THE ISM IN DISTANT GALAXIES

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Abstract. The interstellar medium (ISM) is a key ingredient in galaxy formation and evolution as it provides the molecular gas reservoir which fuels star formation and supermassive black hole accretion. Yet the ISM is one of the least studied aspects of distant galaxies. Molecular and atomic transitions at (sub)millimetre wavelengths hold great promise in measuring macroscopic properties (e.g. masses, morphologies, star formation laws), as well as microscopic properties (e.g. gas densities, temperatures, cooling) of high-z galaxies. In this overview I summarize the growing number of high-z molecular line detections, highlighting some of the most intriguing results along the way. I end by discussing a few areas where future facilities (e.g. ALMA, EVLA, CCAT, LMT) will drastically improve on the current state of affairs.

1 Introduction

In the 17 years since the first discovery of $^{12}$CO (hereafter CO) at high $z$ in IRAS F10214+4724 (Brown & Vanden Bout 1992; Solomon, Radford & Downes 1992), a serendipitously discovered type-2 QSO at $z = 2.29$, little more than 60 molecular line detections at $z > 1$ have been made (Fig. 1). This relatively modest progress is in spite of early search campaigns (Evans et al. 1996; van Oijk et al. 1997), and reflects an unfortunate combination of limited receiver sensitivity and the lack of atmospheric transmission in certain (sub)mm bands, which makes such observations extremely challenging. For the same reasons early efforts were primarily limited to CO observations of extremely luminous, optically selected QSOs (e.g. Ohta et al. 1996; Omont et al. 1996) and high-z radio galaxies (HzRGs – e.g. Papadopoulos et al. 2000; De Breuck et al. 2003). In order to enhance the chances of success, the targeted objects were often strongly lensed systems and/or pre-selected to have strong thermal dust emission.

These first molecular line detections in QSOs and HzRGs were of great importance as they unambiguously demonstrated the existence of large molecular gas
reservoirs enriched in C and O in the early Universe. A prime example is the detection of CO in the highest known redshift QSO (J114816.64+525150.3 at $z = 6.419$ – Walter et al. 2003; Bertoldi et al. 2003), which implies significant enrichment of the gas at a time when the Universe was only 1/16th of its present age and had only recently been reionized. Many of these systems have since been revisited in more detail, resulting in remarkable new results such as exquisite high-resolution CO images (e.g. Carilli et al. 2002; Riechers et al. 2008), nearly fully sampled CO spectral line distributions (SLEDs) (Weiß et al. 2007), and in some cases detections of HCN and HCO$^+$ (e.g. Solomon et al. 2003; Riechers et al. 2006) as well as atomic transitions of C$\text{I}$ and C$\text{II}$ (e.g. Barvainis et al. 1997; Maiolino et al. 2005).

Parallel to these efforts, CO searches were carried out in high-$z$ galaxies dominated by star formation, resulting in the first detection of molecular gas in submm-selected galaxies (SMGs) (Frayer et al. 1998, 1999). The advent of a large sample of SMGs with spectroscopic redshifts (Chapman et al. 2005) allowed for the first systematic CO survey of a well defined sample of high-$z$ galaxies (Neri et al. 2003; Greve et al. 2005; Tacconi et al. 2006, 2008). The result was robust estimates of the typical gas masses, sizes, kinematics and gas depletion time scales for bright SMGs. CO observations have also been carried out of three optically-faint radio galaxies (OFRGs) – thought to be 'hot-dust' versions of SMGs as they are selected to be luminous in the radio but faint at 850-µm wavelengths – and towards two sBzK galaxies, which are massive, but moderately star forming, disk-like galaxies at $z > 1$ (Daddi et al. 2008). Finally, the recent detections of CO in a few rare examples of strongly lensed Lyman Break Galaxies (LBGs) (Baker et al. 2004;...
Coppin et al. 2007) have allowed for a unique peak into the gas properties of 'ordinary' high-z galaxies, and the kind of studies which will be possible with ALMA.

2 The molecular gas content of distant galaxies

Molecular hydrogen (H$_2$) is by far the main component of molecular clouds and the molecular ISM in general. The lack of permanent dipole moment of the H$_2$ molecule, however, allows only quadrupole $\Delta J = 2$ transitions, with $S(0) : J_u - J_l = 2 - 0$ at 28 $\mu$m being the easiest to excite, but with its $\Delta E_{20}/k_B = 510$ K much too high for the gas temperatures prevailing in the bulk of the molecular gas ($\sim 15 - 60$ K). Moreover, the Earth’s atmosphere is largely opaque at 28 $\mu$m. Consequently, the next most abundant molecule, CO with a Galactic abundance of [CO/H$_2$] $\sim 10^{-4}$, is used. Its permanent dipole moment, and easily excitable rotational transitions (e.g. for $J = 1 - 0$: $\Delta E_{10}/k_B \sim 5.5$ K) with frequencies at mm and submm wavelengths where neither dust in the Galaxy, nor the Earth’s atmosphere are significantly absorbing, make CO the ideal bulk H$_2$ mass tracer.

The high optical depths of the CO transitions do not prevent them from tracing the entire volume and mass of an ensemble of clouds where large velocity gradients keep $\Delta v_{\text{cloud}} \gg \Delta v_{\text{thermal}}$, and thereby the entire ensemble fully transparent to CO line emission (i.e. the high optical depths arise only locally). If the additional assumption of virialized clouds is made then the total H$_2$ gas mass ($M_{\text{gas}}$) is directly proportional to the total CO luminosity ($L'_{\text{CO}}$): $M_{\text{gas}} = \alpha L'_{\text{CO}}$ (e.g. Dickman et al. 1986), where $\alpha$ is the CO-to-H$_2$ conversion factor and depends on the CO brightness temperature ($T_b$) and the gas density ($n$) according to $\alpha \propto \sqrt{n/T_b}$. Three decades of Galactic CO observations have established a CO-to-H$_2$ conversion factor that applies to molecular clouds in our Galaxy ($\alpha_G = 4.6$ $M_\odot$/(K km s$^{-1}$ pc$^2$) – this includes a 36% correction for He). The fact that denser clouds are usually warmer keeps $\alpha_G$ constant within a factor of $\sim 2$ (e.g. Young & Scoville 1991). However, in local Ultra Luminous Infra-Red Galaxies (ULIRGs), which harbour extreme tidal fields and radiation pressures capable of disrupting molecular clouds, the appropriate conversion factor is $\alpha_{\text{IR}} = 0.8$ $M_\odot$/(K km s$^{-1}$ pc$^2$), i.e. 5$\times$ smaller than the Galactic value (Solomon et al. 1997).

What CO-to-H$_2$ conversion factor should be used to infer the gas masses of high-z galaxies? It is usually assumed that conditions at high redshifts are akin to those in local ULIRGs, and high-z gas masses are therefore derived using $\alpha_{\text{IR}}$. However, $\alpha_{\text{IR}}$ was deduced from a small sample, and particular relations (such as $M_{\text{new stars}} = 2/3 L'_{\text{CO}}$) were assumed to derive it (Downes & Solomon 1998) – relations which may not apply within the wider local ULIRG class, let alone their high-z counterparts. Even if $\alpha_{\text{IR}}$ is appropriate for extreme, IR-luminous galaxies, which make up the bulk of the high-z CO detections, a conversion factor closer to $\alpha_G$ probably apply to the recent CO detections towards LBGs and sBzK galaxies. In the metal-poor H$_2$ gas expected in LBGs, for example, CO may photodissociate while leaving the largely self-shielding H$_2$ clouds intact. In fact, a high-resolution CO study of a combined sample of SMGs, sBzK/BX and LBGs at $z \sim 2 - 3$ found that only by assigning a Galactic conversion factor to the UV/optical selected
galaxies and a ULIRG conversion factor to the SMGs, could the dynamical masses be reconciled with realistic gas fractions (Tacconi et al. 2008).

The published high-z CO detections to date yield median CO luminosities of QSOs, HzRGs, and SMGs of $\langle L'_{\text{CO}} \rangle = 3.5 \times 10^{10}$, $4.5 \times 10^{10}$, and $3.7 \times 10^{10}$ K km s$^{-1}$ pc$^2$, respectively. Assuming $\alpha = \alpha_{\text{IR}}$ and thermalized transitions, meaning CO line ratios of unity, the corresponding gas masses become $\langle M_{\text{gas}} \rangle = 2.8 \times 10^{10}$, $3.6 \times 10^{10}$, and $3.0 \times 10^{10}$ M$_\odot$. The median CO luminosities found for OFRGs, sBzK, and LBG galaxies are $\langle L'_{\text{CO}} \rangle = 1.6 \times 10^{10}$, $1.1 \times 10^{10}$, and $2.9 \times 10^9$ K km s$^{-1}$ pc$^2$, respectively, with corresponding gas masses of $\langle M_{\text{gas}} \rangle = 1.3 \times 10^{10}$, $8.8 \times 10^9$, and $2.3 \times 10^9$ M$_\odot$. The bulk of $z > 1$ galaxies with CO detections have $L'_{\text{CO}} > 1 \times 10^{10}$ K km s$^{-1}$ pc$^2$, which is $\sim 3 - 5 \times$ larger than local ULIRGs (Solomon et al. 1997) and reflects the bias towards luminous systems at high redshifts.

Currently, a direct comparison of the gas masses in local and distant galaxies is complicated by the fact that while local galaxies are readily detected in the low CO lines ($J = 1 - 0, 2 - 1$), the high-$J$ lines are difficult to access due to the atmosphere. For distant galaxies, the situation is reverse: most high-$z$ galaxies are first detected in high-$J$ lines ($J = 3 - 2$ or higher), which are the brightest lines and are redshifted into clean atmospheric windows. Only then are searches for CO $J = 1 - 0$ attempted. All low-$J$ detections to date have been of sources with previous detections in higher CO lines. This introduces a bias in the sense that at high redshifts, galaxies with dense and warm gas are preferred over those with a more quiescent ISM. Furthermore, it means that the CO $J = 1 - 0$ luminosity, and therefore the gas mass, must be inferred from assumptions about the excitation conditions of the gas. For example, the gas masses inferred from CO $J = 1 - 0$ observations towards the two distant starbursts ERO J16450+4626 ($z = 1.44$) and SMM J13120+4242 ($z = 3.41$) (Greve, Ivison & Papadopoulos 2003; Hainline et al. 2006) were substantially larger ($4 - 10 \times$) than previous estimates based on CO $J = 5 - 4$ and the assumption that the line was thermalized. Similar claims have been made for a few QSOs (Papadopoulos et al. 2001), although more recent observations find no evidence for cold gas reservoirs in QSOs (Riechers et al. 2007).

3 Spatially and kinematically resolved ISM observations at high $z$

Spatially and kinematically resolved molecular line observations hold enormous potential for direct imaging of galaxy assembly in the distant Universe – a process for which several distinct scenarios can be envisaged. Does it occur via numerous discrete short bursts within a huge gravitationally bound gas reservoir, or via multiple mergers of gas-rich galaxies (‘wet’ mergers) interspersed with prolonged quiescent intervals, or perhaps a single widespread starburst (‘monolithic’ collapse)? Resolved gas-kinematics also provide estimates of galaxy sizes, dynamical masses, merger fraction etc., key quantities to test against model predictions.

Sub-arcsecond interferometric CO observations of SMGs with the IRAM PdBI, capable of spatially resolving their gas kinematics, have revealed compact (FWHM diameter $\lesssim 1.6$ kpc), sometimes multiple, morphologies with velocity gradients of
Fig. 2. Left: Position-velocity diagram and composite colour map of the CO $J = 2 - 1$ emission towards the QSO BRI 1335–0417 ($z = 4.41$) at $\sim 0.3''$ (FWHM) resolution. CO emission is observed across the velocity range indicated in the top left corner, with red, green and blue colours indicating redshifted, central and blueshifted emission relative to the systemic redshift. Adapted from Riechers et al. (2008). Right: Velocity-integrated CO $J = 7 - 6$ emission (shown in red) towards the SMG SMM J16350+4057 ($z = 2.39$) at $\sim 0.5''$ (FWHM) resolution, with the line profiles from two distinct regions within the source also shown. Blue and green colours show the rest-frame UV and optical morphologies, respectively. Adapted from Tacconi et al. (2008).

$\sim 500$ km s$^{-1}$, suggestive of compact rotating disks (Fig. 2). Although the individual components are compact, they are in some cases found up to $\sim 10$ kpc apart, yet clearly part of the same system. The invoked central gas densities are substantially higher than those of starforming $z \sim 2$ galaxies selected in the UV/optical, suggesting that SMGs may represent the end phase of a highly dissipative (major) merger between gas-rich galaxies (Tacconi et al. 2006, 2008).

Other observational highlights have come from high-resolution CO observations of $z > 3$ QSOs (Fig. 2), which have successfully probed the gas kinematics on $\lesssim 1$ kpc scales during a period where the host galaxy experiences both extreme starburst activity and accretion onto its central supermassive black hole. When imaged on sub-kpc scales, the molecular gas reservoirs are often found to break up into multiple, compact disk-like components (e.g. Carilli et al. 2002; Riechers et al. 2008) — a morphology not too dissimilar to that of $z \sim 2$ SMGs. However, the CO line profiles of QSOs are on average narrower ($\langle$FWHM$\rangle \simeq 300$ km s$^{-1}$) than in SMGs ($\langle$FWHM$\rangle \simeq 700$ km s$^{-1}$), and more often resembles a single Gaussian profile: only $\sim 10\%$ show evidence of double peaks, yet for SMGs this fraction is $\sim 30 - 50\%$ (Greve et al. 2005; Carilli & Wang 2006). While a number of factors, such as significantly different host masses and/or sizes, could affect these findings, it is more likely that it reflects the (optical) selection of QSO which, unlike the SMG selection, prefers systems where the gas is rotating in a disk parallel with the sky plane (Carilli & Wang 2006).

Whether a picture similar to that seen in $z > 3$ QSOs holds for HzRGs is
currently not known. In a few of the most powerful HzRGs there is evidence from (low-resolution) CO observations that the molecular gas is extended on scales of \( \gtrsim 5 \) kpc, is spatially and kinematically offset from the radio galaxy, and exhibit velocity-gradients \( \gtrsim 500 \) km s\(^{-1}\) (e.g. De Breuck et al. 2003). These findings are consistent with HzRGs being massive proto-ellipticals undergoing a major starburst, yet since there has been no sub-arcsecond CO survey of HzRGs to date, one cannot rule out scenarios in which the CO traces large-scale molecular outflows, possibly compressed halo-gas induced by the radio galaxy jets, or streaming, non-virialized gas caused by close-encounters.

High-resolution CO observations of high-z galaxies also provide a unique opportunity to couple the dynamical masses of galaxy spheroids \( M_{\text{sph}} \) (inferred from CO) to the masses of their central supermassive black holes \( M_{\text{BH}} \) (inferred from optical spectroscopy) at epochs where both were undergoing significant growth. Understanding the physical origin of the locally observed \( M_{\text{BH}} - M_{\text{sph}} \) relation (Magorrian et al. 1998) is a key scientific goal, as it suggests a fundamental, yet unknown, connection between black hole accretion and star formation.

From a comprehensive CO survey of optically luminous \( M_B \sim -28 \), submm-detected QSOs at \( z \sim 2 \), Coppin et al. (2008) estimated an average \( M_{\text{BH}}/M_{\text{sph}} \) ratio of \( \sim 9 \times 10^{-3} \), nearly an order of magnitude above the local ratio \( \sim 1.4 \times 10^{-3} \), while CO observations of \( z > 4 \) QSOs suggest even higher \( M_{\text{BH}}/M_{\text{sph}} \) ratios (e.g. Walter et al. 2004). In contrast, CO studies of SMGs (in conjunction with X-ray and optical/near-IR observations) have shown that SMGs lie a factor of \( \sim 3 - 5 \) below the local \( M_{\text{BH}} - M_{\text{sph}} \) relation (Alexander et al. 2008). Clearly, the \( M_{\text{BH}} - M_{\text{sph}} \) relation evolves with redshift, but it appears that the evolution occurs differently for different types of galaxies. In optically luminous QSOs, the build-up of the spheroid stellar mass lags the the black hole growth, while in SMGs the situation appear to be reversed. A level of uncertainty is inherent in these conclusions, however, owing to the sometimes poorly constrained CO sizes and inclination angles. More worrying, though, for such potentially dynamically unsettled systems is the possibility that the molecular gas might not always be centered around the black hole or even be a good probe of the dynamical mass. Examples of such AGN/H\(_2\) configurations have recently been found at both high and low z (Ivison et al. 2008; Riechers et al. 2008; Papadopoulos et al. 2008).

4 The star formation efficiency of galaxies across Cosmic time

The well known Schmidt/Kennicutt star formation law (Schmidt 1959; Kennicutt 1998), which relate the surface density of star formation rate to the surface gas density \( \Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{1.4\pm0.2} \), manifests itself in locally observed relations between IR luminosity (gauging the star formation rate) and molecular line luminosity (tracing the gas). The best known is the IR-CO relation \( L_{\text{IR}} \propto L_{\text{CO}}^{1.4-1.7} \), a non-linear relation when averaged over local spirals, LIRGs and ULIRGs. In fact the slope depends on the particular galaxy sample: it is linear \( (N \simeq 1) \) for normal spirals and superlinear \( (N \simeq 1.4 - 1.7) \) for starbursts and (U)LIRGs (Gao 2007).
Greve et al. (2005) found that bright SMGs follow the non-linear IR-CO relation established for local (U)LIRGs, thereby extending the relation to the distant Universe and the highest IR luminosities \( L_{\text{IR}} \simeq 10^{13} \, L_\odot \). Adopting \( L_{\text{IR}}/L_{\text{CO}}' \) as a measure of the star formation efficiency \( SFE \propto SFR/M(H_2) \), this would indicate that SMGs form stars more efficiently than local galaxies. Possible examples of even higher star formation efficiencies are OFRGs (Chapman et al. 2008), which have \( \sim 4 \times \) higher \( L_{\text{IR}}/L_{\text{CO}}' \) ratios than typical SMGs (Fig. 3). Galaxies with low \( SFEs \) are also encountered at high redshifts, as demonstrated by Daddi et al. (2008) who found \( L_{\text{IR}}/L_{\text{CO}}' \) ratios comparable to that of local spirals in two \( z \sim 1.5 \) sBzK galaxies, i.e. an order of magnitude below that of SMGs.

Going instead to a dense gas tracer such as HCN, one finds a linear star formation law extending from Galactic clouds to spirals and (U)LIRGs (Gao & Solomon 2004; Wu et al. 2005), indicating that the star formation rate per unit dense gas (as measured by \( L_{\text{IR}}/L_{\text{HCN}}' \)) is virtually independent of the star formation environment (Fig. 3). To date observations of HCN at high-\( z \) have resulted in only five detections and 8 upper limits (Gao et al. 2007 and references therein), and as a result the nature of the IR-HCN relation at high-\( z \) is uncertain. There is tentative evidence, however, that the high-\( z \) galaxies, and possibly even the most luminous local ULIRGs depart from a linear IR-HCN relation (Graciá-Carpio et al. 2008). Recent theoretical models tie such \( L_{\text{line}} - L_{\text{IR}} \) relations to a common underlying \( H_2 \) cloud density hierarchy and a \( SFR \propto \langle \rho_{\text{gas}} \rangle^{1.5} \) relation (e.g. Krumholz & Thompson 2007; Narayanan et al. 2008). The exponent in the \( L_{\text{line}} - L_{\text{IR}} \) relation is then
8 The Role of Disk-Halo Interaction in Galaxy Evolution: Outflow vs Infall?

Fig. 4. Left: Modeled CO SLEDs based on multi-line CO survey of 7 QSOs and 4 SMGs between $z = 1.4$ and $z = 4.7$. Adapted from Weiss et al. (2007). Right: The $L_{\text{CO}}/L_{\text{IR}}$ ratios for normal starforming galaxies, ULIRGs and the only two $z > 1$ galaxies with [Cii] detections to date, namely SDSS J1148+5152 ($z = 6.42$) and FSC10026+4946 ($z = 1.12$). Upper limits for BR1202−0725 ($z = 4.69$) and PSS J2322+1944 ($z = 4.11$) are also shown. Adapted from Hailey-Dunsheath et al. (2008).

a sensitive function of the $n_{\text{crit}}/\langle n \rangle$ ratio, where $n_{\text{crit}}$ is the critical density of the line being observed. However, the strong variations of HCN 4 − 3/1 − 0 ratios ($\sim 0.1 − 1$) found even among ULIRGs with similar IR, HCN, CO $J = 1 − 0$ luminosities (Papadopoulos 2007) as well as possible influences of a hard, AGN-originating X-ray spectrum on the HCN abundance (e.g. Lepp & Dalgarno 1996) may make the tracing of dense gas far from straightforward.

5 The physical properties of the ISM in distant galaxies

A detailed picture of the physical properties of the ISM (e.g. abundances, temperature and density distribution, and thermal balance) will require ample sampling of the CO, HCN, and HCO$^+$ rotational ladders, along with key diagnostic atomic transitions such as [Cii] 158 $\mu$m, [Cl] 369 $\mu$m, and [Cl] 609 $\mu$m. Already, multiple CO transitions have been observed in a number of high-z QSOs and SMGs (Weiβ et al. 2007), yielding the first insights into the full CO SLEDs of galaxies at any redshift (Fig. 4). The CO SLEDs of QSOs typically peak at higher transitions ($J = 8 − 7$) than those of SMGs ($J = 6 − 5$), indicating that the former harbour denser and warmer gas.

If these observed CO SLEDs are representative of the first objects emerging from the epoch of reionization at $z > 7$, it will have ramifications for the ability of ALMA to detect CO in such objects. ALMA, with its lack of receivers below
84 GHz, will only be able to observe the $J = 8 - 7$ line and above for such objects. However, these lines are generally not highly excited in $z \sim 2 - 6$ QSOs, let alone in SMGs, suggesting that such observations will be challenging even with ALMA (Walter & Carilli 2008). The situation might even be worse, since the currently known high-$z$ CO SLEDs are biased towards high-$J$ by a) strong lensing (in some cases), which favours compact high-$J$ emitting regions over the more extended low-$J$ emitting gas; b) a general pre-selection of high-$z$ objects as strong IR/far-IR emitters before CO follow-up is carried out, which means low excitation CO SLEDs (such as that of HR 10 – Papadopoulos & Ivison 2002) could be missed; c) a further pre-selection in the sense that high-$z$ objects are first detected in high-$J$ CO lines before low-$J$ lines are attempted (see § 2). This could herald bad news for the use of high-$J$ lines to yield an unbiased view of the $z > 7$ Universe, since the CO SLED turn-over may happen at $J = 4 - 3$ for many systems, including the starbursting ones when between star formation bursts. For these objects, the EVLA (and possibly the SKA) is likely to be the facilities of choice, since they will have the frequency coverage and sensitivity to detect the low-$J$ CO lines.

The detection of the $[\text{C}\text{ii}]$ 158 $\mu$m line towards J1148+5251 at $z = 6.42$ (Maiolino et al. 2005), the first of its kind, indicated a more feasible pathway for ALMA to study $z > 7$ objects. Not only is the $[\text{C}\text{ii}]$ line observable with ALMA at these redshifts, but in J1148+5251 it is $\sim 5 \times$ brighter than the brightest CO line observed in this source ($J = 6 - 5$), suggesting that $[\text{C}\text{ii}]$ 158 $\mu$m will be the line of choice when studying the earliest objects with ALMA, and that a strong synergy will develop between ALMA ($[\text{C}\text{ii}]$) and the EVLA (low-$J$ CO lines).

The $[\text{C}\text{i}]$ and $[\text{C}\text{ii}]$ lines have great diagnostic power in determining the physical properties of the ISM. Neutral carbon is well mixed in cloud interiors and holds the promise of probing the bulk H$_2$ gas mass and its temperature (via the $[\text{C}\text{i}]$ 2-1/1-0 ratio) at high redshifts without being tied to assumptions about virialized clouds. Testing its H$_2$-tracing capabilities in local starbursts have yielded results in accordance with the standard CO-based method (Gerin & Phillips; Papadopoulos & Greve 2004). The $[\text{C}\text{ii}]$ 158 $\mu$m line is the main cooling agent of the ISM in our own Galaxy and in typical starbursts in the local Universe, where it carries a significant fraction of the IR total luminosity ($L_{\text{CO}}/L_{\text{IR}} \simeq 5 - 10 \times 10^{-3}$). However, cooling via $[\text{C}\text{ii}]$ is about an order of magnitude less efficient in local ULIRGs ($L_{\text{CO}}/L_{\text{IR}} \simeq 2 - 5 \times 10^{-4}$ – e.g. Gerin & Phillips 2000) than in normal starburst galaxies. This is a trend followed by J1148+5152 (Fig. 4), and raises the question of how the gas cools in very luminous galaxies. Recent high-$J$ CO observations of the local IR-luminous galaxy Mrk 231 indicate that the CO emission from the dense gas may produce about the same amount of cooling radiation as the $[\text{C}\text{ii}]$ line (Papadopoulos et al. 2007), suggesting a totally different thermal balance than in lower luminosity galaxies. On the other hand, $[\text{C}\text{i}]$ would be more ubiquitous than high-$J$ CO lines in the ISM of galaxies, across a wide swath of conditions: not only does it remain luminous in metal-poor systems (e.g. Lyman-alpha emitters) but it is also not tied to star-forming sites; in fact even the CNM and WNM H I phases have significant $[\text{C}\text{i}]$ emission contributions. The latter makes this line an excellent dynamical mass probe, but also though to interpret in terms of H$_2$ mass
alone since non-trivial corrections must be made for [C\textsc{ii}] emission from atomic and even ionized gas (e.g. Madden et al. 1997).

6 What will the future bring?

The combined efforts of future cm/(sub)mm facilities (ALMA, CCAT, LMT), and upgraded existing facilities (IRAM PdBI+30m, CARMA, eSMA, EVLA, GBT, e-Merlin), will allow for unbiased, large-scale surveys of molecular and atomic lines in galaxies out to $z \sim 10$. One could envisage multiplexed, broadband cm/mm spectrometers (akin to Z-Spec and ZEUS) on large single-dish (sub)mm telescopes such as CCAT and LMT carry out large ‘blind’ molecular line searches that objectively sample line luminosity functions (in terms of redshift and luminosity). ELVA and ALMA would facilitate detailed studies via the low- to mid-$J$ CO/HCO$^+$/HCN lines and atomic transitions ([C\textsc{i}]/[C\textsc{ii}] and [N\textsc{ii}]). Herschel will observe the high-$J$ ($J > 5 - 4$) CO lines in local (U)LIRGs, resulting in fully sampled CO SLEDs in the local Universe, which undoubtedly will be of great use in our exploration of distant galaxies. In the next decade, therefore, we expect to see a genuine revolution in our ability to study the cosmic star formation and ISM evolution, resulting in definite answers to all (and many more) of the issues outlined in this text.

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