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Observations of Molecules in High Redshift Galaxies

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Abstract. I present an overview of the molecular gas observations in high redshift galaxies. This field has seen tremendous progress in the past few years, with an increased number of detections of other molecules than CO. The molecular line observations are done towards different classes of massive starbursts, including submillimeter galaxies, quasars, and massive gas-rich disks. I will highlight results of detections of HCN, HCO+, and other small molecules, as well as the Spitzer detections of PAHs. Additionally, I will discuss about the excitation of CO and other species in the high-z galaxies and put this in the context of new telescopes such as ALMA.

Keywords. ISM: molecules, galaxies: evolution, galaxies: ISM, galaxies: high-redshift, galaxies: starburst, quasars: emission lines, infrared: ISM, radio lines: galaxies, submillimeter

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1. Introduction

The number of observations of molecular gas in high redshift galaxies has increased tremendously over the past decade. The first detection of CO in a high redshift, $z > 1$(†), galaxy was towards IRAS F10214+4724 ($z = 2.2867$; Brown & Vanden Bout, 1991; Solomon, Radford & Downes, 1992), which is an IR-luminous galaxy. For a long time it was also the best studied high redshift galaxy as it is one of the brightest IR galaxies at cosmological distance due to gravitational lensing. Observations of molecular gas in high redshift galaxies an important part of studying galaxy formation and evolution as the molecular gas traces the gas that is available for star formation and the gas that is present in the star forming regions.

In this contribution I will give an overview of the numerous molecular line studies in high redshift galaxies. This field has expanded rapidly in the past few years with many new and exciting results, and thus I will not attempt to give a complete collection of all high redshift molecular line detections, but rather give a broad overview highlighting how these studies provide valuable insight in the nature of high redshift star forming galaxies and how it places the galaxies in the context of galaxy formation and evolution. Even though the combination of molecular and atomic lines allows for a detailed analysis of the underlying physics, I focus here on the molecular line results. Observations of atomic fine-structure lines towards high-z galaxies is another major challenge.

About half of the stars that we see in present galaxies has been formed during the first few billion years after Big Bang. Through observations of high-z starbursts, we are able to study the early phases of massive galaxies, that is so to say the childhood of the massive galaxies. Massive starbursts are rare phenomena in the local Universe, typically seen in ultra-luminous IR galaxies (ULIRGs). However, at high redshift $z > 1$ starbursts prevail and produce about 30% of the total energy output, hence constituting a significant

† Assuming $H_0 = 71$, $\Omega_M = 0.27$, and $\Omega_\Lambda = 0.73$, $z = 1$ corresponds to a Universe age of 5.9 Gyr, similarly, $z = 3$ and 6 correspond to 2.1 and 0.95 Gyr, respectively.

population at early times. Most high-z starbursts with star formation rates (SFR) larger $100\,M_\odot$/yr, and often $> 1000\,M_\odot$/yr, have been discovered through submm continuum observations (so-called submillimeter galaxies, SMGs; e.g. Smail *et al.* 1997). The submm light is the redshift far-infrared dust emission that arise from the dust-enshrouded massive star forming regions.

Molecular line studies of high redshift galaxies are used to address many different scientific questions, including:
– What is the total molecular gas mass and gas fraction? How does the gas fraction evolve?
– What is the evolution the molecular gas density on cosmological time scales?
– What is the dynamics of the gas?
– What are the excitation conditions in high-z galaxies?
– What fuels the gas reservoir, mergers vs. accretion?
– What is the relative importance of star formation and AGN, both in quasars and in starburst galaxies?

I will show results for observations of small molecules and the excitation conditions that are probed using their rotational transitions. I will also highlight results for large molecules, namely the PAHs.

2. Small molecules

Despite H_2 being the most prevalent molecule in space, it is difficult to observe because it has no permanent dipole moment. Hence many other molecules are used to probe the conditions in different environments of the ISM, star forming regions, and AGN.

2.1. *Molecular hydrogen*

UV-lines of the rotational-vibrational state of molecular hydrogen are redshifted into bands that are observable using ground-based telescopes. These lines would be very difficult to detect in emission, however, a number of projects have successfully detected H_2 in absorption towards damped Lyα absorption systems (DLAs).

Ledoux *et al.* (2006) detected molecular hydrogen in absorption in the very high redshift damped Lyα absorption system (DLA) at $z = 4.224$ towards the quasar PSS J1443+2724. The detected absorption lines are rotational levels of the vibrational ground state at rest wavelengths in the far-UV part of the spectrum. They derive column densities of $\log N(H_2)\sim 17.5$. Ledoux *et al.* (2006) finds that the density of the gas is $n < 50\,\mathrm{cm}^{-3}$ and suggests that the gas seen in the absorbing galaxy has been left over from previous star formation activity.

Observations of H_2 emission lines is very challenging and only few lines have been successfully detected. In IRS spectroscopy of a multiply imaged galaxy behind the Bullet Cluster, Gonzalez *et al.* (2010) find tentative detections of two pure rotational lines, H_2 0–0 $S(4)$ and H_2 $S(5)$. This is the first detection of these lines in high redshift galaxies. For a single temperature gas, the observed flux ratio gives a temperature $T \sim 375\,\mathrm{K}$. With an estimated warm molecular gas mass of $M_{H_2} \sim 2.2 \times 10^8\,M_\odot$ (assuming a lensing magnification of 100), this suggest a relatively cool dusty starburst in a low-mass dwarf galaxy ($M_\star \sim 4 \times 10^9\,M_\odot$; Gonzalez *et al.* 2010).

2.2. *Carbon monoxide*

With a low dipole moment of 0.1 Debye, hence easily excited, and being the second most abundant molecule in interstellar space, CO is commonly used as a tracer of molecular gas. With an excitation temperature of 5.52 K for the rotational $J = 1 - 0$ transition, CO(1-0) traces essentially all molecular gas, predominantly excited by H_2 collisions.

The majority of our knowledge about molecular gas comes from observations of CO – in particular for high redshift galaxies. Depending on the exact redshift, the CO(3-2) or CO(4-3) are redshifted into the mm bands. These lines are generally brighter than the ground transition, and there are many atmospheric windows at millimeter wavelengths, hence making those transitions a prime choice for molecular gas searches.

In the 1990's the number of CO observations in high-z galaxies was limited to a small number of extremely luminous galaxies, mostly quasars (e.g. Ohta et al., 1996; Barvainis *et al.*, 1997; Downes *et al.*, 1999; Guilloteau *et al.*, 1999). In the past decade the number CO observations has sky-rocketed thanks to a number of improvements: (i) Large samples of high-redshift galaxies have been established through observations across different wavelengths. For example today more than 35000 quasars are known at $z > 2$. Through systematic searches with the instruments SCUBA, MAMBO, LABOCA, Spitzer MIPS, and very recently with Herschel PACS / SPIRE, the number of high-z massive starburst galaxies, such as SMGs, continues to rise. (ii) The advances in receiver and correlator technology, which have provided more sensitive instruments. Moreover, the increased bandwidth coverage that is now reaching up to several GHz makes it possible to observe several thousand km/s velocity ranges in one go. As a result, it is possible to search for CO based on UV redshifts that might be offset from the systemic redshift of the targeted galaxy — this is in particular important for quasars.

Despite these important improvements, molecular gas observations at high-z are challenging. So far obtaining a CO detection typically requires several hours of observations per individual object. This means that this research field is only slowly moving from studying a few individual sources to systematic surveys of large samples – to contrast the number of known quasars at $z > 2$, the number of $z > 2$ quasars with a CO detection is currently around 30.

I here summarize some of the main results in high-z CO observations:

Quasars: It has been found that about 1/3 of optically selected quasars have thermal far-infrared emission with dust temperatures comparable to what is found in the starburst galaxies, $T_{\rm dust} \sim 30 - 50$ K, with implied far-infrared luminosities of $> 10^{12-13}$ L$_\odot$ (e.g. Omont et al., 2001; Carilli *et al.*, 2001). It is expected that a significant fraction of the FIR luminosity is indeed powered by star formation. One of the arguments for this is the detection of molecular through CO, showing the existence of gas reservoirs with masses of the order $M_{H_2} \sim 10^{10}$ M$_\odot$. Qualitatively quasars are found to follow the $L'_{\rm CO} - L_{\rm FIR}$ relation known for starbursts (illustrated in Fig. 1), however, there is a large scatter around the relation, which can be assigned to the fact that the far-infrared luminosity might be powered by both the star formation and AGN, as well as to the fact that many quasars have only been observed in CO(3-2), (4-3), or (5-4) transitions which might be subthermally excited. In some case CO is not detected towards a quasar. For example in the case of PSS J1057, which has a very high far-infrared luminosity, the CO non-detection implies an upper limit significantly away from the $L'_{\rm CO} - L_{\rm FIR}$ relation (Knudsen *et al.*, in preparation). This indicates that the far-infrared emission is powered by the AGN. Among the numerous results that have been derived from CO studies of quasars include the location of $z = 6$ quasars the $M_{\rm BH} - M_{\rm bulge}$ correlation from nearby massive galaxies (Häring & Rix, 2004). This is the relation between the mass of the central super-massive black hole and the mass of the bulge and this relation suggests that the evolution of the SMBH and the bulge is coeval. The results from Wang *et al.* (2010)

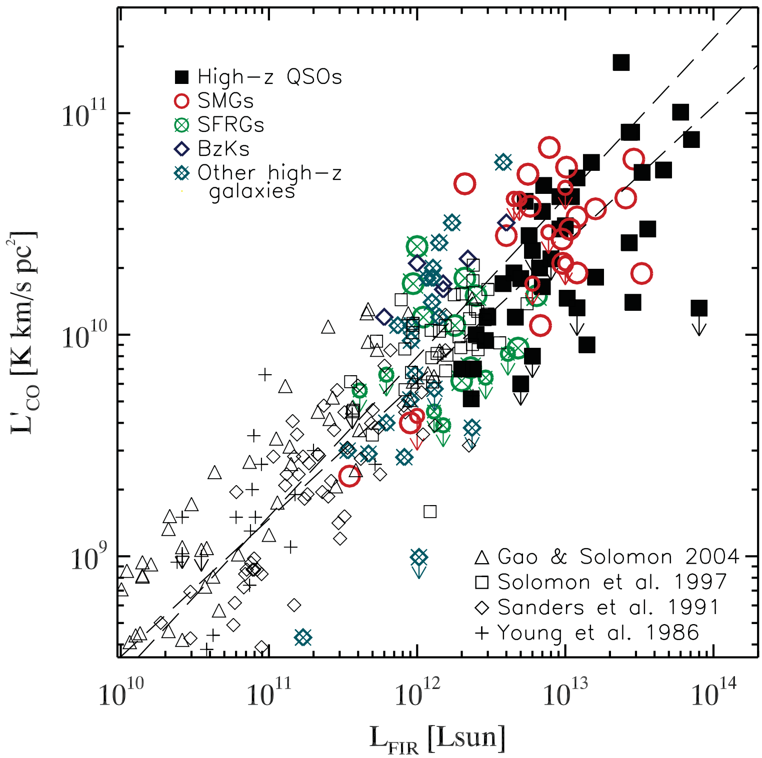

Figure 1. $L_{\rm FIR}$ and $L'_{\rm CO}$ plotted for nearby spiral and starburst galaxies (Young *et al.* 1986; Sanders *et al.* 1991; Solomon *et al.* 1997; Gao & Solomon, 2004a), high redshift starburst galaxies (e.g. Neri *et al.*, 2003; Baker *et al.* 2004; Kneib *et al.* 2005; Greve et al., 2005; Tacconi *et al.*, 2006, 2010; Knudsen *et al.*, 2009; Daddi *et al.*, 2010; Casey *et al.* 2011), and high redshift quasars (e.g. Downes *et al.*, 1999; Guilloteau *et al.*, 1999; Walter *et al.*, 2003; Hainline *et al.*, 2004; Riechers *et al.*, 2006; Maiolino *et al.*, 2007; Coppin *et al.*, 2008; Wang *et al.*, 2010; Knudsen *et al.*, in prep). The dashed lines show the best-fit to the $\log L_{\rm FIR} - \log L'_{\rm CO}$ from Greve *et al.* (2005) and Riechers *et al.* (2006a).

shows that the $z = 6$ quasars have a much large $M_{\rm BH}$ than nearby massive galaxies, when using sensitive CO observations as one of the only means to derive the $M_{\rm bulge}$.

Submillimeter galaxies: Obtaining CO observations for SMGs has been very challenging with the most important reason for this being the difficulties of identifying the correct counterpart galaxy and obtaining a spectroscopic redshift. A CO detection helps confirm the validity of the counterpart and redshift determination. Intensive efforts using in particular the IRAM PdBI have so far produced a similar number of detections as for the quasars. Among the largest samples so far are Greve *et al.* (2005) and Tacconi *et al.* (2006, 2008). The majority of the CO detected SMGs have been detected in blank-field studies meaning that they are more luminous than local ULIRGs and thus representing starburst environments that are found in the local Universe. SMGs found in galaxy cluster fields have been gravitationally lensed and their properties are more like those found in local LIRGs and ULIRGs — however, the number of studied lensed SMGs is small (e.g. Kneib *et al.* 2005; Knudsen *et al.* 2009).

The molecular gas masses found in SMGs are similar to those found in quasars, namely on the order of 10^{10} $M_\odot$. The gas depletion time is estimated to be around 10-40 Myr (e.g. Tacconi *et al.*, 2006), and implied gas fractions of $20-50\%$ e.g. Tacconi *et al.* (2008).

High angular resolution studies of the molecular gas are used for dynamical studies of the SMGs, and e.g. Engel *et al.* (2010) has shown that most SMGs appear to be major merger events. Other studies also suggest that some SMGs are not major mergers, but could be disks at early stages that are growing through accretion of "cold" intergalactic gas where some of the support for this is derived from the CO detections, namely through mapping combined with multiple J transition (e.g. Carilli *et al.* 2010)

Other starburst galaxies: Also other starburst galaxies have had successful CO detections, this include Lyman Break Galaxies (e.g. Baker *et al.*, 2004; Coppin *et al.* 2007) and submillimeter-faint star-forming radio galaxies (Casey *et al.* 2011). Here I highlight the results for BzK selected galaxies. Daddi *et al.* (2008, 2010) have observed CO towards six BzK-selected galaxies, which have been observed from mm to UV wavelengths. They have UV morphologies that are consistent with clumpy unstable disks – contrary to the majority of SMGs, which appear to be interacting or merging galaxies (e.g. Engel *et al.* (2010). Other properties where BzKs appear to be fundamentally different from SMGs include the size of the gas reservoirs and gas depletion time scale. The size of the molecular gas is estimated to be $6 - 11$ kpc in BzKs, while $< 2 - 4$ kpc in SMGs (e.g. Daddi *et al.* 2010; Tacconi *et al.* 2008). The gas depletion time for BzKs are ~ 0.5 Gyr, which is about an order of magnitude longer than for SMGs that have $\tau_{\rm dep} \sim 10 - 50$ Myr.

2.3. *Water*

Detection of water emission lines in high redshift galaxies is difficult. Several searches for different H_2O lines in both quasars and starburst galaxies, have yielded non-detections (e.g. Riechers *et al.* 2006, Wagg & Momjian 2009, Edmonds *et al.* 2009, McKean 2011). A few tentative detections (Bradford *et al.* 2009, Lupu *et al.* 2011, McKean *et al.* 2011) and a three detections have been published. In the Cloverleaf quasar, Casoli *et al.* (1994) detected the H_2O $2_{02} \rightarrow 2_{11}$ line using the IRAM 30m.

Impellizzeri *et al.* (2008) detected the 22 GHz maser line in the $z = 2.64$ quasar MG J0414+0534. The maser is likely induced by a relativistic jet interacting a gas cloud or associated with the circumnuclear accretion disk.

For the H-ATLAS source SDP.17b (J090302.9-014127B), which is a strongly lensed galaxy at $z = 2.3$, Omont *et al.* (2011) report a detection of the H_2O $2_{02} \rightarrow 2_{11}$ line. The results suggest that SDP.17b could be the host of a luminous AGN similar to the nearby Mrk 231 galaxy.

2.4. *HCN, HCO^+, and CN – tracers of dense gas*

While, due partly to its abundance, the rotational emission lines from CO are several time brighter than those of other small molecules, other molecules such as HCN, HCO^+, and CN, provide a valuable insight into the denser gas. The dipole moment is substantially larger for HCN ($\mu_{\rm HCN} = 2.98$D), HCO^+ ($\mu_{\rm HCO^+} > 3$D), and CN ($\mu_{\rm CN} = 1.45$D), than for CO ($\mu_{\rm CO} = 0.12$D), and hence the critical density for collisional thermal excitation is around 10^{4-5} cm^{-3} in the ground transition, which is significantly larger than for CO. Therefore these molecules are expected to probe the dense gas regions of the actual star formation as is also the case in the Galaxy. Studies of local starbursts and AGN show that the ratio between HCN and HCO^+ can be used in analysis of distinguishing between starburst and AGN due to the difference in their physical and chemical properties (e.g. Imanishi *et al.* 2009).

The HCN and HCO^+ lines are many times fainter than the CO lines, and so far the successful detections towards high redshift galaxies have only been made towards very bright objects, mostly quasars. A number of searches have been carried out, especially for

HCN (e.g. Vanden Bout *et al.* 2004; Carilli *et al.* 2005). The Cloverleaf quasar ($z = 2.5$) was the first high-z galaxy for which an HCN-detection was confirmed (Solomon *et al.* 2003), where the HCN line luminosity imply that the mass of the very dense gas is $\sim 10^{10}$ $M_\odot$. The detection of HCO^+(4-3) and (1-0) in the Cloverleaf shows that HCO^+(4-3) is subthermally excited similarly to local starburst galaxies (Riechers *et al.*, 2006b, 2011a). Same conclusions are not reached for extreme $z = 3.9$ quasar APM08279+5525 (Wagg *et al.*, 2005; Garcia-Burillo et al. 2006; Riechers *et al.* 2010).

In nearby galaxies, there is a stronger correlation between the HCN line luminosity and the far-infrared luminosity (used as a proxy for the SFR) than is found for CO (Gao & Solomon 2004b). Gao *et al.* (2007) combined high-z HCN observations and showed that the high-z galaxies systematically lie above the local $L_{\rm FIR} - L'_{\rm HCN}$ relation — this included upper limits derived from HCN-non-detections. This suggests that the SFR per unit dense molecular gas is higher than that of ULIRGs and nearby star forming galaxies. Moreover, when comparing the HCN with CO, there is a strong indication of a higher fraction dense molecular gas in the high-z galaxies.

A detection of HNC(5-4) has been published by Guélin *et al.* (2006) in APM08279. HNC(5-4) has a critical density around $\sim 10^7\,{\rm cm}^{-3}$, and the abundance ratio between HNC and HCN is known to have large variations in different environments. For APM08279, the abundance ratio [HNC]/[HCN] is found to be close to one, which is much larger than what is found Galactic hot, dense molecular clouds (Guélin *et al.* 2006).

Finally, the cyanide radical, CN, which is typically found in regions that are exposed to UV radiation field from stars, has also been detected at high-z. Tracing the dense interfaces between a molecular clouds and ionizing fronts, CN is likely a good tracer of the photochemistry in those layers. The ratio between HCN and CN might provide diagnostics for the relative importance of PDRs in a source, hence also trace the UV field. The first high-z detection of CN(3-2) was reported by Riechers *et al.* (2007), who detected this line in the Cloverleaf quasar. The CN line luminosity is slightly brighter than that of HCN and HCO^+. Riechers *et al.* (2007) also find that the Cloverleaf CN-detection follows the $L'_{\rm CN} - L_{\rm FIR}$ relation known from local galaxies, and thus shows promise as a valuable line for high-z galaxy studies.

3. Excitation of molecular gas

With a series of different J-transition observations for a specific molecule it is possible to estimate or determine the excitation conditions of the molecular gas. Typically the derived physical properties are temperature and density, however, depending on the model employed this could also include intensity of the radiation field. The most commonly used molecule is CO because of the relatively brighter lines. The low-J transitions will trace the cold and less dense gas, while the higher-J transitions will trace the dense gas. SMGs, quasars, and massive BzK-selected galaxies have proven to have different excitation conditions and different dominant gas components.

3.1. *Excitation in starburst galaxies*

Through multi-J ^{12}CO observations from $J = 10-9$ to $J = 3-2$ and $J = 1-0$ in the SMG SMMJ2135-0102, $z = 2.3$, a.k.a. the Cosmic Eyelash, the phases of the gas components have been studied and modeled in detail (Danielson *et al.* 2011). The CO observations have been combined with detections of [CI], [CII], and HCN. With 14 detections and 20 upper limits from molecular lines and atomic fine-structure lines, this is one of the best studied high-z starburst galaxies. Using both LVG models (large velocity gradient) and PDR models (photodissociation region), Danielson *et al.* (2011) found that the CO line SED would be best fit with two-phase gas components, one component being a warm, dense luminous component with $T \sim 60\,\mathrm{K}$ and densities of $n_{H_2} \sim 10^{3.6}\,\mathrm{cm}^{-3}$, and the other component being a low-excitation, cool extended massive component with $T \sim 25\,\mathrm{K}$ and $n_{H_2} \sim 10^{2.7}\,\mathrm{cm}^{-3}$. Furthermore, the UV radiation field is about 1000 times more intense that in the Galaxy.

The analysis of the CO line SED of the Cosmic Eyelash, demonstrates very well the amount detail that can be derived about high-z starbursts, however, it is also a demanding study requiring molecular observations from several different mm and submm telescopes. Some other studies of SMGs have obtained multi-J CO observations (e.g. Weiss *et al.*, 2005, 2007; Riechers *et al.*, 2011d; Carilli *et al.* 2010). These have not had the same number of CO transitions as in the case of the Eyelash, however, they provide results for a larger number of sources. In Weiss *et al.* (2005, 2007) presented high-J ($J > 3$) observations of both SMGs and quasars, with the finding that SMGs typically have a turn-over in CO SED around $J = 5-4$, which is a bit lower than in quasar starbursts. Furthermore, the CO line SEDs can be fitted with a single gas component (using LVG models). It is however important to keep in mind that the Weiss *et al.* (2007) study does not include CO(1-0) and is therefore not sensitive to an extended, low-dense gas component. Ivison *et al.* (2011) and Riechers *et al.* (2011b) combined $J = 1-0$ observations with $3-2$, or $4-3$ and $6-5$, observations of $z = 2$ and $z = 3.4$ SMGs and demonstrated that CO SED fitting require more than one gas component, similarly as described above for the Eyelash. Additional to the dense, warm gas present in the star forming region, evidence for an extended, low density is found. The extended component have typical sizes $> 10\,\mathrm{kpc}$ with no evidence for large-scale flows of cold gas (Ivison *et al.*, 2011). These extended, low dense gas component likely contributes at least 30-50% to the total molecular gas reservoir in SMGs.

3.2. *Excitation in quasars*

Contrary to the SMGs, quasars appear not to have an extended molecular gas reservoir. This has been found in two studies of both $z \sim 4$ and $z \sim 2$ quasars using the CO(1-0) line compared to high-J transitions (Riechers *et al.*, 2006a, 2011e).

In the study from Weiss *et al.* (2007), quasars have also been observed. The CO line SEDs can be fitted with a single temperature / density model (using LVG models), in good agreement with the CO(1-0) results from Riechers *et al.* (2006, 2011e). A notable difference between the CO line SEDs of quasars and SMGs is the fact that the line SED has a turn-over at higher J, in most cases around $J = 7-6$ or $J = 8-7$. The molecular gas is possibly concentrated in a more compact region in the quasars, and the presence of the quasar is expected to influence the excitation. In the case of APM08279, the CO line SED differs from all other known cases. The SED turns over only around $J = 10-9$, and the fitted LVG model suggests a kinetic temperature of $\sim 200\,\mathrm{K}$ close to the dust temperature and a density $\sim 2.5 \times 10^4\,\mathrm{cm}^{-3}$ (Weiss *et al.*, 2007).

For the two quasars, APM08279 and the Cloverleaf, there exists observations of several HCN and HCO^+ lines. These two quasars show different excitation properties. For the Cloverleaf, the HCO^+ line SED indicate a subthermal excitation of the $J = 4-3$ transition with $(4-3)/(1-0)$ ratio similar to the local starburst galaxy NGC253 (Riechers *et al.* 2011a; Knudsen *et al.*, 2007). The excitation is consistent with being purely collisionally excited. The results look remarkably different for APM08279, where strong HCN(6-5), HNC(6-5), and HCO^+(6-5), emission has been detected (Riechers *et al.*, 2010). In this case, modeling of the HCN-excitation indicate that collisional excitation cannot alone account of the high strength of the line emission, but radiative excitation through strong IR-radiation field, which efficiently pumps the high-J lines, likely provide sufficient excitation. APM08279 is an extreme and unique case, for which so far there has been no other high-z galaxy found with similar excitation properties.

3.3. *Excitation in massive disk galaxies*

While SMGs and quasars show compact and high-excitation molecular gas, recent studies of BzK-selected massive star forming disk galaxies ($z \sim 1.5$) yield results that show different properties.

Observations of CO in $J = 3-2$, $2-1$, and $1-0$ in these massive disk galaxies have revealed low gas excitation. The CO(3-2) appears to be subthermally excited (Dannerbauer *et al.* (2009). A subthermal excitation might also be the case for the CO(2-1) line, however, the data are not sufficiently sensitive to confirm this (Aravena *et al.*, 2010). The galaxy BzK-21000 has the best sampled CO SED, and the results of LVG model fitting imply a temperature of $T_{\rm kin} = 20 - 150\,{\rm K}$ and density of $n_{H_2} = 400 - 2500\,{\rm cm}^{-3}$ (Dannerbauer *et al.* 2009; Aravena et al., 2010), which are very different from the temperature and density estimated for quasars and SMGs, as discussed above. While the CO SED is different from both nearby and high-z starbursts, it very similar to what is seen in our own Milky Way. Low excitation of the molecular gas as found in the BzK star forming galaxies could provide a possible explanation why CO(4-3) was not detected in the lensed $z_{\rm spec} = 4.04$ SMG SMMJ163555+661300 (Knudsen *et al.*, 2010). In general, while it is thought that SMGs are progenitor of nearby massive elliptical galaxies, the BzK selected massive disk galaxies are related to the nearby massive disks galaxies (which later might become part of a major merger event).

4. Observations of PAHs

Polycyclic aromatic hydrocarbons (PAHs) are large molecules (with sizes up to a few nm) found in the star forming regions. The vibrational modes of PAHs produce emission lines that are seen in the mid-infrared part of the spectrum. The main spectral features are observed at rest frame wavelengths 6.2, 7.7, 8.6, 11.3, 12.7, and 17 μm coming from stretching and bending of the C$-$C or C$-$H bonds (e.g. Draine 2003). PAHs are excited by the UV photons from star formation. Calzetti *et al.* (2005) find in a study of M51, that the PAHs are heated by photons coming from current star formation (< 10 Myr) as well as recent star formation (< 100 Myr). However, in intense UV-radiation fields, the PAHs could be ionized or destroyed (e.g. Tacconi-Garman *et al.*, 2005, and references therein). A correlation between the PAH emission and the star formation rate has been found, though there is also a dependence on, e.g., metallicity (Calzetti (2011) and references therein).

In the local Universe, both normal and starburst galaxies show strong PAH emission and with little variation in strength and shape (e.g. Rigopoulou *et al.*, 1999). However, towards AGNs the PAH emission is weak, potentially caused by destruction of the PAHs or by a dilution of the PAHs emission feature by the warm continuum from the AGN. Hence, in AGN and quasar studies the mid-infrared continuum from hot dust is expected to dominate the mid-infrared spectra.

With the launch of the Spitzer Space Telescope, the infrared spectrograph IRS enabled observations of PAHs towards high redshift galaxies. A large series of projects have been carried out for galaxies ranging from lyman break galaxies to quasars.

4.1. *Ly-α blobs*

While high-z PAHs studies has been observations of individual galaxies, Colbert *et al.* (2011) obtained Spitzer spectroscopy of Ly-α blobs (LABs). The LABs are Lyα

nebulae with Lyα fluxes $\sim 10^{43-44}$ erg/s extended over $\sim 50 - 150$ kpc and typically found within high-z galaxy over-densities. The flux is comparable to that of high-z radio galaxies, however, there is no evidence that it should arise from interaction with jets. The actual source of energy exciting the hydrogen gas is not known. Models and observations point towards different types of scenarios, which include superwind outflows and cooling flows (e.g. Matsuda *et al.*, 2004). In the study from Colbert *et al.* (2011), two out of the six sample sources that are infrared-bright sources associated with LABs show only continuum emission suggesting that they are dominated by an AGN. The other four sources show PAH emission line, implying signification star formation. Despite that in two of the PAH detected sources have estimated SFRs that would imply sufficient energy from supernova outflows to power the LABs, there is no conclusive evidence that these infrared-bright galaxies could be the single source responsible for the LABs.

4.2. *Starburst galaxies*

Massive starbursts like those seen in SMGs are probably the most obvious targets for observations of PAHs at high redshifts. With star formation rates on the order of $1000\,M_\odot$/yr the PAH emission lines are expected to be bright, and therefore also provide a means to, for example, determine the redshift for sources with very faint optical counterparts. A large number of other PAH studies of high-z starburst galaxies that have been selected through different selection criteria have been published (e.g. Yan *et al.* 2005; Rigby *et al.*, 2008; Dasyra *et al.* 2009; Desai *et al.*, 2009; Siana *et al.*, 2009; Fadely *et al.* 2010). Here I focus on the SMGs.

Both Pope *et al.* (2008) and Menéndez-Delmestre *et al.* (2007, 2009) have obtained IRS spectra of more than 30 SMGs in two different studies. The SMGs follow the relation between infrared luminosity and PAH line luminosity that is established for local starburst galaxies (e.g. Peeters *et al.* 2004). An important implication of this is that the PAH luminosity can be used for estimating the SFR in SMGs. Comparing the extinction properties derived from the mid-infrared spectroscopy of SMGs with those of local ULIRGs, Menéndez-Delmestre *et al.* (2009) argues that the PAH emission arise from a more extended region ($> 1 - 2$ kpc) than is seen in the compact star forming regions of ULIRGs.

The PAH results for the SMGs suggest that the mid-infrared spectral properties are somewhat different from those of $z \sim 2$ 24μ-selected ULIRGs (e.g. Sajina *et al.* 2007; Dasyra *et al.* 2009), as the latter displays mid-infrared spectra of both star formation dominated and AGN dominated emission (e.g. Pope *et al.* 2008). An important point about PAH studies of SMGs is that while X-ray studies can show the presence of an AGN, the mid-infrared spectroscopy can be used for determining the relative contribution of the AGN and starburst to the generated energy output (e.g. Pope *et al.* 2008).

4.3. *Quasars and AGN*

Even though quasar host galaxies in many cases harbor a massive starburst, the mid-infrared spectra appear different because of the AGN hot dust emission, which contribute significantly at these wavelengths. Lutz *et al.* (2008) obtained IRS spectra for 12 $z = 1.8 - 2.8$ radio-quiet quasars, which all show signs of intense star formation activity, however, the far-infrared emission alone does not provide conclusive evidence for the relative heating of the dust by star formation and AGN activity. Using the PAH emission lines, it is possible to model how much dust emission arise from the starburst and how much from the AGN. The reason for this is that the PAH emission from a starburst region is less likely to be dominated by emission from the AGN compared to a number of other star formation tracers. Mid-infrared spectroscopy was also used for local PG quasars to estimate the star formation contribution (e.g. Schweitzer *et al.*, 2006). In the spectra of the 12 quasars, Lutz *et al.* (2008) show PAH detections in nine cases. For the other three the non-detection possibly reflects structure in the continuum emission and the silicate feature rather than an absence of PAH emission. Based on the PAH detections, derived SFRs estimates are up to $\sim 3000\,M_\odot/yr$, strongly supporting that the far-infrared emission is dominated the intense star formation.

In a study by Coppin *et al.* (2010), mid-infrared spectroscopy of PAH emission was used to investigate the relative importance of AGN in SMGs that show signs of the presence of powerful AGN. The near-infrared and mid-infrared photometric colors suggest that these are AGN dominated SMGs; majority of SMGs are known not to have a dominating AGN (e.g. Pope *et al.* 2008). In all eight SMGs PAHs are seen in the spectra, however, there is also a strong mid-infrared continuum. Combined with previous results for other SMGs (also see discussion above), Coppin *et al.* (2010) conclude that about 15% of SMGs have mid-infrared spectra dominated by AGN emission. Though with only two of the eight observed galaxies having bolometrically important AGN, this implies that the total infrared luminosity, $L_{\rm IR}$, is dominated by AGN emission in about 5% of all blank-field SMGs. These AGN-dominated SMGs could represent a later stage in an evolutionary sequence, where the SMGs are followed by an AGN or quasar phase.

5. Outlook

As ALMA is gradually becoming available with cycle-0 in the near future and the complete array only a couple of years away, doing detailed molecular line spectroscopy will be possible even for high redshift galaxies. Once complete, ALMA provides a very desirable combination of high sensitivity and bandwidth of up to 8 GHz, and thereby making it possible to obtain multiple molecules lines within the same observations as well as obtaining observations of other lines than CO for a large number of galaxies. For example, as highlighted above, CN could provide a useful tracer of the dense gas. The CN(3-2) is only about 5.5GHz away from the CO(3-2) line in rest-frame frequency, meaning that for a $z \sim 2-3$ galaxy both lines can observed simultaneously. Within the same spectra other fainter molecular lines are likely to emerge, providing a new challenge for high-z studies, namely astrochemistry.

One of the recent, interesting results is the detection of extended, low density, cool massive molecular gas reservoirs in the high-z star forming galaxies. It is possible that some of these reservoirs are related to secular galaxy evolution, which might be fed through "cold" streams of gas from the intergalactic medium (e.g. Dekel *et al.* 2009). One of the challenges for studying this at increasing redshift is the fact that the CMB temperature rises with redshift. Simple modeling shows that extended molecular disks will be subject to dimming due to the CMB (Weiss *et al.*, in preparation), impacting in particular on the low-J CO transitions.

Finally, deriving the cosmic evolution of the molecular gas space density, Ω_{H_2}, will provide important input for models of galaxy formation and evolution. Ω_{H_2} is predicted to rise rapidly and peak around $z \sim 2-3$ before declining to the known level of the present-day Universe (Obreschkow & Rawlings, 2009), similar to the cosmic star formation rate density. To address, large scale blind searches of molecular gas are needed, requiring a large sensitivity, large velocity/redshift range coverage, and a large field of view. A challenge for the EVLA and the SKA precursor MeerKAT, as these will be able to survey the CO(1-0) emission line from redshift $z \sim 1.5$ to $z > 10$.

6. Summary

• *Small molecules*: Carbon monoxide is the most commonly observed molecule in high redshift galaxies. It provides a confirmation that a molecular gas reservoir is present and that this could be the gas fueling the starburst in the high redshift galaxies so far selected for studies of molecular emission lines. The CO line observations are used for studying many different aspects of the individual galaxies as well as galaxy evolution. For example high angular resolution imaging provide a wealth of information on the dynamics of the starburst region.
Despite that H_2 is the most abundant molecule, the number of successful detections of H_2 at high-z is extremely limited. However, aside from CO, a few other small molecules have been detected in high-z galaxies and used as probes for different conditions. HCN and HCO^+ have been detected towards a small number of bright quasars. Additionally, there is a detection of CN and HNC. The number of detections of these four molecules along with others is expected to increase within the next couple of years as ALMA will be completed.
Water has turned out to be difficult to detect with so far less than a handful of successful detections — all towards galaxies where the AGN might play an important role.

• *Gas excitation*: Quasars appear to have higher excitation conditions than starbursts. Furthermore, quasars appear not to have a significant extended molecular gas component with low density. Starbursts on the other hand do appear to have two important phases in the molecular gas - a dense molecular gas reservoir and the a low-dense gas possibly extended over a larger region. The extended gas reservoirs contain a significant fraction of the total molecular gas. Extreme starbursts like SMGs have higher excitation of the molecular gas than massive gas-rich galaxies found through the BzK selection technique.

• *PAHs at high-z*: Numerous studies of mid-infrared spectroscopy of high redshift galaxies, have shown that PAH observations provide a strong tool for differentiating between star formation dominated and AGN dominated mid-infrared emission. Furthermore, the PAH spectral lines provide a means for determination of the redshift for SMGs that have very faint optical counterparts. The SFR can be estimated from the PAH luminosity. Using this it is possible to separate the contribution to the infrared luminosity from the starburst and the AGN in, e.g., quasars.

• *Future*: With the new and significantly improved capabilities of ALMA, and other radio / mm telescopes, the molecular line observations of high redshift galaxies will move away from single molecule observations into an era where emission lines from several molecules might show up in the same spectrum. This means that it will very soon become possible to do astrochemical studies in galaxies that represent early and extreme phases in the evolution of galaxies.

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Discussion

R. Mauersberger: The SEDs of CO lines in distant galaxies look very different from those of Galactic clouds. IS there still something like an X-factor to convert CO intensity into an H_2 column density?

Knudsen: An expected question! The different types of high-z galaxies represent a variety of physical conditions, and therefore different CO/H_2 conversion factors have to be chosen. As an example, Daddi *et al.* (2008) made careful considerations about this in their study of massive disk galaxies (BzK selected) and assumed a different conversion factor than is normally used in high redshift submm galaxies. Tacconi *et al.* (2008) made a detailed analysis to estimate an X-factor for high-z starburst galaxies.

Guelin: For the type of temperatures (T_K) and densities (n_{H_2}) that prevail in high-z circumnuclear disks, CO lines alone cannot determine independently T_K and n_{H_2}, as these parameters are degenerated. You have to turn to high density tracers like HCN, but those may not be coeval with CO. With all its power, ALMA may not be able to help on this matter as there is little hope to resolve the clouds inside the very distant disks.

Knudsen: Thank you for raising this point. To elaborate a bit more on your comment: A combination of different models (e.g. LVG and PDR) could provide a better insight. Furthermore, including observations of atomic fine-structure lines could add extra information, assuming the emission is from the same region.

M. Gerin: Have you considered looking for absorption lines from hydrides such as ground state water lines?

Knudsen: I have not looked into this option. I expect it would be difficult.