

Constraints on the Star-Forming Interstellar Medium in Galaxies Back to the First Billion Years of Cosmic Time

Dominik A. Riechers¹

¹*California Institute of Technology, 1200 East California Blvd, MC 249-17,
Pasadena, CA 91125, USA*

Abstract.

Constraints on the molecular gas content of galaxies at high redshift are crucial to further our understanding of star formation and galaxy evolution through cosmic times, as molecular gas is the fuel for star formation. Since its initial detection at large cosmic distances almost two decades ago, studies of molecular gas in the early universe have come a long way. We have detected CO emission from >100 galaxies, covering a range of galaxy populations at $z>1$, reaching out to $z>6$, down to sub-kpc scale resolution, and spanning ~ 2 orders of magnitude in gas mass (aided by gravitational lensing). Recently, it has even become possible to directly identify distant galaxies through their molecular emission lines without prior knowledge of their redshifts. The new generation of powerful long wavelength interferometers such as the Expanded Very Large Array (EVLA) and Atacama Large (sub)Millimeter Array (ALMA) thus hold the promise to liberate studies of molecular gas in high redshift galaxies from their heavy pre-selection. This will enable more systematic studies of the molecular gas content in star-forming galaxies back to the earliest cosmic times.

1. Introduction

Recent years have shown a tremendous progress in our understanding of star formation and stellar mass assembly in galaxies through cosmic times. A key diagnostic in such studies is the so-called star formation history of the universe (SFHU), which describes the volume density of star formation in the universe as a function of cosmic time (Madau et al. 1996; Lilly et al. 1996). Since the initial studies 15 years ago, it has become possible to study the buildup of stellar mass through the SFHU as a function of galaxy type and mass, star formation rate (SFR), and cosmic environment, reaching back to the epoch of cosmic reionization, within 1 Gyr of the Big Bang. These studies have shown that the comoving SFR density increases by more than an order of magnitude between $z\sim 0$ and 1, peaks between $z=1$ and 3, and then likely drops gradually out to $z>6-10$ (Hopkins & Beacom 2006; Bouwens et al. 2011). According to this relation, about half of the stellar mass in spheroidal galaxies in the present day universe is built up at $1<z<3$ (leading to the emergence of the Hubble sequence), which thus is dubbed the ‘epoch of galaxy assembly’ (Marchesini et al. 2009). Also, the steep incline toward $z\sim 1$ further steepens for galaxies with higher SFRs, suggesting a substantially higher abundance of intensely star-forming galaxies at high z (Le Floch et al. 2005; Magnelli et al. 2009). On the other hand, the specific SFR (i.e., SFR per total stellar mass of a galaxy) suggests that the more massive a galaxy, the more of its stellar mass it forms at earlier cosmic times, as the most massive galaxies only show quiescent star formation

since $z \sim 1$ ('downsizing'; e.g., Zheng et al. 2007). Overall, the build-up of stellar mass follows the SFR density fairly well (Borch et al. 2006; Bell et al. 2007).

An important, complementary, yet less systematically used diagnostic in studies of galaxy evolution is the molecular gas content of galaxies. Molecular gas is a precursor for star formation, as it is the material out of which stars form. Thus, the relative amount of molecular gas in a galaxy indicates its future potential for star formation, and how much stellar mass (M_\star) a galaxy can assemble by $z=0$ without external gas supply.

This work summarizes the progress in studies of molecular gas at high redshift since the initial investigations almost 2 decades ago. Based on recent breakthroughs in these investigations, it is outlined how it may become possible to study the molecular gas content in distant galaxies in a more systematic fashion in the future.

2. Molecular Gas in High Redshift Galaxies: Fundamentals

Molecular gas (CO) has been detected in >100 high redshift ($z > 1$) galaxies to date (see reviews by Solomon & Vanden Bout 2005; Omont 2007), out to $z=6.42$ (e.g., Walter et al. 2003, 2004; Bertoldi et al. 2003; Riechers et al. 2009a). Except for a few strongly lensed systems (e.g., Baker et al. 2004; Coppin et al. 2007; Riechers et al. 2010a; Riechers 2011), the bulk of these galaxies have massive gas reservoirs of $M_{\text{gas}} > 10^{10} M_\odot$, as determined from their CO line intensities.

A small fraction of these gas-rich galaxies could be spatially resolved in high-resolution CO observations down to $0.15''$ – $0.3''$ resolution (corresponding to 1–2 kpc at $z > 4$; e.g., Carilli et al. 2002; Walter et al. 2004; Riechers et al. 2008a, 2008b, 2009b; Tacconi et al. 2008; Bothwell et al. 2010; Engel et al. 2010). Such studies allow to measure the surface density, dynamics, and overall morphology of the gas, which provides insight on gas supply mechanisms and on the processes driving star formation (e.g., major mergers vs. gas dynamics driven by ordered rotation). Moreover, the constraints on the dynamical structure allow to determine the dynamical mass M_{dyn} , and thus, the shape and depth of the gravitational potential of a galaxy. As M_{dyn} encompasses all components in the gas-rich region of a galaxy (i.e., M_{gas} , dust mass, M_\star , supermassive black hole mass, and dark matter), it enables an independent mass calibration of the most massive constituents, and allows to set upper limits on contributors that are not directly detectable. This is of particular importance for high- z quasars, where the stellar hosts are not detectable at optical/infrared wavelengths due to the brilliance of the luminous active galactic nucleus (e.g., Walter et al. 2004; Riechers et al. 2008a, 2008b). It also provides independent limits on dark matter fractions in galaxies where all baryonic components are individually detectable, and an independent calibration for the conversion factor from CO line luminosity to M_{gas} (e.g., Daddi et al. 2010a).

A main diagnostic for the physical properties of the gas only becomes accessible by studying multiple CO lines in a high redshift galaxy (e.g., Weiß et al. 2005, 2007; Riechers et al. 2006a). Due to the increasing rotational energy required to excite higher-level rotational transitions, it becomes increasingly difficult to collisionally excite high- J lines¹ high enough to keep them in thermal equilibrium with lower- J lines. Thus, the relative strength of the emission from different rotational lines allows to constrain the physical properties of the gas (for collisional excitation, in particular the gas density and

¹ J stands for the upper level rotational quantum number of a rotational CO $J=n \rightarrow n-1$ transition.

temperature). This implies that the fundamental $\text{CO}(J=1\rightarrow 0)$ transition is, in general, a better tracer of the total amount of molecular gas in a galaxy (and thus, M_{gas}), as it is less sensitive to gas excitation conditions than higher- J lines.

One important aspect to keep in mind is that, due to the low critical density of the $\text{CO}(J=1\rightarrow 0)$ line ($\sim 300 \text{ cm}^{-3}$), it is a good tracer of the total amount of molecular gas, but not a particular tracer of the dense regions where star formation actively takes place. Such star-forming cores are traced more reliably by molecules with a higher dipole moment than CO, such as HCN, HCO^+ , HNC, or CN. The $J=1\rightarrow 0$ transitions of HCN, HCO^+ , and HNC have critical densities in excess of 10^4 cm^{-3} , and thus, are good tracers of dense cores. However, due to substantially lower abundances and the more stringent excitation conditions, the ground-level transitions of these molecules typically exhibit 10–30 \times lower line fluxes than $\text{CO}(J=1\rightarrow 0)$ (e.g., Gao et al. 2007; Riechers et al. 2007a). Thus, molecules different than CO have only been detected in a handful of high- z galaxies, and only two systems (the Cloverleaf at $z=2.56$ and APM08279+5255 at $z=3.91$) currently have measurements in more than a single line of a dense gas tracer (e.g., Solomon et al. 2003; Vanden Bout et al. 2004; Carilli et al. 2005; Wagg et al. 2005; Riechers et al. 2006b, 2007b, 2010b, 2011; Garcia-Burillo et al. 2006; Weiß et al. 2007; Gao et al. 2007; Guelin et al. 2007). Thus, studies of the chemical composition and excitation of the dense, actively star-forming component in the molecular interstellar medium of high- z galaxies are still rather limited.

3. CO Detections at High Redshift: Galaxy Populations

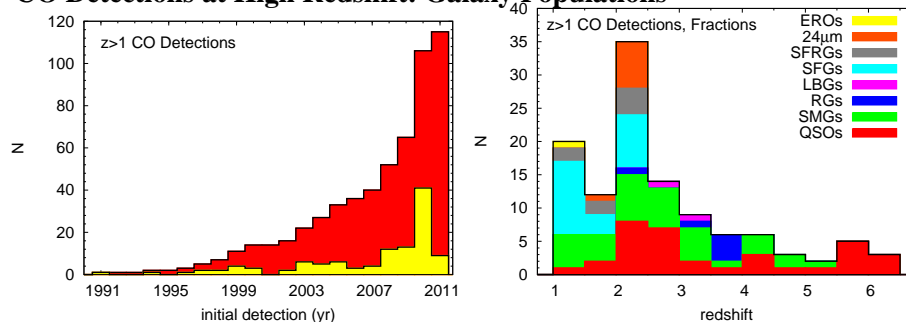


Figure 1. Detections of CO emission in $z>1$ galaxies. *Left*: Total number of detections (red) and detections per year (yellow) since the initial detection in 1991/1992. *Right*: Detections as of 2011 as a function of redshift, and color encoded by galaxy type (see Sect. 3; Riechers et al., in prep.).

A number of different high- z galaxy populations have been studied in CO emission to date. These populations can be split into eight (at least partially overlapping) categories according to their selection, but fall into two main categories: (sub)millimeter-luminous and (sub)millimeter-faint galaxies (see Fig. 1; Riechers et al., in prep.). Historically, (sub)millimeter brightness was considered a prerequisite for CO searches. However, with the improvement in sensitivity and bandwidth of interferometers used for CO searches since ~ 3 years ago, this restriction could be overcome.

The (sub)millimeter-luminous systems are typically either directly selected in the observed-frame (sub)millimeter continuum (submillimeter galaxies) or pre-selected through other diagnostics (typically brightness of an active galactic nucleus (AGN) in the optical or radio, i.e., quasars and radio galaxies) and then detected in the (sub)millimeter continuum before they are followed up in CO emission. The (sub)millimeter-faint systems are pre-selected through other star formation diagnostics in the optical/near-infrared,

mid-infrared and radio continuum (or a combination), and classified by this selection (massive gas-rich star-forming galaxies, lensed Lyman-break galaxies, extremely red objects, $24\mu\text{m}$ -selected galaxies, radio-selected star-forming galaxies). Some of these samples are specifically selected against being (sub)millimeter-luminous (usually to probe galaxies with different dust and gas properties than SMGs), while others may contain few systems that can be classified as SMGs. These samples are, however, not systematically selected against each other, and thus contain at least partial overlap.

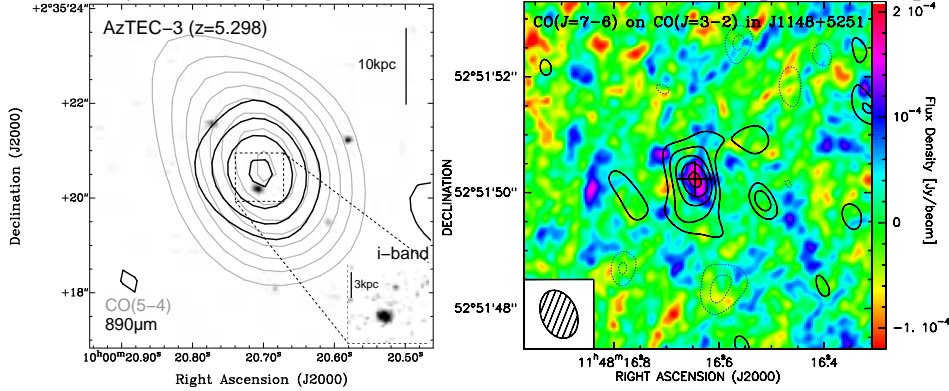


Figure 2. Highest redshift detections of CO emission in SMGs and quasars. *Left*: CO($J=5\rightarrow4$) emission in the $z=5.298$ SMG AzTEC-3 (PdBI; gray contours), overlaid on a HST i -band image. The black contours indicate the $890\mu\text{m}$ (rest-frame $140\mu\text{m}$) continuum emission, as measured by the SMA. The inset shows a zoom-in of the region where the CO and $890\mu\text{m}$ emission peak (Riechers et al. 2010c). *Right*: CO($J=7\rightarrow6$) image of the $z=6.42$ quasar J1148+5251 (PdBI contours), overlaid on a $0.3''$ resolution CO($J=3\rightarrow2$) image obtained with the VLA. The molecular gas in the host galaxy of this quasar is distributed over 5 kpc scales (Walter et al. 2004; Riechers et al. 2009a).

Quasar Host Galaxies (QSOs): Quasars were the first high- z galaxies detected in CO emission (e.g., Brown & Vanden Bout 1991; Solomon et al. 1992; Barvainis et al. 1994; Ohta et al. 1996; Omont et al. 1996). To date, the host galaxies of 34 $z>1$ quasars were detected in CO emission, 14 of which are gravitationally lensed. Initial detections are typically obtained in mid- J CO lines redshifted to 3 mm. All of these quasars are far-infrared-luminous, i.e., detected at observed-frame (sub)millimeter wavelengths (see Riechers 2011 for a recent summary). Almost half of the detections are at $z>4$, reaching out to $z=6.42$ (Fig. 2). This makes quasars the best-studied population in CO emission at very high z . Also, they were probed in a wide range of CO transitions, reaching from CO $J=1\rightarrow0$ up to $J=11\rightarrow10$ (e.g., Weiss et al. 2007). They have molecular gas masses in the range of $\sim 0.1\text{--}20\times 10^{10} M_{\odot}$. The faint end ($\lesssim 10^{10} M_{\odot}$) can currently only be probed with the help of gravitational lensing (e.g., Riechers 2011).

Submillimeter Galaxies (SMGs): Since 1998, 34 (sub)millimeter galaxies were detected in CO emission, 16 of which are considered to be gravitationally lensed (e.g., Frayer et al. 1998; Solomon & Vanden Bout 2005; Engel et al. 2010; Lupu et al. 2011). CO is detected out to the most distant SMG currently known at $z=5.3$ (Fig. 2; Riechers et al. 2010c; Capak et al. 2011). Initial detections are typically obtained in mid- J CO lines redshifted to 3 mm. Historically, most SMGs were selected at $850\mu\text{m}$ or $1.1/1.2\text{ mm}$, but with the advent of Herschel, the selection has at least partially shifted to shorter wavelengths ($250\text{--}500\mu\text{m}$, e.g., Negrello et al. 2010). SMGs have molecular gas masses in the range of $\sim 0.3\text{--}15\times 10^{10} M_{\odot}$, the least massive of which are typically strongly lensed (e.g., Sheth et al. 2004; Kneib et al. 2005).

Massive Gas-Rich Star-Forming Galaxies (SFGs): Daddi et al. (2008, 2010a) and Tacconi et al. (2010) have observed a population of high- z massive, gas-rich star-forming galaxies in CO emission that are undetected at (sub)millimeter wavelengths. The six galaxies by Daddi et al. are selected through the so-called BzK technique (a two color selection around the redshifted 4000 Å break) to be massive, star-forming galaxies. These galaxies are at $z=1.4\text{--}1.6$, and CO $J=2\rightarrow 1$ was detected in all of them. Tacconi et al. selected a sample of 19 massive star-forming galaxies at $z=1.1\text{--}2.4$ in the ultraviolet/optical (overlapping with massive Lyman-break galaxies), of which they detect 16 in CO $J=3\rightarrow 2$ emission. The parent populations of these galaxies are more than an order of magnitude more common than SMGs, reaching projected space densities of $>1\text{ arcmin}^{-2}$ (e.g., Daddi et al. 2007). For the combined sample of 22 detections, gas masses of $\sim 2\text{--}50\times 10^{10} M_{\odot}$ are found.²

Star-Forming Radio-selected Galaxies (SFRGs): Chapman et al. (2008) and Casey et al. (2009) have observed a sample of (sub)millimeter-undetected star-forming galaxies at $z=1.3\text{--}2.2$ selected through their 20 cm radio continuum fluxes in CO emission. They detect 8/14 galaxies in CO $J=2\rightarrow 1$, $J=3\rightarrow 2$, or $J=4\rightarrow 3$, emission, finding typical molecular gas masses of $8\times 10^9 M_{\odot}$ (including two BzK-selected galaxies from Daddi et al. 2008 into their sample). The selection of these galaxies appears to overlap with the BzK selection.

24 μ m-selected Galaxies (MIPS Galaxies): Yan et al. (2010) have observed CO $J=2\rightarrow 1$ or $J=3\rightarrow 2$ emission toward nine ultra-luminous infrared galaxies (ULIRGs) at $z=1.6\text{--}2.5$ selected by their high 24 μ m luminosities (24 μ m fluxes of 1.1–1.5 mJy as measured with Spitzer/MIPS). These galaxies are typically undetected at 1.2 mm down to ~ 1 mJy, suggesting that they trace a different high- z ULIRG population than (sub)millimeter-selected galaxies. These galaxies are typically mergers, and their rest-frame mid-infrared luminosities appear to be dominated by dust-obscured AGN. Yan et al. detect 8/9 galaxies, suggesting an average molecular gas mass of $1.7\times 10^{10} M_{\odot}$. Iono et al. (2006) report a detection of CO $J=2\rightarrow 1$ and $J=3\rightarrow 2$ emission from another 24 μ m-selected galaxy, which however appears to be a strongly lensed SMG (and thus, is counted as such here).

Lensed Lyman-break Galaxies (LBGs): With current instrumentation, it is not possible to detect ‘typical’ Lyman-break Galaxies (LBGs) in molecular line emission. However, aided by strong gravitational lensing, Baker et al. (2004) and Coppin et al. (2007) detected CO($J=3\rightarrow 2$) emission toward two young $z\sim 3$ LBGs that are lensing-magnified by factors of $\mu_L\sim 30$. One of these galaxies is weakly detected in continuum emission at 1.2 mm, but even with such strong lensing magnification not at levels comparable to SMGs. Through subsequent CO($J=1\rightarrow 0$) observations, Riechers et al. (2010a) find their (lensing-corrected) total molecular gas masses to be $5\text{--}9\times 10^8 M_{\odot}$, which are the lowest currently observed at high z .

Radio Galaxies (RGs): Six galaxies at $z\sim 2.4\text{--}3.8$ selected through powerful radio AGN were detected in molecular line emission (e.g., Scoville et al. 1997; Papadopoulos et al. 2000; De Breuck et al. 2003a, 2003b, 2005; Greve et al. 2004). These six galaxies also show strong (sub)millimeter continuum emission. They have typical molecular gas masses of $5\text{--}10\times 10^{10} M_{\odot}$.

²In contrast to all other samples discussed here, a conversion factor of $M_{\text{gas}}/L'_{\text{CO}}=\alpha_{\text{CO}}=3.2\text{--}3.6 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ is used here, rather than $0.8 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$.

Extremely Red Objects (EROs): Andreani et al. (2000) and Greve et al. (2003) have detected CO emission from an Extremely Red Object (i.e., with very red optical/infrared colors of $R-K > 6$) at $z=1.4$, finding a total molecular gas mass of $6 \times 10^{10} M_{\odot}$. Despite its selection in the optical/infrared, this galaxy appears to show properties that are similar to SMGs (and is, indeed, detected at submillimeter wavelengths in the continuum), but possibly with a lower-than-average CO excitation within this population.

4. CO Excitation

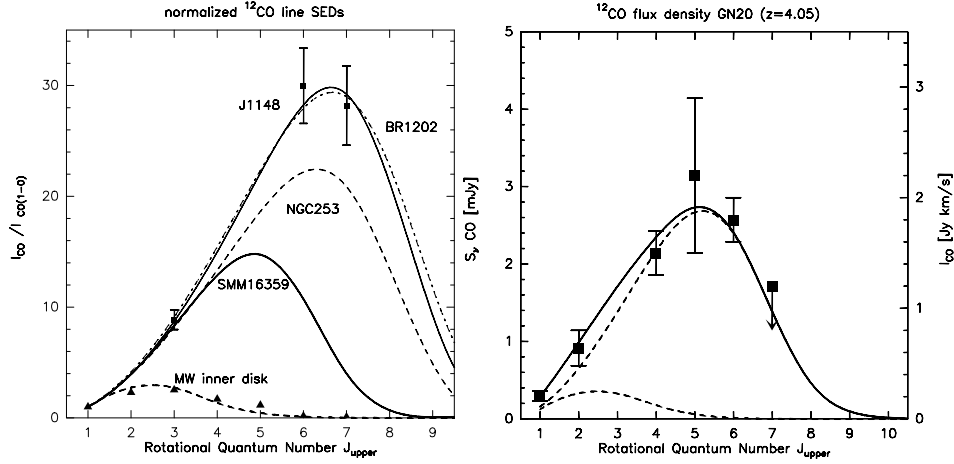


Figure 3. CO excitation diagrams and LVG models (lines) for high- z galaxies. *Left:* Comparison of CO line ladders of the $z=6.42$ quasar J1148+5251 (squares and solid line) and the $z=4.69$ quasar BR 1202-0725 (dash-dotted line) to the nucleus of the nearby starburst galaxy NGC 253 (dashed line), the $z=2.52$ SMG J16359+6612 (thick solid line), and the inner disk of the Milky Way (triangles and thick dashed line; Riechers et al. 2009a). *Right:* CO excitation of the $z=4.05$ SMG GN20. The dashed lines indicate the two gas components required to fit the observed CO excitation, and the solid line shows the sum of both components (Carilli et al. 2010).

In lack of spatial resolution in most studies of CO emission out to the largest cosmic distances, one of the most insightful diagnostics is to study the CO excitation of high- z galaxies. In an idealized case of thermal equilibrium, all rotational transitions of CO in a galaxy would exhibit the same brightness temperature and line luminosity L'_{CO} , which implies that their peak flux densities increase toward higher- J lines, scaling with ν_{line}^2 . However, the energy requirements to keep higher- J CO lines in thermal equilibrium get increasingly higher (which can be expressed as higher critical densities and excitation temperatures), making it increasingly more difficult to maintain equilibrium. Thus, by modeling the intensity of different rotational levels of CO relative to equilibrium, it is possible to constrain the physical properties of the gas (in particular its density and kinetic temperature). In lack of detailed constraints on the gas distribution and local radiation field, the most common approach is to model the collisional excitation of CO using the large velocity gradient (LVG) approximation (e.g., Scoville & Solomon 1974; Goldreich & Kwan 1974). This method utilizes an escape probability formalism (i.e., photons produced locally can only be absorbed locally) resulting from a strong velocity gradient, which helps to minimize the number of free parameters in models of the collisional line excitation.

By measuring the fluxes of multiple CO transitions in high- z galaxies, LVG models allow for a comparison of the gas properties of different high- z galaxy populations (see Fig. 3 for examples). High redshift quasars appear to be dominated by high-excitation gas components, where the line peak fluxes typically start to decrease in $J>6$ transitions. This yields characteristic gas kinetic temperatures of $T_{\text{kin}}=50$ K and characteristic gas densities n_{gas} of few times 10^4 cm^{-3} (e.g., Riechers et al. 2006a, 2009a), comparable to what is found in the nuclei of nearby ULIRGs. More extreme examples such as the $z=3.911$ quasar APM08279+5255 are observed, but for such systems, significant contributions from radiative excitation from the AGN and/or star-forming regions remain a possibility (e.g., Weiß et al. 2007). In contrast, SFGs appear to be dominated by colder, less dense gas components in which the line peak fluxes typically start to decrease in $J>3$ transitions. This yields characteristic gas kinetic temperatures of $T_{\text{kin}}=25$ K and characteristic gas densities n_{gas} of few times 10^3 cm^{-3} (Dannerbauer et al. 2009; Aravena et al. 2010), comparable to what is found in nearby spiral/disk galaxies and the Milky Way. Given the integrated star formation rates of SFGs, the presence of some denser, higher excitation gas is expected, but the relative strength of such components is not constrained well at present. SMGs appear to contain a mix of dense, high excitation gas (even though somewhat lower than in quasars on average, with line peak fluxes starting to decrease in $J>5$ transitions) and low excitation gas as found in SFGs (Fig. 3, right; e.g., Carilli et al. 2010; Harris et al. 2010; Riechers et al. 2010c; Ivison et al. 2011). The high-excitation gas component in SMGs typically dominates the line fluxes in $J\geq 2$ lines. However, due to a potential difference in $\alpha_{\text{CO}}=M_{\text{gas}}/L'_{\text{CO}}$, this does not imply that this component dominates the gas mass (e.g., Carilli et al. 2010; Riechers et al. 2010c). Only limited information is available on the CO excitation of young, lensed LBGs to date, but their excitation appears consistent with the somewhat intermediate levels found in nearby luminous infrared galaxies (Riechers et al. 2010a).

5. Luminosity Relations and the Star Formation Law

The CO luminosity L'_{CO} is commonly considered to be a measure for the total molecular gas mass M_{gas} in a galaxy, while the (far-) infrared luminosity L_{FIR} is considered to be a measure for the star formation rate (SFR; e.g., Solomon & Vanden Bout 2005). Thus, the relation between L'_{CO} or M_{gas} and L_{FIR} or SFR may be considered a spatially integrated version of the Schmidt–Kennicutt ‘star formation law’ between gas surface density and star formation rate surface density (e.g., Schmidt 1959; Kennicutt 1998).

Even in galaxies with luminous AGN, L_{FIR} is commonly used as a proxy for the star formation rate in the host galaxy. In principle, both the AGN and star formation can heat the dust that gives rise to the continuum flux observed in the FIR, but the characteristic dust temperatures of AGN heating are typically a factor of a few higher than those of dust heating by young stars. Thus, the warm dust in AGN-starburst systems observed in the rest-frame FIR is commonly thought to be dominated by heating within the host galaxy, in particular in the most intense, dust-enshrouded starbursts. If, however, L_{FIR} were to be dominated by the AGN, one would expect an elevated L_{FIR} for such galaxies in the $L'_{\text{CO}}-L_{\text{FIR}}$ relation. In Figure 4 (right panel), a comparison of the $L'_{\text{CO}}-L_{\text{FIR}}$ relation for nearby and high- z quasars to nearby galaxies, ULIRGs and SMGs without dominant AGN is shown (Riechers 2011). For galaxies with low L'_{CO} , there is an indication for an excess in L_{FIR} for quasars relative to other systems; however, there is no evidence for such a trend at high L'_{CO} . This may suggest that, in systems with

relatively low gas and dust content, the AGN contributes significantly to L_{FIR} , but not in systems with high gas and dust content. Thus, for the massive high- z systems, L_{FIR} appears to be a good proxy for the SFR even in quasars (Riechers 2011).

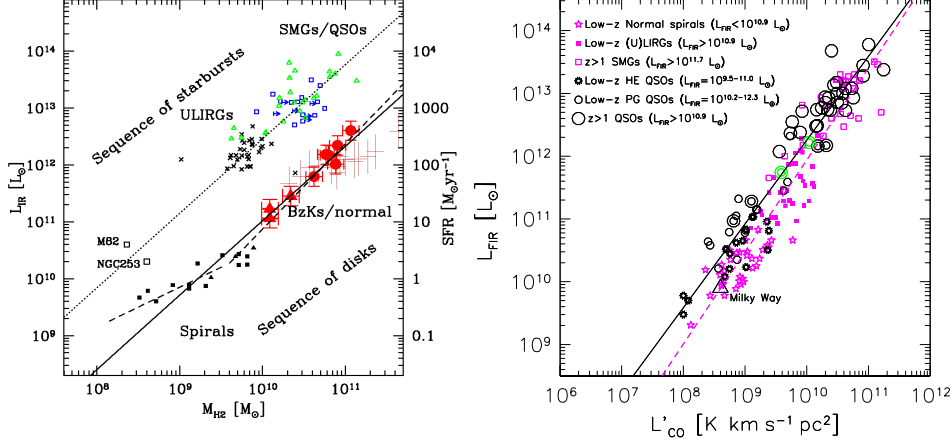


Figure 4. Comparison of CO luminosity/gas mass with (far-) infrared luminosity as a tracer of the star formation rate in low- and high- z galaxies. *Left:* $M_{\text{gas}}-L_{\text{IR}}$ relation for low- z spirals, starbursts and ULIRGs, and high- z SFGs (“BzKs/normal”), SMGs, and quasars. The solid line represents a fit to spiral galaxies and SFGs, and the dotted line shows the same trend offset by 1.1dex in L_{IR} (which is consistent with the starburst galaxies, ULIRGs, SMGs and quasars). These two lines may represent two sequences for disk and starburst galaxies, with the offset being due to different dynamical timescales for star formation (e.g., Daddi et al. 2010b). *Right:* $L'_{\text{CO}}-L_{\text{FIR}}$ relation for quasars at low and high z (fitted by the solid line), and galaxies without dominant AGN at low z (spirals and (U)LIRGs) and at high z (SMGs; fitted by the dashed line). At high L'_{CO} , galaxies with and without dominant AGN statistically occupy the same region, while at low L'_{CO} , there is tentative evidence for an offset of quasars toward higher L_{FIR} . This may indicate that AGN heating contributes significantly to L_{FIR} at low L'_{CO} , but not at high L'_{CO} (Riechers 2011).

More fundamentally, the question occurs if star formation progresses the same way in all types of galaxies. In disk-like spiral galaxies like the Milky Way, star formation occurs in molecular clouds with compact, dense cores, confined by self gravity (e.g., Solomon et al. 1987). In mergers, such as the Antennae (NGC 4038/39), star formation appears to peak on relatively large scales in the dense overlap region between the merging galaxies, leading to the formation of so-called super star clusters (e.g., Wilson et al. 2003). In the nuclei of ULIRGs, the most extreme nearby starbursts, star formation appears to occur in a dense, intercloud medium, bound by the potential of the galaxy, rather than virialized clouds (e.g., Downes & Solomon 1998). As a first consequence, the conversion factor from observed CO luminosity to gas mass $M_{\text{gas}}/L'_{\text{CO}} = \alpha_{\text{CO}}$ is different for these different kind of galaxies (e.g., $\alpha_{\text{CO}} = 0.8 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$ is typically used for ULIRGs, while $\alpha_{\text{CO}} = 4.6 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$ is used for the Milky Way). For “ULIRG-like” starbursts at high z such as quasars, SMGs, and $24 \mu\text{m}$ -selected galaxies (many of which show merger-like characteristics, e.g., Fig. 5), an ULIRG conversion factor is commonly adopted (e.g., Solomon & Vanden Bout 2005). For SFGs, $\alpha_{\text{CO}} = 3.2-3.6 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$ is typically used, comparable to those in nearby disk galaxies (e.g., Daddi et al. 2010a; Tacconi et al. 2010).

The differences between starburst and disk galaxies are also reflected in the star formation law. When comparing the $M_{\text{gas}}-L_{\text{IR}}$ relation for three largest CO-detected

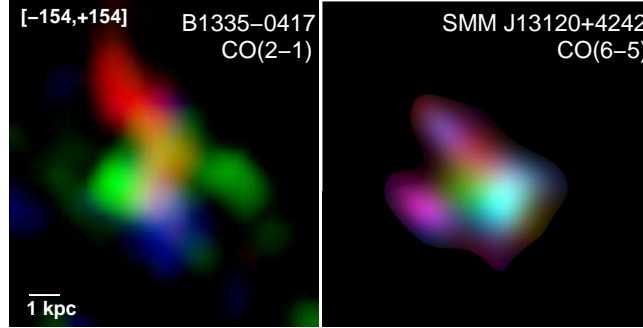


Figure 5. Velocity maps of the $z=4.4$ quasar host galaxy BRI 1335-0417 (Riechers et al. 2008a), and the $z=3.4$ SMG J13120+4242 (Engel et al. 2010). BRI 1335-0417 was observed at a resolution of $\sim 0.15''$ (~ 1.0 kpc), tapered to $0.32'' \times 0.30''$ here. J13120+4242 was observed at a resolution of $0.59'' \times 0.47''$ (~ 4 kpc). Both systems show a complex morphology and velocity structure inconsistent with a rotating disk, suggesting that they are major, gas-rich mergers with >5 kpc scale gas reservoirs.

samples at high z , i.e., quasars, SMGs, and SFGs to low redshift galaxies, two interesting trends occur (using α_{CO} as outlined above, but note that the trends are visible independent of this choice). First, SFGs extend the relation found for nearby spiral galaxies to higher M_{gas} . Second, quasars and SMGs extend the trend found for the most intense nearby starbursts and ULIRGs to higher M_{gas} . Both trends agree with the same slope, but are offset by 1.1 dex in L_{IR} . Daddi et al. (2010b) interpret this as evidence for two sequences in this relation for disk galaxies and starbursts, which occur due to the different dynamical timescales of star formation in these systems (Fig. 4, left; see also Genzel et al. 2010).

6. Detectability of CO Emission at High Redshift: Recent Developments

Until recently, all CO detections at $z > 1$ were obtained based on precise, spectroscopic redshifts from optical/infrared diagnostics, biasing studies toward those systems that are bright at such wavelengths. This is due to the fact that, until recently, radio/millimeter-wave telescopes had very narrow fractional bandwidths that covered less or little more than the (typically few 100 km s^{-1} wide) CO emission lines. However, with the recent advent of so-called “Z-machines” like EMIR on the 30 m telescope (8% fractional bandwidth), the Zpectrometer on the Green Bank Telescope (GBT; 34% fractional bandwidth at 1 cm) and Z-spec on the Caltech Submillimeter Observatory (CSO; 46% fractional bandwidth at 1 mm – instrument is currently on the Atacama Pathfinder Experiment (APEX)) and wide-band correlators on millimeter interferometers, in particular the Plateau de Bure Interferometer (PdBI) and the Combined Array for Research in Millimeter-wave Astronomy (CARMA; 4%–8% fractional bandwidth at 3 mm), this situation has drastically changed. The first optically faint high- z galaxy redshift to be identified directly through CO emission was the $z=4.05$ SMG GN20 (Daddi et al. 2009), but this discovery was serendipitous. Weiß et al. (2009) have identified a lensed $z=2.93$ SMG through a CO search with EMIR on the 30 m. Lupu et al. (2011) and Frayer et al. (2011) have identified five $1.5 < z < 3.0$ lensed SMGs with Z-spec and the Zpectrometer on the CSO and GBT. Scanning the 3 mm band with CARMA, Riechers (2011) has identified a lensed type-2 quasar at $z=2.06$ in CO. The 3 mm band covers a least one CO transition at virtually any redshift < 0.44 and > 1.0 , making it a particularly suitable band for CO redshift searches. These studies show that, with the recent upgrade

in instrumentation (and even more so with ALMA and the fully upgraded EVLA in the future), it has now become possible to directly identify galaxy redshifts through CO emission, liberating studies of molecular gas at high z from one of their main biases. By targeting strongly lensed sources, these studies greatly increase the number of galaxies with detected CO emission. Also, they offer a great demonstration of what studies ALMA will enable in 1–2 orders of magnitude fainter systems.

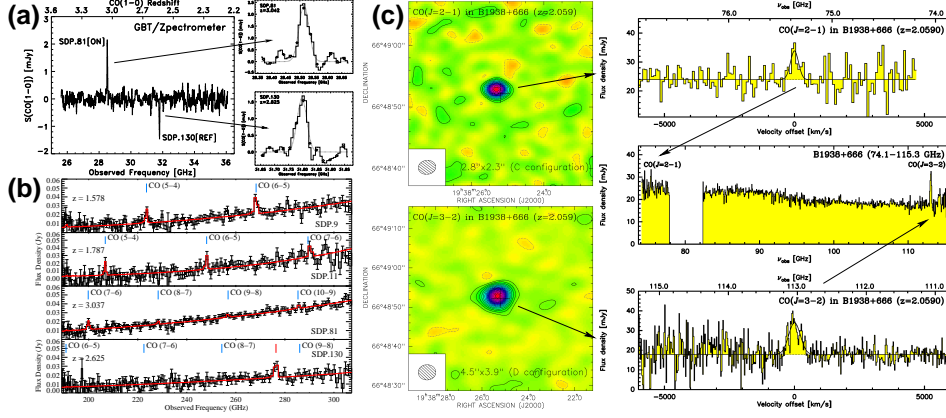


Figure 6. “Blind” CO searches toward high- z galaxies. *a*: Detection of $\text{CO}(J=1\rightarrow0)$ emission toward two lensed $z>2$ SMGs with the GBT/Zpectrometer, redshifted to ~ 1 cm wavelength (Frayser et al. 2011). The instrument position-switched between both sources for calibration purposes, making one of the lines artificially appear as negative in the difference spectrum. *b*: Detection of high- J CO emission toward four lensed $z>1.5$ SMGs with CSO/Z-spec, redshifted to ~ 1 mm wavelength (Lupu et al. 2011), two of which are the same sources as in panel *a*. *c*: Detection of $\text{CO } J=2\rightarrow1$ and $3\rightarrow2$ emission toward a $z=2.06$ type-2 quasar, scanning the 3 mm band with CARMA (Riechers 2011). These are some of the first examples of galaxies that were identified through CO redshifts with wideband spectrometers on single-dish telescopes and wide-band correlators on millimeter interferometers.

7. Implications for Future Systematic Studies of Molecular Gas in the Early Universe

Based on studies of molecular gas in selected high- z galaxies, we have learned that we can characterize different galaxy populations in the early universe based on the properties of their molecular interstellar medium content. Also, recent technological improvements have yielded direct “blind” redshift identifications of high- z galaxies through CO line emission. Moreover, studies of CO emission in FIR-faint galaxies have shown that the projected density of CO-luminous high- z galaxies likely exceeds 1 arcmin^{-2} , which is comparable to the field-of-view of ALMA at 3 mm, and a fraction of the field-of-view of the EVLA at 1 cm. In other words, sufficiently deep studies that probe sufficient cosmic volume (by covering a large range in redshift for CO emission lines) with these instrument may yield detections of CO emission in high- z galaxies pointing at any position in the sky, despite their limited field-of-view.

This suggests that studies of redshifted CO emission comparable to optical “Deep Fields” (i.e., blindly targeted $\gtrsim 10 \text{ arcmin}^2$ size fields studied to faint levels) will become feasible with the next generation of radio/(sub)millimeter telescopes, and are a critical complement to CO intensity mapping studies at $>5'$ resolution that are aimed

at studying large scale structure and that will place valuable constraints on cosmic reionization (e.g., Gong et al. 2011; Carilli 2011; Bowman et al., in prep.). At optical/infrared wavelengths, Deep Field studies have provided critical constraints on the SFHU and the stellar mass density of the universe. Comparable studies in molecular line emission have the potential to provide comparable constraints on the prerequisite material for star formation, i.e., the molecular gas mass density of the universe (which is linked to the SFHU through the star formation law, and is the material available for stellar mass assembly in galaxies). Such a Deep Field study of the molecular gas mass density of the universe thus has the potential to substantially further our understanding of galaxy formation throughout cosmic times.

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