders & Mirabel 1996 and references therein) although this sample was more restricted in redshift than the one we present in this paper. It has been interpreted as an increasing star formation efficiency (SFE; SFR divided by M(H$_2$)) as a function of molecular gas mass. Here, our data sample confirms this broad interpretation.

As for nearby galaxies, the infrared luminosities of these sources are expressed for a larger aperture than the one used for the CO data. As previously mentioned (see Subsect. 2.1), this effect on the SFR-CO line luminosity relationship has been investigated through SCUBA data. Unfortunately, as for the case of nearby galaxies, the intermediate-z sources we are using here have indeed not been all observed by SCUBA, therefore no correction on their infrared data has been performed directly. We have however taken fully into account the effect of different spatial resolutions on the slope values listed in Table 3 (increased error bars as explained in Subsect. 2.1).

In the samples presented in Yao et al. (2003); Gao & Solomon (2004a,b); Narayanan et al. (2005), some sources such as ARP 220 are in common. For removing any calibration effects on the SFR-CO relationships, we have followed the recommendation of Narayanan et al. (2005) and applied their scaling factor equal to 0.26 for the CO(3-2) and to 0.45 for the CO(1-0). They specified that this effect may indeed occur when various instruments (and thus various calibration processes) are used.

Note that the intermediate-z sources increase significantly the number of CO observations used in the correlations either in the SFR-CO(1-0) line luminosity or in the SFR-CO(3-2) line luminosity relationships (see triangles in Fig. 2 as well as the fourth column in Table 3). This strengthens the corresponding results.

### 3 RESULTS

#### 3.1 General arguments

We present in Fig. 2, the SFR-CO line luminosity relationships we have obtained for the total CO line emission, the CO(1-0), CO(3-2) and CO(7-6) line emissions. In the same vein, we have obtained the SFR-CO line luminosity relationships for the other CO transitions: J=2-1 and from J=4-3 to J=12-11. SFR-CO line luminosity relationships for CO data higher than CO(7-6) are less relevant than the correlation involving lower-J CO lines. Indeed, most of the data in CO(8-7), CO(9-8), CO(10-9), CO(11-10) and CO(12-11) are from modelled fit, similarly to the fits presented in Fig. 1. In such cases, correlations between the SFR and the CO luminosity are not constrained by many observational measures. Thus, we exclude these correlations from the following analysis.

As one can see in Fig. 2, a proportionality exists between the CO and infrared luminosities over a large range of redshift (galaxies from z approx. 0 up to z approx. 6 sources). This characteristic has been previously seen (Sanders et al. 1991; Sanders & Mirabel 1996 and references therein) although this sample was more restricted in redshift than the one we present in this paper. It has been interpreted as an increasing star formation efficiency (SFE; SFR divided by M(H$_2$)) as a function of molecular gas mass. Here, our data sample confirms this broad interpretation.

To quantify better these relationships, we performed linear regressions (using the software xmgrace). The corresponding output parameters are listed in Table 3. Note that IC 10 has been excluded from these calculations. For the SFR-CO(3-2) relationship we have also excluded NGC 7817, as Narayanan et al. (2005) suggested. Indeed these two
Figure 1. Observed and predicted CO spectral energy distributions (Jy km s\(^{-1}\)) of the following high redshift sources (from top to bottom, and by increasing order of redshift): HR 10, IRAS F10214, The Cloverleaf QSO, SMM J14011, VCV J1409, 4C60.06, APM 08279, PSS J2322, TN J0924 and SDSS J1148 (see plots). Observations and their corresponding error bars are represented by black bullets (see references listed in Solomon & Vanden Bout 2005) while LVG predictions (see Appendix A) are symbolized with grey triangles. To make the plots more easily readable, we have connected the CO LVG predictions (grey lines). One could notice that, except for the source HR 10, the position of the maximum of the SED is located at rather high-J (\(J_{\text{upper}} \gtrsim 4\)).
Table 2. Infrared and CO line luminosities of the sources in our sample (see squares symbols in Fig. 2). For distant galaxies, we also list in the last column the lens magnification factor we have found in Solomon & Vanden Bout (2005) and use in this study (see Fig. 2). Intermediate-z sources values are not shown in this table since already described in details in the references mentioned in the text. When an asterisk is seen, it means that the value has been estimated from observations only.

| Name          | L_0^2 IR / L_⊙ | L_0^2 CO(tot) / L_⊙ | Ref. | L_0 CO(1-0) / Kkms^{-1}pc^2 | Ref. | L_0 CO(3-2) / Kkms^{-1}pc^2 | Ref. | L_0 CO(7-6) / Kkms^{-1}pc^2 | Ref. | Lens magn. factor |
|---------------|----------------|----------------------|------|----------------------------|------|----------------------------|------|----------------------------|------|------------------|
| IC 10         | 8.2×10^9       | 4.4×10^2             | 1 & 2| 5.6×10^6                  | 1 & 2| 3.5×10^5                  | 1 & 2| 7.3×10^4                  | 1 & 2|                  |
| NGC 253       | 2.8×10^9       | 3.3×10^3             | 2 & 3| 1.5×10^9                  | 1 & 2| 1.4×10^8                  | 1 & 2| 8.0×10^6                  | 1 & 2|                  |
| IC 342        | 1.5×10^9       | 8.4×10^4             | 1 & 2| 1.6×10^8                  | 1 & 2| 9.7×10^6                  | 1 & 2| 1.2×10^5                  | 1 & 2|                  |
| He 2-10       | 6.2×10^9       | 3.4×10^3             | 2 & 3| 2.1×10^8                  | 1 & 2| 1.1×10^7                  | 1 & 2| 1.0×10^6                  | 1 & 2|                  |
| NGC 4038      | 6.9×10^9       | 5.5×10^5             | 1 & 2| 2.1×10^9                  | 1 & 2| 1.9×10^8                  | 1 & 2| 1.3×10^7                  | 1 & 2|                  |
| Overlap       | 6.9×10^9       | 6.7×10^5             | 1 & 2| 3.3×10^9                  | 1 & 2| 2.9×10^8                  | 1 & 2| 1.7×10^7                  | 1 & 2|                  |
| M 83          | 1.3×10^9       | 1.0×10^5             | 1 & 2| 3.1×10^8                  | 1 & 2| 3.3×10^7                  | 1 & 2| 2.7×10^6                  | 1 & 2|                  |
| NGC 6946      | 1.5×10^9       | 1.0×10^5             | 1 & 2| 1.4×10^8                  | 1 & 2| 1.1×10^7                  | 1 & 2| 1.3×10^6                  | 1 & 2|                  |

a : L_{IR} is the 8 – 1000 μm total infrared luminosity deduced from either Sanders et al. (2003) (nearby sources) or Solomon & Vanden Bout (2005) (high-z galaxies). For the distant objects, L_{IR} are corrected from the lens magnification effect (see text in Subsect. 2.2). b : L_{CO(tot)} is the total CO line luminosity obtained after the use of models for predicting the emission of the missing (non-observed) CO lines (see the Subsects. 2.1 and 2.2 and, for more details, the Appendix A and the modelling work of Bayet et al. 2004, 2006).

References : 1: See Bayet et al. (2006); 2: This work; 3: Bayet et al. (2004); 4: Solomon & Vanden Bout (2005); 5: Weiß et al. (2007)

Sources show very small L_{CO} value with respect to the locus of other objects. This is especially true for IC 10 over several CO transitions (see Fig. 2).

Deviations from the SFR-CO trend can be expected for subsolar metallicity such as IC 10 (12 log(O/H)= 8.31 ± 0.2 from Arimoto et al. 1996). As shown by Lequeux et al. (1994), a CO deficit (and a [CII] excess), relative to the infrared luminosity is expected for low metallicity systems. At low metallicity, molecular hydrogen can still be formed on grains, although the threshold between atomic and molecular hydrogen is slightly shifted compared to what is seen in our Galaxy (see the discussion on the FUSE results by Tumlinson et al. 2002). In addition, CO is more easily destroyed by FUV photons than H2. In diffuse and translucent clouds, the decrease of CO photodissociation with increasing A_v is provided by the combined effect of self-shielding and dust extinction. At lower metallicities, these two effects get more closely link with the stars in formation. Indeed, the CO(1-0) tends to emit from both dense core and more diffuse molecular filaments and cloud atmosphere (n_{cr} ~ 10^2 – 10^3 cm^{-3}) leading to a non-linear relationship, whereas the HCN is typically only thermalized in the dense cores of molecular clouds (n_{cr} ~ 10^5 cm^{-3}), allowing thus linearity. However, the fact that, in a similar sample of galaxies Yao et al. (2003); Narayanan et al. (2005) also found a linear SFR-CO(3-2) relationship provide evidence against the sole HCN-related chemistry explanation (The critical density of the CO(3-2) is n_{cr} ~ 10^4 cm^{-3}).

More recent theoretical analysis (Krumholz & Thompson 2007; Narayanan et al. 2008) have shown that the relationship between the SFR and molecular line luminosity in star-forming clouds (and thus, the value of the slope of the linear regressions) depends rather on how the critical density of the molecular transition compares to the mean density of the observed sources. Lines with critical densities smaller than the mean density in a observed region (e.g. CO(1-0)) probe the total molecular gas and the SFR-molecular line relationship slope is in agreement with the Kennicutt-Schmidt index (slope ~ 1.5). On the contrary, lines with critical densities larger than the mean density (e.g. HCN(1-0) and CO(3-2)) show luminosities rising faster than linearly with increasing mean gas density and the SFR-molecular line relationship is sub-linear (slope < 1.0). In this paper,
we confirm observationally these conclusions (see Table. 3) extending them, in addition, to a larger interval in redshift.

3.2 More detailed analysis

Fig. 2 and Table 3 show that the SFR -CO(5-4),-CO(6-5) and -CO(7-6) line luminosity relationships are the tightest correlations (highest values of the correlation coefficients). Thus, between all the CO transitions, for the data sample we present here, these transitions might be considered as the best star formation rate indicators in galaxies. The total CO luminosity is also a very good tracer of star formation rate in galaxies since it shows a tight correlation (correlation coefficient of 0.984).

These tight SFR-high-J CO correlations contrast with the one seen for the CO(1-0) line. Indeed, even if we restrict the sample of CO(1-0) observations to only the 17 sources we used in the SFR-higher-J CO line luminosity relationships, considering like that the same statistics, the correlation coefficient of the CO(1-0) line is still the lowest (see Table 3). This has been previously mentioned by Riechers et al. (2006). In the same vein, it has been shown by Bussmann et al. (2008) that the higher-J HCN line such as the HCN(3-2) transition is more tightly correlated to the SFR traced by the infrared luminosity than the HCN(1-0) line. We could thus conclude that the CO(1-0) line is not a good indicator of star formation rates in galaxies.

In a more detailed analysis of the plots seen in Fig. 2, it is interesting to note that, even if the linear regressions fit rather well in all cases the observations, they however become slightly not so relevant at low CO luminosity, and thus, especially for the SFR-high-J CO relationships. This tendency is even more obvious in the SFR-CO(3-2) plot. The galaxies IC 342 and Henize 2-10 seem to be mainly responsible of this divergence. In the SFR-CO(7-6) plot as well as in the correlations involving higher-J CO lines, it is more difficult to see this trend, probably because the statistics is reduced to 17 sources. This leads to a less accurate linear regression than in the SFR-CO(3-2) case. In the SFR-CO(7-6) line luminosity relationship, one could also notice that the deficit of CO luminosity of the galaxy IC 342 is even more enhanced. The fact that IC 342 is a less active galaxy and that Henize 2-10 is small in our nearby source sample may also play a role. Indeed, as compared to more active galaxies (such as NGC 253), they may contain less dense gas. This has been recently confirmed by Bayet et al. (2009) who detected the CS(7-6) line with much more difficulties in IC 342 than NGC 253 (signal-to-noise ratio lower by a factor of 3 between the two sources). Consequently, more observations of high-J CO lines in quiet nearby galaxies are needed to explain better this characteristic. Another possible explanation may also be the degree of thermalization varying from one environment to another as explained in Narayanan et al. (2008).

In the same way, it is noticeable that a small discrepancy between the linear regressions and the observations appears for sources showing the highest infrared luminosities (see Fig. 2 in the upper right corners). However, contrarily to the previous case (nearby sources), this effect is not seen for the SFR-CO(7-6) plot nor for the other SFR-higher-J CO correlations. On the contrary, it appears clearer for lower-J CO lines. One very simple first assumption should be that this discrepancy may be caused by the fact that such active (high-z) galaxies is expected to have a higher percent of dense gas than in local galaxies. Indeed these objects are known to undergo more violent star-burst phases. The gas component traced by the CO(1-0) line may not be (relatively) as abundant and as bright as in the local Universe. This hypothesis may be confirmed by the localization of the CO SED maximum seen rather at high-J CO lines (see Fig. 1) which are known to trace a warmer and denser gas (see Bayet et al. 2004, 2006).

3.3 Comparison with model predictions

It is essential to confront the results we have obtained to the model developed by Krumholz & Thompson (2007); Narayanan et al. (2008). More especially, Narayanan et al. (2008) provided some estimations of linear regression slopes for various SFR-CO line luminosity relationships. In Fig. 3, we have reproduced the Figure 7 of Narayanan et al. (2008) adding the new observational constraints we have obtained (see the open white circles with error bars in Fig. 3). Fig. 3 thus provides the variation of the slope of the SFR-CO luminosity relationship with respect to the transition of CO investigated. The best predicted (from models) SFR-CO slopes are represented by a dashed black line while the horizontal grey lines symbolize its scatter. This scatter is computed by randomly drawing a sample of 19 galaxies (which is similar to the size of our nearby and high-z source sample) out of a set of 100 model galaxies 1000 times. Here, our measurements are consistent with other measurements (see the crosses in the Fig. 3) and with model predictions up to the SFR-CO(3-2) relationship. However, for higher-J CO line, some discrepancies are seen. As mentioned in Narayanan et al. (2008), these discrepancies may likely due to the fact that these models do not include any high-z sources. Most of these sources have an increasing fraction of AGN as compared with this of the local galaxies. These embedded AGN might thus significantly contaminate the infrared luminosity of the sources (Tran et al. 2001; Kim et al. 2002; Veilleux et al. 2002), as well as be responsible of an increase of the gas temperature, leading to a higher slope in the linear regression. In a simple view, the star-formation being warmer in such distant objects, the temperature effect is expected especially enhanced for the high-J CO line relationships. Temperature contamination, imperfectly taken into account in the models, is thus more expected in such CO lines than in low-J CO transitions.

4 CONCLUSIONS

In this paper we have investigated the relevance of using the CO line emissions as indicators of star formation rate. For the first time, we have both studied this question over a large number of CO transitions (12) and over a large sample of source going up to a redshift of z>6. We have shown that the SFR-total CO, -CO(5-4),-CO(6-5) and -CO(7-6) line luminosity relationships are the tightest correlations, making these lines the best indicators of the star formation rates. The results we have obtained also strongly confirmed the predictions from Krumholz & Thompson (2007); Narayanan
Figure 2. Examples of SFR-CO line luminosity relationships we have obtained, expressed in log-log scales. From left to right, we plotted the total integrated infrared luminosity $L_{IR}$ (in $L_\odot$) versus the total CO (in $L_\odot$), the CO(1-0), the CO(3-2) and the CO(7-6) luminosities (in Kkm$^{-1}$pc$^2$) (see Sect. 2). The squares correspond to the sources we studied in details in this paper (see Subsects. 2.1 and 2.2) while the triangles correspond to the literature data we have added from Yao et al. (2003); Gao & Solomon (2004a,b); Narayanan et al. (2005) (see Subsect. 2.3). The black filled squares represent the nearby sources while the white opened squares symbolize the high-z sources. In all plots, IC 10 is separated from other nearby sources (see Subsect. 3.1) and represented by open white circles. In the plot representing the SFR-CO(3-2) luminosity relationship one can see a lambda symbol corresponding to the source NGC 7817 we have also excluded (see Subsect. 3.1). The linear regressions have been obtained using the xmgrace software. They are represented by black lines. For keeping the figures clear, we plotted the typical errors bars of the observations (included in the calculations of the linear regressions), only on the SFR-CO(7-6) luminosity correlation. These errors correspond to a $\pm 1\sigma$ uncertainties both on the $L_{IR}$ and on the molecular CO line luminosities.

Table 3. Results of the linear regressions (slope and correlation coefficients) for the relationships between SFR and the CO transitions from J=1-0 to J=12-11 (see Fig. 2 for some examples of SFR-CO line correlations). The linear regressions have been obtained using the software xmgrace, including the error bars of the observations in the calculations. In these linear regressions, we excluded two sources from the calculations: IC 10 for all the regressions and NGC 7817 for the SFR-CO(3-2) relationship (see Sect. 3.1). We have isolated the SFR- total CO luminosity relationship from others because we have used different units.

| Molecular line Luminosities | Slope   | Correlation Coeff. | Number of sources |
|----------------------------|---------|--------------------|------------------|
| CO(1-0)$^a$                | 1.41±0.26 | 0.82               | 17               |
| CO(1-0)$^b$                | 1.14±0.08 | 0.82               | 103              |
| CO(2-1)                    | 1.20±0.10 | 0.95               | 17               |
| CO(3-2)$^a$                | 1.00±0.07 | 0.97               | 17               |
| CO(3-2)$^b$                | 0.99±0.06 | 0.89               | 81               |
| CO(4-3)                    | 0.94±0.05 | 0.98               | 17               |
| CO(5-4)                    | 0.90±0.04 | 0.98               | 17               |
| CO(6-5)                    | 0.86±0.04 | 0.98               | 17               |
| CO(7-6)                    | 0.80±0.04 | 0.98               | 17               |
| CO(8-7)                    | 0.74±0.05 | 0.97               | 17               |
| CO(9-8)                    | 0.67±0.06 | 0.94               | 17               |
| CO(10-9)                   | 0.61±0.07 | 0.92               | 17               |
| CO(11-10)                  | 0.57±0.07 | 0.90               | 17               |
| CO(12-11)                  | 0.53±0.07 | 0.89               | 17               |
| CO(tot)$^c$                | 0.62±0.04 | 0.97               | 16$^c$           |

$^a$: Without any additional literature data; $^b$: With additional literature data; $^c$: Markarian 231 is not included in this linear regression calculation because we did not find any estimation of its CO(11-10) and CO(12-11) lines luminosities needed for estimating properly its total CO luminosity.

Figure 3. Predicted slopes in log($L_{IR}$)-log($L'_{CO}$) space as a function of J transitions of CO, as seen in the study of Narayanan et al. (2008) (Figure 7). The grey horizontal lines are the model predictions and the crosses, some observations Narayanan et al. (2008) used. Observational constraints on the slope measured from CO(1-0) to CO(7-6) presented in this paper are symbolized by open white circles (with error bars). From the CO(4-3) line, the best-fit slopes (dashed line) given by the predictions from Narayanan et al. (2008) become not consistent with our observational results.

et al. (2008) who showed that the SFR-CO line luminosity relationships are above all regulated by the Kennicutt-Schmidt law, which sets the way in which observed transitions trace molecular gas. In other words, the SFR-CO line luminosity relationships depends on how the critical density of the molecule compares to the mean density of observed source. We confirm in this paper that, for the CO lines with $j_{upper} >3$, the SFR-CO line luminosity relationship are indeed sub-linear. However some discrepancies between model predictions and observations appear for higher-
J CO lines (from CO(4-3)) relationships. These differences may be likely due to the fact that, in the model the high-z sources are not included (possible temperature contamination from AGN heating processes). Anyway, more observations (ALMA, Herschel) of CO in both nearby and high-z sources, especially the high frequency CO transitions could also be very helpful for explaining these discrepancies.

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REFERENCES

Arimoto N., Sofue Y., Tsujimoto T., 1996, PASJ, 48, 275
Bayet E., Gerin M., Phillips T. G., Contursi A., 2004, A&A, 427, 45
Bayet E., Gerin M., Phillips T. G., Contursi A., 2006, A&A, 460, 467
Bayet E., Lintott C., Viti S., Martín-Pintado J., Martín S., Williams D. A., Rawlings J. M. C., 2008, ApJ Letter, 685, L35
Bayet E., Lintott C., Viti S., Martín-Pintado J., Martín S., Williams D. A., Rawlings J. M. C., 2009, ApJ, in preparation
Bertoldi F., Cox P., Neri R., Carilli C. L., Walter F., Omont A., Beelen A., Henkel C., Fan X., Strauss M. A., Menten K. M., 2003, A&A, 409, L47
BoSELLI A., Lequeux J., Gavazzi G., 2002, A&A, 384, 33
Bryant P. M., Scoville N. Z., 1999, Aj, 117, 2632
Bussmann R. S., Narayanan D., Shirley Y. L., Juneau S., Wu J., Solomon P. M., Vanden Bout P. A., Moustakas J., Walker C. K., 2008, ApJ Letter, 681, L73
Carilli C. L., Solomon P., Vanden Bout P., Walter F., Beelen A., Cox P., Bertoldi F., Menten K. M., Isaak K. G., Chandler C. J., Omont A., 2005, ApJ, 618, 586
Condon J. J., Helou G., Sanders D. B., Soifer B. T., 1990, ApJS, 73, 359
Cox P., Omont A., Djorgovski S. G., Bertoldi F., Pety J., Carilli C. L., Isaak K. G., Beelen A., McMahon R. G., Castro S., 2002, A&A, 387, 406
de Jong T., Dalgarno A., Chu S.-I., 1975, ApJ, 199, 69
Dey A., Graham J. R., Ivison R. J., Smail I., Wright G. S., Liu M. C., 1999, ApJ, 519, 610
Gao Y., Solomon P. M., 2004a, ApJS, 152, 63
Gao Y., Solomon P. M., 2004b, ApJ, 606, 271
Goldreich P., Kwan J., 1974, ApJ, 189, 441
Graciá-Carpio J., García-Burillo S., Planesas P., Fuente A., Usero A., 2008, A&A, 479, 703
Greve T. R., Bertoldi F., Smail I., Neri R., Chapman S. C., Blain A. W., Ivison R. J., Genzel R., Omont A., Cox P., Tacconi L., Kneib J.-P., 2005, MNRAS, 359, 1165
Israel F. P., Baas F., 2001, A&A, 371, 433
Kennicutt Jr. R. C., 1998a, Annu. Rev. A&A, 36, 189
Kennicutt Jr. R. C., 1998b, ApJ, 498, 541
Kennicutt Jr. R. C., Calzetti D., Walter F., Helou G., Hollenbach D. J., Armus L., Bendo G., Dale D. A., Draine B., 2007, ApJ, 671, 333
Kim D.-C., Veilleux S., Sanders D. B., 2002, ApJS, 143, 277
Kobulnicky H. A., Johnson K. E., 1999, ApJ, 527, 154
Kramer C., Mookerjea B., Bayet E., García-Burillo S., Gerin M., Israel F. P., Stutzki J., Wouterloot J. G. A., 2005, A&A, 441, 961
Krumholz M. R., Thompson T. A., 2007, ApJ, 669, 289
Lequeux J., Le Bourlot J., Des Forets G. P., Roueff E., Boulanger F., Rubio M., 1994, A&A, 292, 371
Leroy A., Bolatto A., Walter F., Blitz L., 2006, ApJ, 643, 825
Malhotra S., Kaufman M. J., Hollenbach D., Helou G., Rubin R. H., Brauher J., Dale D., Lu N. Y., Lord S., Stacey G., Contursi A., Hunter D. A., Dinerstein H., 2001, ApJ, 561, 766
Martín S., Mauersberger R., Martín-Pintado J., Henkel C., García-Burillo S., 2006, ApJS, 164, 450
Massey P., Armandroff T. E., 1995, Aj, 109, 2470
Mauersberger R., Henkel C., Wielebinski R., Wiklind T., Reuter H.-P., 1996, A&A, 305, 421
McCall M. L., 1989, Aj, 97, 1341
Narayanan D., Cox T. J., Shirley Y., Davé R., Hernquist L., Walker C. K., 2008, ApJ, 684, 996
Narayanan D., Groppi C. E., Kulesa C. A., Walker C. K., 2005, ApJ, 630, 269
Papadopoulos P. P., Isaak K. G., van der Werf P. F., 2007, ApJ, 668, 815
Pety J., Beelen A., Cox P., Downes D., Omont A., Bertoldi F., Carilli C. L., 2004, A&A, 428, L21
Riechers D. A., Walter F., Carilli C. L., Knudsen K. K., Lo K. Y., Benford D. J., Staguhn J. G., Hunter T. R., Bertoldi F., Henkel C., Menten K. M., Weiss A., Yun M. S., Scoville N. Z., 2006, ArXiv Astrophysics e-prints
Rigopoulou D., Lawrence A., White G. J., Rowan-Robinson M., Church S. E., 1996, A&A, 305, 747
Rowan-Robinson M., Crawford J., 1989, MNRAS, 238, 523
Sanders D. B., Mazzarella J. M., Kim D.-C., Surace J. A., Rowan-Robinson M., Crawford J., 1999, MNRAS, 306, 523
Sanders D. B., Mazzarella J. M., Kim D.-C., Surace J. A., Rowan-Robinson M., Crawford J., 1999, MNRAS, 306, 523
Sanders D. B., Mazzarella J. M., Kim D.-C., Surace J. A., Rowan-Robinson M., Crawford J., 1999, MNRAS, 306, 523
Sanders D. B., Mirabel I. F., 1996, Annu. Rev. A&A, 34, 749
Sanders D. B., Scoville N. Z., Soifer B. T., 1991, ApJ, 370, 158
Saviane I., Hibbard E. J., Rich R. M., 2004, Aj, 127, 660
Schmidt M., 1959, ApJ, 129, 243
Solomon P. M., Vanden Bout P. A., 2005, Annu. Rev. A&A, 43, 677
Tacconi L. J., Neri R., Chapman S. C., Genzel R., Smail I., Ivison R. J., Bertoldi F., Blain A., Cox P., Greve T., Omont A., 2006, ApJ, 640, 228
Thim F., Tammann G. A., Saha A., Dolphin A., Sandage A., Tolstoy E., Labhardt L., 2003, ApJ, 590, 256
Thompson M., Hatchell J., MacDonald G., Millar T., 2002, in Crowther P., ed., Hot Star Workshop III: The Earliest Phases of Massive Star Birth Vol. 267 of Astronomical Society of the Pacific Conference Series, A Sub-mm Imaging Survey of Ultracompact HII Regions. pp 429–+
Tran Q. D., Lutz D., Genzel R., Rigopoulou D., Spoon H. W. W., Sturm E., Merin B., Hines 2001, ApJ, 552, 527
Tully R. B., 1988, Science, 242, 310
Tumlinson J., Shull J. M., Rachford L. F., Browning M. K., Snow T. P., Fullerton A. W., Jenkins E. B., Savage B. D.,
APPENDIX A: SINGLE COMPONENT LVG MODELLING RESULTS FOR THE HIGH-Z SOURCES

As mentioned in Subsect. 2.2, a complete observed CO SED does not exist for J=1-0 to J=12-11 in high-z sources. We thus have collected CO line emissions from Solomon & Vanden Bout (2005) and performed a Large Velocity Gradient (LVG) analysis to derive the missing CO integrated line intensities. The results of this modelling work is shown in Fig. 1 and in the following Table A1.

We have run LVG models (Goldreich & Kwan 1974; de Jong et al. 1975), already well described in various papers. The version we have used in this study is the one presented by the author.

For determining the missing CO line intensities, we have constrained the predicted CO line intensity ratios with the observed values (computed from Solomon & Vanden Bout 2005) via a reduced χ² method as performed in Bayet et al. (2004, 2006, 2008). This LVG model is basically running with three free parameters: the gas density n(H₂), the kinetic temperature (T_k) and the CO column density divided by the line width (N(¹²CO)/Δv). We have investigated the following range of LVG input parameters: 5 K < T_k < 255 K, 1 × 10¹² cm⁻²/kms⁻¹ < N(¹²CO)/Δv < 1 × 10¹⁰ cm⁻² and 1 × 10³ cm⁻³ < n(H₂) < 1 × 10⁷ cm⁻³.

For determining the missing CO line intensities, we have constrained the predicted CO line intensity ratios with the observed values (computed from Solomon & Vanden Bout 2005) via a reduced χ² method as performed in Bayet et al. (2004, 2006, 2008).

We have used a single LVG component for reproducing the entire set of CO data in high-z sources, being fully conscious that this modelling approach is not ideal for reproducing the widespread view that the ISM contains dense, star-forming molecular cloud cores and more diffuse gas in cloud envelopes, even in high-z sources. Motivated also by, on average, the small number of CO detections, we have thus considered this approach as reasonable for the purpose of this paper.

We recommend to use the predicted physical properties derived and listed in Table A1 as only indicative values. We indeed remind the reader that we were not trying to model each source individually, deriving the accurate set of physical properties for the molecular gas, but that we rather aim to obtain satisfactory estimations of the CO line intensities in these sources. Note that, for APM 08279 (Weiß et al. 2007), the use of two LVG components has been made but, such as the sum of both CO components agrees with the observed CO SED. Thus, the choice of a one or a two LVG components model does not affect significantly the SFR-total CO luminosity relationships we present in this paper.

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Table A1. Results of the single component LVG model analysis. We presented in this table the physical properties of the best LVG model (having the lowest-χ² value when compared to the observations).

| Source      | T_k (K) | n(H₂) (cm⁻³) | N(CO)/Δv (cm⁻²/kms⁻¹) |
|-------------|---------|--------------|------------------------|
| HR10        | 255     | 1.0 × 10¹¹   | 8.0 × 10¹⁸             |
| IRAS F10214 | 15      | 8.0 × 10⁵    | 3.0 × 10¹⁸             |
| VCV J1409   | 185     | 1.7 × 10⁴    | 4.5 × 10¹⁵             |
| 4CO60.07    | 180     | 1.7 × 10³    | 1.5 × 10¹⁸             |
| APM 08279   | 255     | 9.0 × 10³    | 8.5 × 10¹⁷             |
| PSS J2322   | 30      | 5.0 × 10⁴    | 2.2 × 10¹⁶             |
| TN J0924    | 205     | 1.4 × 10⁷    | 2.5 × 10¹⁸             |
| SDSS J1148  | 100     | 7.9 × 10⁴    | 4.5 × 10¹⁵             |