DETECTING CO AT HIGH REDSHIFT

LINDA J. TACCONI
Max-Planck-Institut für extraterrestrische Physik
Postfach 1603
D-85748 Garching
Germany

1. Introduction

Searches for molecular line emission from high redshift galaxies have become one of the recent highlights in millimeter astronomy, largely because detection of this emission enables one to study the potential for star formation in galaxies at epochs close to galaxy formation. Such information is crucial to models of galaxy evolution. Thus far, most of the searches have been to try to detect any of the rotational lines of CO, although many authors have also inferred the presence of molecular gas through detections of cold dust in the submillimeter region of the spectrum. In addition to providing information about the physical properties of the molecular gas in distant galaxies (when more than one transition or isotope is detected), the CO lines can be used to place stringent constrints on the dynamical masses of these systems. Moreover, since millimeter data has spectral resolutions of typically a few tens of km/s, one can pin down the redshift of the host galaxy with extremely high precision. One of the driving forces in most of the searches for CO emission at high redshift is the fact that molecular gas is known to be an important constituent in the low redshift counterparts to the types of objects that one expects to find at high redshifts, the Ultraluminous Infrared Galaxies (ULIRGs), (*e.g.* Mirabel and Sanders 1985; Sanders *et al.* 1986), powerful radio galaxies (*e.g.* Mazzarella *et al.* 1993), and nearby quasars (*e.g.* Barvainis *et al.* 1989), for example.

Here I review some of the results from the two most distant objects yet detected in CO, and list some other attempts to find CO at $z>2$. I apologize to the many authors whose work I have not included in this paper: limited space and a rapidly evolving field precludes completeness.

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2. IRAS F10214+4724 at z=2.23

Many observers first turned their millimeter telescopes to high z objects in search of molecular gas after the discovery of the extremely IR luminous galaxy IRAS F10214+4724 at a redshift of 2.23 by Rowan-Robinson *et al.* (1991). With the first detection of CO from this object by Brown and vandenBout (1991, 1992), F10214 has a redshift which is nearly a factor of 10 greater than any previously detected CO sources. At $L_{IR} \sim 10^{14}$ $L_\odot$, it is also the most IR luminous object in the sky. In the past few years, there have been many studies in addition to the above references to reconfirm the CO detections, to observe many line transitions of CO in order to get estimates of the molecular gas properties, and to observe the emission at high spatial resolution with millimeter interferometers to determine the source structure (Solomon, Downes and Radford 1992; Kawabe *et al.* 1992; Sakamoto *et al.* 1992; Radford, Brown and VandenBout (1993); Downes, Solomon and Radford 1995). These observations show that this unusual galaxy is very rich in molecular gas with $M(H_2) \sim M_{dyn} \sim 10^{11}h^{-1}$ $M_\odot$. Here M_{dyn} is the estimated dynamical mass of the galaxy from the CO linewidth. CO line emission ratios indicate molecular gas which on average is both warm ($T_{kin} \sim 50$ K) and dense ($n(H_2) \sim 5 \times 10^3$ cm^{-3}, conditions which are similar to those found in massive star forming regions in our galaxy (Solomon, Downes and Radford 1992).

3. The Cloverleaf Quasar at z=2.56

The second strong CO emitter at z>2 is the Cloverleaf (H1413+117), a gravitationally lensed quasar so named because the optical image is split into four spots by the lens (Magain *et al.* 1988). It is the only broad absorption line quasar known to be lensed, and was chosen as a likely target for a CO detection by the fact that it was found to have submm emission due to dust (Barvainis, Antonucci and Coleman 1992). The original CO J=3→2 detection was made by Barvainis *et al.* (1994) with the IRAM interferometer, where they detected a peak flux of 23 mJy. The detection was immediately confirmed by the authors in several other lines of CO as well as CI with single dish observations. Assuming that there is no amplification of the CO emission by the lens, the Cloverleaf is very similar in its overall CO and FIR properties to F10214+4724. That is, $M_{gas} \geq M_{dyn}$ and $L \sim 10^{14}$ $L_\odot$. The CO emission is bright in many transitions, and the J=4→3 line is brighter than the J=3→2 line, likely indicative of gas which is both warm and dense. Detailed modeling of the molecular lines in the Cloverleaf is now underway using all available information (Barvainis *et al.* 1995).

4. What is Unique about F10214 and The Cloverleaf?

Although many observers have made long and deep searches to detect mmolecular gas from galaxies at z>2 (*e.g.* Evans *et al.* 1995; Röttgering *et al.* 1995) only F10214+4724 and the Cloverleaf have confirmed CO detections (although there are a few cases where authors are awaiting reconfirmation of tentative detections, for example see the comment at the end of this paper). The question which obviously arises from this is whether F10214 and the Cloverleaf are intrinsically unique objects in the early universe or whether they share some other common property which makes them relatively easy to detect. One possibility is that these two objects are very luminous members of the class of long sought after primeval galaxies, since in both cases the gas mass dominates the dynamical mass. This scenario is not likely given the fact that both sources contain large amounts of cold dust.

A more widely accepted picture now is that both sources are gravitationally lensed by a foreground object. Of course, the Cloverleaf is one of the most well known of the gravitational lens candidates, but based on the initial detection of CO, it was not known whether the CO emission was amplified by the lens. High resolution observations of CO at both the Owens Valley Interferometer and the IRAM interferometer show that the CO source is extended on scales of $\sim1''$, and could well indicate that there is CO emission corresponding to the 4 optical images of the quasar. These data are as yet unpublished. There is also very strong evidence that F10214 is a gravitational lens system, however (Matthews *et al.* 1994; Graham and Liu 1995; Broadhurst and Lehár 1995; Serjeant *et al.* 1995). Gravitational lens models (*e.g.* Broadhurst and Lehár 1995) can explain the multi-component source structures seen in recent sub-arcsecond resolution near infrared images (*e.g.* Graham and Liu 1995). In this picture the symmetric arc seen in the NIR images is the lensed IRAS source, which is centered on the weaker compact intervening lensing galaxy. The NIR images also show evidence for a fainter counter image to the north of the compact component (Graham and Liu 1995). Furthermore, the recent CO images of Downes, Solomon and Radford (1995) are indicative of CO emission which is coincident with the NIR arc. In both the Cloverleaf and F10214, the CO distributions suggest, therefore, that the molecular emission is amplified by the lens. If this is the case, then the molecular mass estimates and IR luminosities have been overestimated. Revised mass estimates (*e.g.* Downes, Solomon and Radford 1995) show that the gas masses are no longer greater than the dynamical masses, and that these objects are likely the very distant counterparts to the nearby ULIRGS.

The success at studying the molecular gas properties of the Cloverleaf quasar and F10214, and the lack of strong detections in other sources seems to indicate that, with the current detection capabilities, observers need the assistance of gravitational lenses to detect molecular line emission from galaxies at high z. Careful studies of gravititional lens candidates in CO lines and the submm continuum are therefore needed to further investigate properties of molecular clouds in the early universe. Such studies will be made easier in the near future with the addition of more antennas to the current millimeter interferometers and the arrival of new large single dish telescopes.

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D. Clements: There are an increasing number of high redshift objects being detected in the submm continuum, so prospects for further CO detections are good. The submm continuum acts as a signpost to where to point your CO spectrometer.

R. Windhorst: It is perhaps worth pointing out that Yamada *et al.* (1995, A.J. in press) detected the high redshift weak radio galaxy 53w002 at z=2.390 in CO with the Nobeyama telescope. Perhaps Toru, who is in the audience wants to comment on this. The interpretation of this result is possibly complicated because 53w002 is surrounded by at least 3 other confirmed objects at z=2.40 (see poster 144 with the deep HST images of Windhorst *et al.*.

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