Imaging CO Emission in Gas Rich Galaxies at High Redshifts

M. S. Yun

National Radio Astronomy Observatory, P.O. Box 0, Socorro, NM 87801

N. Z. Scoville and A. S. Evans

California Institute of Technology, Pasadena, CA 91125

Abstract. Observations of the cold, dense gas at high redshifts directly address fundamental questions regarding the early evolution of galaxies and quasars. The Owens Valley Millimeter Array provides excellent sensitivity and *resolutions better than 1″*. The spatial distribution of redshifted CO emission is found to be resolved in most detected objects. For example, 1 kpc size scale for the CO emitting region is inferred using a gravitational lens model in z=2.6 quasar H1413+117. Our new observations suggest that the CO source in z=4.7 quasar BR 1202-0725 may be spatially displaced from the optical quasar.

1. Introduction

It has long been hypothesized that the early evolution of galaxies is extremely rapid with a burst of high luminosity. The optical searches for such luminous proto-galaxies have been fruitless, however, indicating that perhaps such activity is not directly visible (e.g. Pritchet & Hartwick 1990, Djorgovski & Thompson 1993). Therefore, studies of optically thin tracers capable of directly probing heavily enshrouded activity are highly desirable. Observations of redshifted rotational transitions of CO at high redshifts have revealed that massive galaxies with a massive cold molecular gas reservoir ($M_{H_2} > 10^{10}\ M_\odot$) exist even at $z \sim 5$ and that copious metal production started at early epochs (see below).

The Owens Valley Millimeter Array is an excellent instrument for studying gas-rich systems at high redshifts. The large collecting area (510 m^2 which is equivalent to a 26-m diameter telescope) and the use of cross-correlated signals provide the high sensitivity comparable to the largest existing millimeter telescopes with a significant reduction in instrumental systematics that plague single dish detection experiments. More importantly, its ability to *produce images at resolutions better than 1″* proves to be a powerful tool as the spatial distribution of redshifted CO emission is found to be resolved in most detected objects. We highlight below the new insights obtained using this imaging capability in several interesting recent cases.

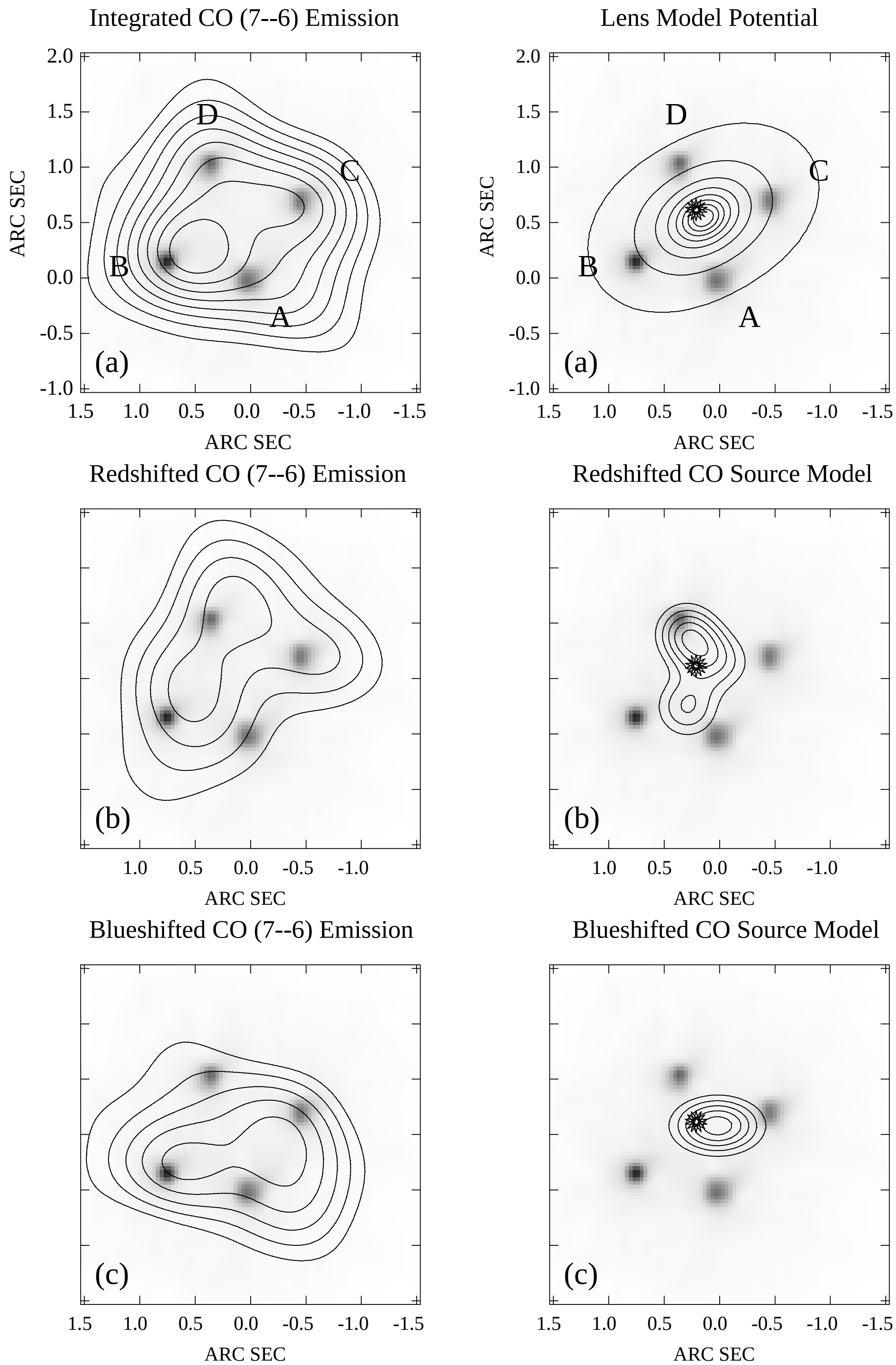

Figure 1. (a) Integrated CO (7–6) emission in z=2.3 quasar H1413+117 at 0.9″ resolution superposed on the optical HST image; (b) & (c) images of the red- and blue-shifted halves show a different morphology, suggesting that the CO emission originates in an extended region with distinct kinematics and displaced from the optical quasar; (d) gravitational lens model used to map the actual positions of the quasar (mark with a star) and the red- and blue-shifted CO sources, shown in pannels (e)&(f) (see Yun et al. 1997).

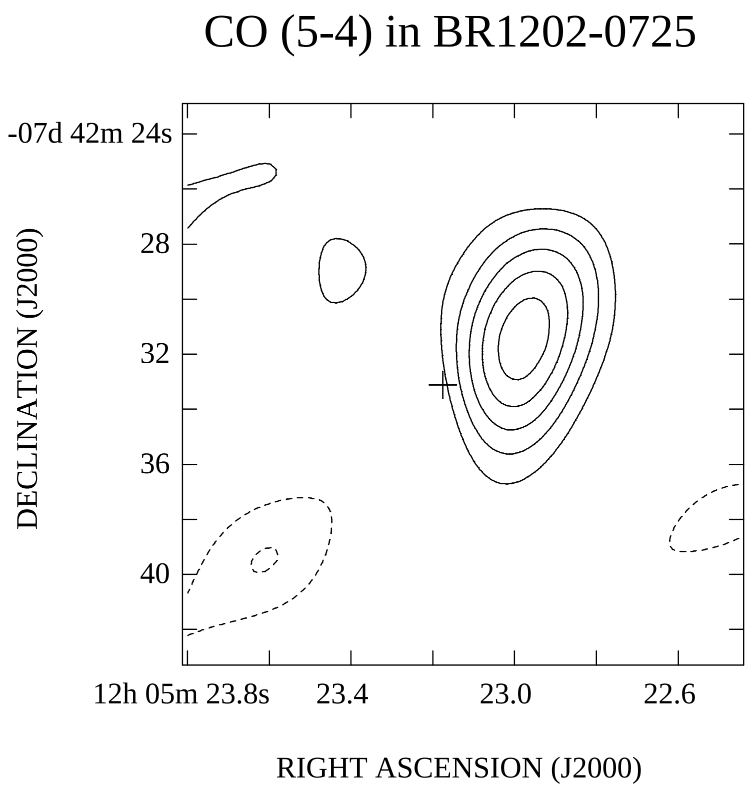

Figure 2. Integrated CO (5–4) emission in z=4.7 quasar BR 1202-0725 at 5″ resolution (Evans et al. 1998). The cross marks the position of the optical quasar, and the peak of the CO emission is offset by about 3″ to the northwest, towards the second submillimeter continuum source reported by Omont et al. (1996) and the cometary Lyman-α companion discovered by Hu et al. (1996).

2. Gravitationally Lensed Quasar H1413+117 (the Cloverleaf)

The CO (7–6) emission in z=2.6 gravitationally lensed quasar H1413+117 (redshifted to 226.7 GHz) is imaged at 0.9″ resolution (Figure 1 and Yun et al. 1997). The CO morphology in the integrated light (Figure 1a) is remarkably similar to the optical light, suggesting that the CO emitting region is compact and smaller than the Einstein radius of the gravitational lens. The red- and blue-shifted halves of the emission show distinctly different morphologies, however, suggesting that the each half comes from extended regions displaced from the optical quasar (Figure 1b&c). Using a gravitational lens model (Figure 1d), we infer a 1 kpc (0.3″) extent for the CO emitting structure surrounding the quasar whose kinematic structure is roughly consistent with a rotating disk. The observed properties of the CO emitting gas are similar to the nuclear starburst complexes found in the ultralumous infrared galaxies in the local universe ($M_{H_2} = 2.5 \times 10^{10} M_\odot$, $T \geq 50$ K, $n \geq 10^4$ – e.g. Mrk 231, Bryant & Scoville 1995), and metal enrichment by vigorous star formation within this massive, compact nuclear gas complex can explain the abundant carbon and oxygen present in the ISM of this system observed when the universe was only a few billion years old.

3. z=4.7 Quasar BR 1202-0725

The detection of bright CO emission in z=4.7 quasar BR 1202-0725 (Ohta et al. 1996, Omont et al. 1996) clearly demonstrates that dusty, gas-rich galactic systems with significant heavy metal production were already present at $z \sim 5$. Our confirmation observations using the OVRO array have easily detected the CO emission with a good S/N (see Figure 2), but we also find the *peak of the CO emission displaced from the optical quasar position* by about $3''$ to the northwest. This offset in position is probably real since the position of the phase calibrator 3c273 is known to better than $1''$. This offset is also in the direction of the second 1mm continuum source reported by Omont et al. and the cometary Lyman-α companion discovered by Hu et al. (1996), but no optical or radio counterpart exists. If this position offset is confirmed, then this CO source represents a unique opaque object at high redshift with extreme dust and gas content ($M_{H_2} = 7 \times 10^{10} M_\odot$) but low optical luminosity, the likes of which have not been seen yet.

4. z=0.93 Hyperluminous IRAS Galaxy FSC 15307+3252

The hyperluminous IRAS galaxy FSC 15307+3252 at $z_{opt} = 0.9257 \pm 0.0012$ is the second highest redshift object detected by IRAS (after z=2.3 lensed galaxy FSC 10214+4724) and one of the most luminous galaxies with log $L_{60\mu} = 12.6$ (Cutri et al. 1994). Both the optical spectrum (Seyfert 2) and the radio continuum power (log $P_{1.4GHz}$ = 25.1 W Hz^{-1} – from the VLA FIRST Survey database by Becker et al. 1997) suggest some nuclear activity, and the presence of polarized broad emission lines suggests that this galaxy may host a "buried QSO" (Hines et al. 1995; Liu et al. 1996).

The observed properties of FSC 15307+3252 are nearly identical to the more distant IRAS galaxy FSC 10214+4724 where bright (lensed) CO emission has already been detected (Brown & Vanden Bout 1991, Solomon et al. 1992). Strong dust emission in highly redshifted galaxies has been one of the best indicators of a large molecular gas content and bright CO emission, and the large 60 μ luminosity and infrared-to-optical luminosity ratio make FSC 15307+3252 an excellent candidate for a CO search. Therefore we have conducted a search for the redshifted CO (3–2) emission at 239.4 GHz between December 1996 and February 1997. CO emission is searched in the redshift range of z=0.9240-0.9275, but no CO emission is detected within our sensitivity (see Figure 3). The derived upper limit on the molecular gas mass is $M_{H_2}(3\sigma) \leq 8.8 \times 10^9 M_\odot$, which is 2-3 times smaller than the infrared luminous galaxies in the local universe. The inferred FIR-to-CO luminosity ratio is extremely large, $L_{60\mu}/L'_{CO} \geq 1900$, although it is typically 100-200 for ultraluminous infrared galaxies (Solomon et al. 1997). Possible explanations for the absence of bright CO emission include a rapid gas exhaustion or conversion from molecular phase to atomic or ionized phase (see Yun & Scoville 1998). Alternatively the CO emission may be located at a redshift significantly different from the optical and UV emission lines.

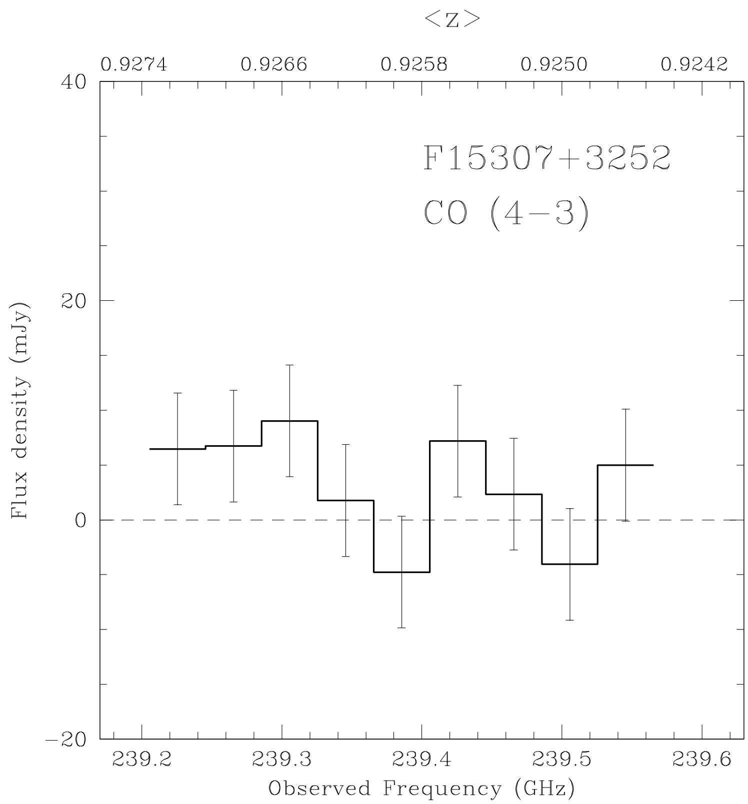

Figure 3. Integrated CO (4–3) spectrum in z=0.93 hyperluminous IRAS galaxy FSC 15307+3252 at 3″ resolution (Yun & Scoville 1998).

5. Summary and Concluding Remarks

Imaging CO emission at high angular resolution has provided significant new insights on high redshift gas rich galaxies. The detail gas distribution and kinematics are determined using a gravitational lensing model in z=2.6 quasar H 1413+117. The derived molecular gas properties are strikingly similar to those found in the ultraluminous infrared galaxies in the local universe, and highly dissipative processes such as a merger of two gas-rich galaxies may also be responsible for these gas-rich high redshift systems (Scoville et al. 1994). The CO source in z=4.7 quasar BR 1202-0725 may be an extremely dusty, gas-rich system with no optical counterpart. On the other hand, dusty galaxies or "buried QSO's" with little cold molecular gas may also exist (e.g. FSC 15307+3252), and the evolution of the ISM in these galaxies may be dynamic.

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References

Becker, R.H., Gregg, M.D., Hook, I.M., McMahon, R.G., White, R.L., Helfand, D.J. 1997, ApJ, 479, L93

Brown, R.L., Vanden Bout, P.A. 1991, AJ, 102, 1956

Bryant, P.M., & Scoville, N.Z. 1996, ApJ, 457, 678

Cutri, R.M., Huchra, J.P., Low, F.J., Brown, R.L., Vanden Bout, P.A. 1994, ApJ, 424, 65

Djorgovski, S., & Thompson, D. 1993, in *IAU Symp. 149, The Stellar Populations in Galaxies*, eds. Renzini, A., Barbuy, B. (Kluwer, Dordrecht), p.337

Evans et al. 1998, in preparation

Hines, D.C., Schmidt, G.D., Smith, P.S., Cutri, R.M., Low, F.J. 1995, ApJ, 450, 1

Hu, E.M., McMahon, R.G., Egami, E. 1996, ApJ, 459, L53

Liu, M.C., Graham, J.R., Wright, G.S. 1996, ApJ, 470, 771

Ohta et al. 1996, Nature, 382, 426

Omont et al. 1996, Nature, 382, 428

Pritchet, C.J., & Hartwick, F.D.-A. 1990, ApJ, 355, L11

Scoville, N.Z., Hibbard, J.E., Yun, M.S., van Gorkom, J.H. 1994, in the *Symposium on Interaction Induced Activity and Galaxies*, ed. I. Shlosman

Scoville, N.Z., Yun, M.S., Brown, R., Vanden Bout, P. 1995, ApJ, 449, L109

Solomon, P.M., Radford, S.J.E., Downes, D. 1992, Nature, 356, 318

Solomon, P.M., Downes, D., Radford, S.J.E., Barrett, J.W. 1997, ApJ, 478, 144

Yun, M.S., Scoville, N.Z., Carrasco, J.J., Blandford, R. 1997, ApJ, 479, L9

Yun, M.S., & Scoville, N.Z. 1998, in preparation