Molecular Emission Lines from High Redshift AGNs

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ABSTRACT

A brief overview is given of the current status of molecular emission line observations at high redshift. New observations are presented of CO in the gravitationally lensed quasar MG 0414+0534 (detected) and the unlensed quasar PG 1634+706 (not detected). Also noted are the results of a partially completed search for water maser emission in several redshift bands above \( z = 0.4 \).

1. Introduction

Molecular lines at high redshift have generated considerable interest as probes of the gaseous content of early galaxies, as signifiers of star formation, and as indicators of AGN activation processes. Thermal lines of species like CO trace large masses of molecular hydrogen, typically \( \sim 10^9 - 10^{11} M_\odot \), if detected in the distant universe. According to AGN activation scenarios developed over the past decade, it seems likely that many quasars and active galaxies turn on when fuel in the form of molecular gas is forced into a galactic nucleus during the course of an interaction or merger between two galaxies. This model connects IR-luminous galaxies and classical quasars in an evolutionary sequence that leads from concentration of gas in the nucleus through its consumption or expulsion, eventually revealing a mature, optically bright AGN (e.g., Sanders et al 1988; Barnes and Hernquist 1996). During this sequence the compressed gas may pass through a luminous nuclear starbursting phase.

Using molecular lines we hope to study these processes as they occurred in the early universe. The observations push current instruments to their limits, and consequently only a few sources have been detected at high-\( z \). Several of these detections have been aided by a boost from gravitational lensing. Below I summarize the observational situation with regard to thermal (i.e., non-maser) molecular lines, including discussion of a new detection of CO from a lensed quasar at \( z = 2.64 \).

I also briefly discuss an ongoing new search for \( H_2O \) masers at high redshift.

2. Thermal Lines

2.1. Low-\( z \)

In the late 80’s, with improvements in millimeter telescope sensitivities and impetus from far-IR detections by IRAS, IR-luminous galaxies and nearby AGNs began to be observed in molecular emission lines [primarily CO(1–0)]. The AGNs detected included Mrk 231 (Sanders et al 1987), Mrk 1014 (Sanders, Scoville, & Soifer 1988), I Zw 1 (Barvainis, Alloin, & Antonucci 1989), and a few other low-\( z \) quasars (Sanders et al 1989; Alloin et al 1992). Revealing maps of the nucleus of NGC1068 in both CO and HCN

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1Invited review to appear in “Highly Redshifted Radio Lines,” eds C. Carilli et al.
have been made with millimeter-wave interferometers (Tacconi et al 1994; Sternberg, Genzel, & Tacconi 1994; Helfer & Blitz 1995). At moderate redshift, Scoville et al (1993) detected CO in the radio galaxy 3C48 (z = 0.369). This measurement was interesting because 3C48 is a radio loud object which is clearly undergoing a merger that has dumped copious molecular gas into an elliptical host (see Stockton & Ridgway 1992, and commentary by Barvainis 1993).

2.2. High-z: The ‘old’ standbys

At high redshifts, the granddaddy of them all is of course IRAS F10214+4724, at z = 2.28, which has been detected in CO(3–2), CO(4–3), and CO(6–5) (Brown & Vanden Bout 1992; Solomon, Downes, & Radford 1992), but probably not in CO(1–0) (detection reported by Tsuboi & Nakai 1994 but not confirmed by Barvainis 1995). A gravitationally lensed IR-galaxy/hidden-quasar, F10214 has now been imaged in high resolution in CO, showing the 1.5′′ arc morphology seen in near-IR images (Downes, this volume). Various considerations suggest that the CO magnification factor is ∼10 (Downes, Solomon, & Radford 1995). The CO source has been reported to be extended as well on scales of 4 – 5″, well beyond the boundaries of the infrared morphology (Scoville et al 1995).

The second gold-standard CO source at high-z is H1413+117, the Cloverleaf quasar (Barvainis et al 1994; Wilner, Zhang, & Ho 1995), another lensed object. A total of 6 millimeter transitions at z = 2.558 have been reported: CO(3–2), CO(4–3), CO(5–4), CO(7–6), CI (3P_1−3P_0), and HCN(4–3) (Barvainis et al 1997). Detailed non-LTE modelling of the CO line strengths suggests that the molecular gas is warm (∼100 K), dense (n_H_2 ≥ 3 × 10^3 cm^{-3}), and not very optically thick (τ_{CO} ≤ 3). Recent high-resolution (0.5″) imaging with the IRAM Plateau de Bure Interferometer (PdBI) has clearly resolved the four optical spots in CO(7–6) emission. In the process of analyzing the CO images, evidence for a cluster of galaxies at z ∼ 1.7 was uncovered (Kneib et al 1997). This cluster appears to be providing an extra boost in addition to that of the (unseen) primary lensing galaxy. The CO morphology of the four spots is slightly different in the red and blue halves of the line profile, and projecting back to the source plane suggests that the CO is embedded in a rotating disk-like structure of diameter ∼ 200 pc (Kneib et al 1997; Alloin, this volume). The effective angular resolution on the CO source using this procedure is ∼0.03″, or about 17 times smaller than the synthesized beam! Yun et al (1997) also modelled the morphology of the red and blue halves of the CO(7–6) line, using 0.9″ resolution OVRO images. They arrived at a larger structure (∼1 kpc) than that derived by Kneib et al (1997), having a different position angle. Why these two results differ is not known.

The third confirmed CO source is a quasar at z = 4.7, BR1202–0125, which is one of the highest redshift objects known. Detected in CO(5–4) by Ohta et al (1996) and Omont et al (1996), it was also detected in CO(6–5) by Omont et al (1996). The CO maps show two spots on the sky, one at the position of the optical quasar, and another of equal strength about 4″ to the northeast. There is no optical emission associated with the northeast position in deep images (Hu, McMahon, & Egami 1995). Whether the northeastern CO spot is a lensed image of the quasar emission or a dark companion galaxy is not known. In the lensing hypothesis, the northeast optical counterpart could be obscured by a patch of dust in the lensing galaxy.

It is worth noting that all of the CO-detected objects mentioned above also have far-IR (IRAS) or 1 mm/submm continuum detections, indicative of highly luminous dust sources accompanying the CO-emitting gas. Indeed, the presence of dust emission was the prime selection criterion for targeting CO searches in these objects, as it has been for most other studies of distant CO.
2.3. High-z: Three newcomers

Three new high-z CO systems have been reported recently. All three detections were made with interferometers (which are more reliable than single dishes for measurement of weak, broad lines), but all, as of this writing, have yet to be confirmed using another instrument or in another CO transition.

The first is the $z = 2.39$ radio galaxy 53W002, with a detection of CO(3–2) using the OVRO interferometer reported by Scoville et al (1997). This object is interesting because it appears to lie within a cluster of roughly 20 Ly-α emission line objects, the most distant such cluster known (Pascarelle et al 1996). Previously, a possible detection of CO(1–0) had been reported from 53W002 by Yamada et al (1995). The Scoville et al result is particularly intriguing because of a claimed extension of the CO source by about 3″ or 15 kpc, with a velocity gradient along the major axis. Such a large, luminous CO source, if real, would be unprecedented – all previously known ultraluminous CO sources have been confined to the inner kiloparsec or so of the host galaxy nucleus. In contrast to the three confirmed CO sources discussed above, 53W002 does not show any evidence for gravitational lensing effects, nor has it been detected as a dust source in the far-IR or submm continuum.

The second new source is BRI1335–0415, a quasar at $z = 4.41$ detected in CO(5–4) by Guilloteau et al (1997) using the PdBI. This object was previously detected as a dust source in the continuum at 1 mm; it shows no a priori evidence for lensing. The authors state that, given the uncertainties in the CO-to-M(H₂) conversion factor, the molecular mass in this system could be as high as $10^{11} M_\odot$. This can be compared to the case of the Cloverleaf where because of lensing, and line modelling which suggests a low CO-to-M(H₂) conversion factor, the estimated H₂ mass may be as low as a few $\times 10^9 M_\odot$ (Barvainis et al 1997). A more likely value for BRI1335–0415 is $M(H_2) \sim$ a few $\times 10^{10}$, using the conversion factor appropriate for ultraluminous IR galaxies (Solomon et al 1997) and assuming no lensing boost.

The third new detection of CO at high redshift is from MG 0414+0534, a lensed quasar at $z = 2.64$. In the centimeter radio continuum it has four components, with a maximum separation of 2″ (Hewitt et al 1992). We detected the CO(3–2) line at 95 GHz with high SNR using the PdBI (Barvainis et al 1998). The line is quite broad, at $\Delta v_{FWHM} = 580$ km s$^{-1}$, which is about as broad as the very broadest lines seen in low redshift IR-luminous galaxies. Although the synthesized beam size of 2″ was comparable to the separation between the A (= A1+A2) and B radio images, it proved possible to produce individual CO spectra for these components by fitting in the UV plane. These spectra, plus their sum, are shown in Figure 1. When higher SNR and higher resolution observations become available, it may be possible to play the same trick with MG0414+0534 as Kneib et al (1997) did with the Cloverleaf: determining the very small-scale kinematic structure of the CO source by deprojection, using a reasonably accurate model for the lensing potential (such as that of Falco, Lehár, & Shapiro 1997).

Finally, I report here a non-detection (see also Barvainis et al 1998). The radio quiet object PG 1634+706 is an optically luminous quasar at $z = 1.33$, with detections in all four IRAS wavebands. It is the most distant unlensed IRAS source, and among the most luminous. Its spectral energy distribution in the IR/submm is very similar to those of the Cloverleaf and F10214+4724, so PG 1634+706 seemed like a very good candidate for CO detections. We used the adjusted systemic redshift estimate of Tytler & Fan (1992), $z = 1.337$, for the CO(2–1) observations. No emission was detected, at a level somewhat below that expected (by a factor of 2–4) if the CO-to-IR ratio were similar to that of other distant CO sources.

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2A recent measurement of PG 1634+706 in [OIII] λ5007 by Nishihara et al (1997) finds a systemic redshift of $z = 1.336$; therefore the redshift used for the CO(2–1) observations differed from true systemic by only $\Delta z = 0.001$, or 128 km s$^{-1}$.
Fig. 1.— CO(3 – 2) spectra toward MG 0414+0534, smoothed to a resolution of 158 km/s. The velocity offsets are relative to a redshift of 2.639. The lower panel shows the spectrum of lensed component A (= A1+A2), the middle panel component B, and the top panel the sum.
3. Water masers

In a search for very distant maser sources, a program has been started at the Effelsberg 100m telescope (collaborators: C. Henkel, R. Antonucci, S. Baum, A. Koekemoer) to try to detect H$_2$O masers in several high redshift bands (corresponding to the receiver frequency ranges available at the telescope). There is reason to believe that water maser power may scale approximately with x-ray luminosity (Neufeld, Maloney, & Conger 1994), making high-$z$ detections feasible. The interest in high-$z$ water masers centers on their use as probes of the inner nuclear regions in luminous AGNs, and on their potential for making direct measurements of the source distance (as has been done for NGC 4258; see contribution by Herrnstein, this volume). At moderate redshifts, such distance measurements could be turned into direct estimates of $H_0$ independent of the usual distance ladder.

So far we have observed a total of 60 objects in the redshift ranges $0.46 < z < 0.55$, $1.46 < z < 1.79$, and $3.35 < z < 3.83$. No detections have yet been obtained, with typical maser line upper limits of 20 mJy. Observations of 40–50 more sources in other redshift ranges are planned for a future observing run.

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