CO OBSERVATIONS OF HIGH REDSHIFT GALAXIES WITH OWENS VALLEY MILLIMETER ARRAY

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1. Introduction

The peaking of quasar density at $z \sim 2$ as well as the stellar population analysis of galaxies in the local universe suggest that most galaxies must have formed near or prior to the redshift of 2. The identification of the IRAS FSC 10214+4724 with a z=2.3 galaxy ($L > 3 \times 10^{14} L_{\odot}$, Rowan-Robinson et al. 1991) and the subsequent detection of CO emission ($M_{H_2} > 10^{11} M_{\odot}$ – 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 (ISM) in very distant galaxies. For objects of constant CO brightness temperature in the different rotational transitions, 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. The six 10.4-m diameter telescopes in the array provide an effective collecting area of 2040 m^2 – comparable to a 25.5-m diameter telescope. The use of cross-correlated signals significantly reduces the instrumental effects that often plague the single dish observations. The OVRO observations also yield spectral map cubes with typical spatial resolution of $2''$ to $5''$, providing spatial information and, when resolved, kinematic information.

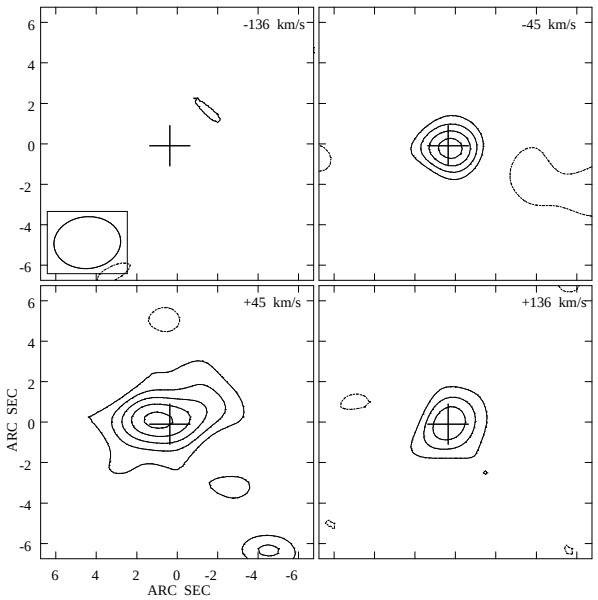

Figure 1. New 2″ resolution CO (3–2) maps of FSC 10214+4724 with 90 km s^{-1} velocity channels (Scoville et al. 1995). The cross marks the VLA radio source position. An extended component with a narrow line width is found in V=+45 km/s channel.

2. FSC 10214+4724 and H1413+117 (the Cloverleaf)

The CO (3–2) emission region in z=2.3 IRAS galaxy FSC 10214+4724 is resolved by our 2″ resolution observations (see 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 & Scoville 1995). The CO morphology is remarkably similar to that of optical light, suggesting the CO emitting region is very compact and coincides with the quasar (see Figure 2). The inferred total H_2 mass, $2.3 \times 10^{11} {A_g}^{-1} h^{-2} M_\odot$ (A_g is amplification factor), is nearly identical to the CO (3–2) measurement by Barvainis et al. (1994), and the CO (3–2) emission must arise from high excitation gas ($n > 10^4$ cm^{-3}, $T > 50$ K).

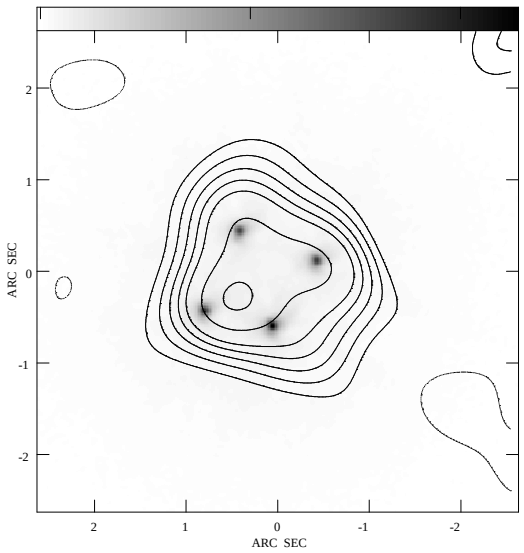

Figure 2. CO (7–6) map of H1413+117 at $1''$ resolution in contours overlaid on the grey scale HST F555W image (Falco 1993).

The dust masses estimated from the continuum emission are about 2×10^8 and $3 \times 10^8 {A_g}^{-1} h^{-2} M_\odot$ for FSC 10214+4724 and H1413+117 (see Downes et al. 1992, Rowan-Robinson et al. 1993, Barvainis et al. 1992). The inferred gas-to-dust ratios are therefore 500 and 800, respectively – similar to the IR luminous systems in the local universe (e.g. Sanders, Scoville, & Soifer 1991). The dust continuum and CO emission are likely co-spatial in distribution and thus similarly amplified by lensing.

3. Summary of Observations

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 FSC 10214+4724 like objects should have been detected. To improve the detection statistics, more IR-selected candidates need to be searched. Detecting the progenitors 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	23 ± 2
FSC10214+4724	2.29	CO (3–2)	14 ± 2^a	250	12 ± 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) ΔV=300 km s^{-1} is assumed.

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