CO OBSERVATIONS OF HIGH REDSHIFT GALAXIES WITH THE OWENS VALLEY MILLIMETER ARRAY

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The peaking of quasar density at $z \sim 2$ as well as the stellar population analysis of galaxies in the local universe suggest that galaxies were formed near or prior to the redshift of 2. The identification of IRAS FSC 10214+4724 with a $z = 2.3$ galaxy (Rowan-Robinson et al. 1991) and the detection of CO emission (Brown & Vanden Bout 1991, Solomon et al. 1992) have substantiated the hypothesized existence of luminous gas-rich galaxies in the early epochs forming stars at prodigious rates. Given that there has been reasonable heavy element production, CO rotational transitions are excellent probes of cold interstellar medium in very distant galaxies. For objects of constant intrinsic CO brightness temperature, the observed line flux is almost independent of redshift at $z = 1$–6 due to the factor $(1+z)^2$ in angular size distance. These molecular transitions are also unambiguous tracers of cold, dense molecular gas where stars are forming.

The Owens Valley Millimeter Array is very well-suited for detecting gas-rich high redshift systems since six 10.4 m diameter telescopes add to an effective collecting area of 510 m^2 – comparable to a 25.5 m diameter telescope. The use of cross-correlated signals significantly reduces the instrumental effects that often plagues the single dish observations. The OVRO observations also yield spectral map cubes with typical spatial resolution of $2''$ to $5''$, providing both spatial and kinematic information.

The CO (3–2) emission region in $z = 2.3$ IRAS galaxy FSC 10214+4724 is resolved by our $2''$ resolution observations (Figure 1). About 1/3 of the total CO flux originates from an extended structure with a narrow line width while the majority of molecular gas belongs to an unresolved structure (Scoville et al. 1995). The small line width for the extended component may be explained if a kinematically distinct section of the galaxy is strongly amplified to a greater angular extent by gravitational lensing.

The CO (7–6) emission from H1413+117 (the Cloverleaf quasar) is also resolved by our $1''$ beam (Yun et al. 1996). The CO morphology is remark-

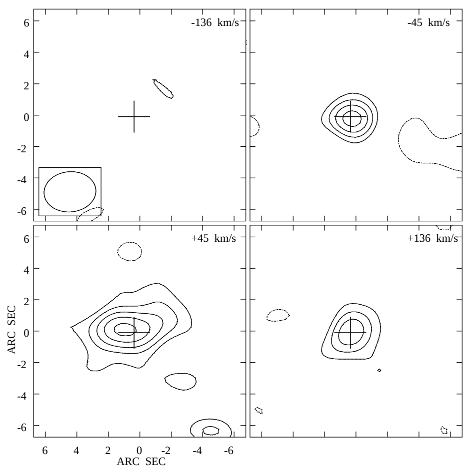

Figure 1

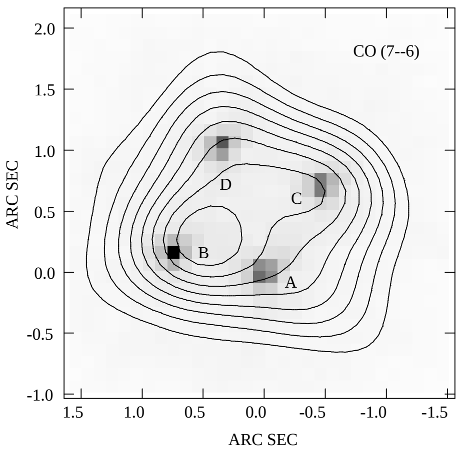

Figure 2

Figure 1. New 2″ resolution CO (3–2) maps of FSC 10214+4724 with 90 km s^{-1} velocity channels (Scoville et al. 1995). The cross marks the VLA radio source position. An extended component with a narrow line width is found in V=+45 km/s channel.
Figure 2. CO (7–6) map of H1413+117 at 1″ resolution in contours overlaid on the grey scale HST F555W image (Falco 1993).

ably similar to that of optical light, suggesting the CO emitting region is very compact and coincides with the quasar (Figure 2). The inferred total H_2 mass, $2.3 \times 10^{10} h^{-2}$ $M_\odot$ (assuming magnification factor 10), is nearly identical to the CO (3–2) measurement by Barvainis et al. (1994). The CO emission must arise from dense high excitation gas ($n > 10^5$ cm^{-3}, $T > 100$ K). The dust masses estimated from continuum emission are about 10^7 $M_\odot$ for FSC 10214+4724 and H1413+117, and the inferred gas-to-dust ratios are ~ 1000, similar to the IR luminous systems in the local universe (e.g., Sanders, Scoville, & Soifer 1991).

The results of the OVRO CO observations of high redshift systems are summarized in Table 1. In the majority of cases, the H_2 mass sensitivity is sufficient to detect the more gas-rich galaxies in the local universe. In all cases, any objects like FSC 10214+4724 should have been detected. Detecting the progenitor of L_* galaxies probably requires an order of magnitude improvement in sensitivity. We note that neither 4C 41.17 (a $z = 3.8$ radio galaxy with dust continuum detection – Chini & Krügel 1994) nor B2 0902+34 (a $z = 3.4$ "protogalaxy" – Eales et al. 1993) were detected in CO. The upper limit on the gas-to-dust ratio is 750 for 4C 41.17. We find the 650μm (rest) continuum emission from B2 0902+34 dominated by non-thermal emission rather than by dust emission.

TABLE 1. Summary of the OVRO CO Observations

Name	z	Transition	S_{CO} (mJy)	ΔV (km s^{-1})	$M(H_2)$ ($h^{-2}10^{10}$ $M_\odot$)
H1413+117	2.56	CO (7–6)	120 ± 12	340	2.3 ± 0.2
FSC10214+4724	2.29	CO (3–2)	14 ± 2^a	250	1.2 ± 0.2
3C 48	0.37	CO (1–0)	7.7 ± 1.9^b	250	3.9 ± 0.8
B2 0902+34	3.40	CO (4–3)	$< 4.1^c$	$(300)^d$	$< 3.3^d$
4C 41.17	3.80	CO (4–3)	< 4.5	(300)	< 4.2
3C 368	1.13	CO (2–1)	< 8.1	(300)	< 4.5
TX 1243+036	3.58	CO (4–3)	< 6.9	(300)	< 5.5
PC 1033+4750	3.68	CO (4–3)	< 6.1	(300)	< 5.5
MG 1019+0535	2.77	CO (3–2)	< 6.2	(300)	< 6.4
TX 0211−122	2.34	CO (3–2)	< 9.1	(300)	< 7.3
4C 28.58	2.95	CO (3–2)	< 7.4	(300)	< 8.5
H0836+113	2.47	CO (3–2)	< 13	(300)	< 11
PC 1643+4631A	3.14	CO (3–2)	< 10	(300)	< 13
PC 1406+123	2.25	CO (3–2)	< 12	(300)	< 13

Notes: (a) Scoville et al. (1995); (b) Scoville et al. (1993); (c) all 3σ upper limits; (d) $\Delta V = 300$ km s^{-1} is assumed.

References

Barvainis et al. 1994, Nature, 371, 586
Brown, R.L., Vanden Bout, P.A. 1991, AJ, 102, 1956
Chini, R., Krügel, E. 1994, A&A, 288, L33
Eales et al. 1993, Nature, 363, 140
Falco E.E. 1993, in *Gravitational Lenses in the Universe*, eds. Surdej et al. (Universite de Liege, Liege), p.127
Rowan-Robinson et al. 1991, Nature, 351, 719
Sanders, D.B., Scoville, N.Z., Soifer, B.T. 1991, ApJ, 370, 158
Scoville, N.Z., Yun, M.S., Brown, R., Vanden Bout, P. 1995, ApJ, 449, L109
Scoville et al. 1993, ApJ, 415, L75
Solomon, P.M., Downes, D., Radford, S.J.E. 1992, ApJ, 398, L29
Yun et al. 1996, Naure, submitted.