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CO Emission from QSO Absorption Line Systems

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By studying the physical conditions in galaxies at different redshifts, we can begin to understand the evolutionary process of starformation from early epochs to the present. Observations of the mm/submm CO lines in these galaxies provide a way to investigate abundances of, and conditions in, potential starforming material. Here we report the detection of CO in emission toward 4 galaxies at redshifts of 0.005 to 0.05. Detections were made in two transitions toward each of the four sources, PKS 0038-019, S4 0248+43, 3C 232, and PKS 1327-206. From these observations we computed the molecular gas mass to be $1.7\times10^8 M_\odot$ to $3\times10^9 M_\odot$. These estimates used the "standard conversion factor" for H_2 column density to integrated CO intensity ratio, $(N(H_2)/I_{co})$, and an H_o=75km/s/Mpc and q_o= 0.5. We also report upper limits to the molecular gas mass in 33 other systems with redshifts ranging from 0.03 to 2.8 to be $< 4 \times 10^8 M_\odot$ to $< 5 \times 10^{11} M_\odot$. All four of our sources detected in CO were selected to be metal line systems (with high HI column densities) and possess strong FIR fluxes detected by IRAS at 60 and/or 100μm. The source possessing the brightest FIR emission among the four is the z=0.05 21 cm absorber toward S4 0248+43. The total observed FIR luminosity for this source is $L_{FIR} = 3.0\times10^{11} L_\odot$. Taking into account its luminosity and the additional correction for the integrated flux from 0.01-100 μm (Sanders et al 1988), this object can be classified as a transition object between a normal luminous galaxy and an ultraluminous IR galaxy. This absorber galaxy may be the only known starburst in front of a quasar.

INTRODUCTION

- **Purpose:** To gain valuable insights into the evolution of galaxies through most of the age of the Universe.
- **Method:** Use millimeter/submillimeter emission lines to study the molecular content of galaxies at different redshifts.
- **High-z candidates:** DLy-α absorption line systems (in general)
- **Low-z candidates:** Mg II absorption line systems (in general)
- **Main reasons for chosing these absorption line systems:**

– Gas-rich; Positions and frequencies are predictable.

SUMMARY OF OBSERVATIONS AND ANALYSIS

• We have observed 37 absorption line systems in various CO transitions using mm/submm-wave telescopes.
• Sample: 26 systems at $0.005 < z < 0.75$ and 11 systems at $1.3 < z < 2.85$

• Several different transitions of CO were used to probe the molecular content of these galaxies: CO1-0 to CO7-6.

• Several observatories were used to perform these observations: NRAO 12m, JCMT and CSO.

• The integration times per object per transition ranged from a couple of hours to a half a day.

• The rms/channel noise level was typically between:

a) 1–2 mK for observations of low–z systems made at the NRAO 12m with channel widths of a few km/s.

b) 4–9 mK for observations of high–z systems made at the JCMT and CSO with channel widths $\sim$ 1 km/s.

• See 'H_2 Mass Calculations' for details on the procedure taken to calculate the molecular mass in the absorption line systems.

• Note: a linewidth of 300km/s was assumed in calculating upper limits to the molecular mass, as were an H_o=75 and q_o=0.5.

H_2 MASS CALCULATIONS

$$M_{H_2} = 5.758 \times 10^4 [\frac{\mu}{4.344 \times 10^{-24}}][\frac{N(H_2)/I_{co}}{2.5 \times 10^{20}}] \times I_{mb}[\frac{\theta_B}{30}]^2[\frac{{D_L}^2}{(1+z)^3}],$$

where μ is mass per hydrogen molecule in grams; θ_B is beam size in arcsecs;

$N(H_2)/I_{co}$ is "standard conversion factor" in cm^{-2}K km^{-1}s;

$$D_L \text{ is the luminosity} - \text{distance in Mpc} = \frac{2.998 \times 10^5 [zq_o + (q_o - 1)((2q_oz+1)^{1/2} - 1)];}{(H_o {q_o}^2)}$$

H_o and q_o are assumed to be 75 K km/s and 0.5, respectively;

I_{mb} is the main beam integrated intensity in K km/s $= 3\Delta T_{rms}(\delta V \times \Delta V)^{1/2}/\eta_{mb}$;

ΔT_{rms} is the 1-σ noise temperature per δV in Kelvin;

η_{mb} is the main beam efficiency; δV is the channel width in km/s;

and ΔV is the linewidth (300 km/s for non-detections).

SUMMARY OF RESULTS

- Out of our sample, we detected CO emission features in 4 galaxies (Q0038–019, Q0248+430, Q0955+326, & Q1327–206) with redshifts ranging from 0.005 to 0.05. Detections were made in two transitions toward each of the four sources.

- Their molecular masses range from $1.7{\times}10^8$ to $3.0{\times}10^9 M_\odot$ (considering the higher of the 2 transitions). (See Table 1.)

- Their 100μm fluxes (as detected by *IRAS*) are among the 5 brightest sources in our sample. Their 100μm fluxes are 2.67Jy (23.4σ) for Q0038–019, 6.86Jy (5.6σ) for Q0248+430, 18.58Jy (197.7σ) for Q0955+326 and 1.63Jy (6.9σ) for Q1327–206.

- The range of upper limits to the molecular masses for the remaining 33 systems are $3.9{\times}10^8$–$2.1{\times}10^{11} M_\odot$ for redshifts of 0.03 to 0.74 and $4.8{\times}10^{10}$–$4.9{\times}10^{11} M_\odot$ for redshifts of 1.33 to 2.84.

- The molecular masses of the detected absorption line systems as well as the upper limits of the non-detected sources are plotted against redshift in Figure 1.

- The upper limits to the molecular masses for the high z systems are comparable to the hyperluminous IR galaxy, F10214+4742 at z$\approx$2.3 and the damped Ly-α system, PC1643+4631A at z=3.137. (See Figure 1.)

- The lines in Figure 1 correspond to detection limits of the specified telescopes and bandpasses. All were based on 8 hours of integration and 2MHz of bandwidth per channel. The typical SSB system temperatures used in calculating the mass limit as a function of redshift were 350K and 1300K for the 230GHz and 345GHz receivers, respectively, at the JCMT, CSO and SMTO. For the 3mm, 2mm and 1mm receivers at the NRAO 12m telescope, SSB system temperatures of 350K, 350K and 575K were assumed.

- For further comparison, the value for the molecular masses in the Milky Way and in Arp220 are indicated in Figure 1.

- For wavelengths longer than 800μm, Milky Way-type objects cannot readily be detected beyond a redshift of 0.4.

- For wavelengths longer than 1.1mm, Milky Way-type objects and Arp220-type objects cannot readily be detected beyond redshifts of 0.15 and 0.6, respectively.

- In addition, ultraluminous FIR galaxies (Sanders *et al* 1991, ApJ **370**, 158), powerful radio galaxies (Mazzarella *et al* 1993, ApJ **409**, 170), radio quiet QSOs (Alloin *et al* 1992, A&A **265**, 429), and damped Ly-α systems (upper limits from Wiklind & Coombes 1994, A&A) are plotted in Figure 1.

- Three high z sources (with non-detections in CO) in common with the sample of Wiklind and Coombes (1994) show similar upper limits to the molecular mass (a few $\times 10^{11} M_\odot$).

- Our results suggest that although some high z galaxies are detectable, the vast majority are at or lie below the detection thresholds of current millimeter/submm telescopes and instrumentation. The current detectable molecular mass limit for z>1.3 is $\sim 2.4 \times 10^{11} M_\odot$ for an integration time of approximately 7 hours.

TABLE 1

Source	z_{abs}	Trans'n	Telesc.	Beam ('')	I^{i}_{mb} (K km/s)	D_{Mpc}	Molec. Mass[j] $M_\odot$
0013-004	1.973	CO6-5	JCMT	21.3	0.439	9.98×10^{3}	$<4.83\times10^{10}$
0038-019[a]	0.018	CO2-1	JCMT	21.9	3.570	7.11×10^{1}	5.22×10^{8}
0038-019[b]	0.018	CO3-2	JCMT	14.6	6.000	7.11×10^{1}	3.90×10^{8}
0100+130G	2.313	CO3-2	NRAO	60.7	0.147	1.19×10^{4}	$<1.36\times10^{11}$
0149+336	2.124	CO3-2	NRAO	57.3	0.104	1.08×10^{4}	$<8.41\times10^{10}$
0151+045	0.160	CO1-0	NRAO	62.2	0.193	6.62×10^{2}	$<1.34\times10^{10}$
0226-038	1.328	CO2-1	NRAO	62.5	0.176	6.42×10^{3}	$<1.44\times10^{11}$
0235+164	0.524	CO1-0	NRAO	81.8	0.318	2.31×10^{3}	$<2.06\times10^{11}$
0248+430[c]	0.051	CO1-0	NRAO	57.8	1.166	2.08×10^{2}	9.31×10^{9}
0248+430[d]	0.051	CO2-1	NRAO	28.9	1.519	2.08×10^{2}	3.03×10^{9}
0446-208	0.067	CO1-0	NRAO	57.3	0.364	2.73×10^{2}	$<4.67\times10^{9}$
0454-220	0.475	CO3-2	JCMT	21.1	0.666	2.08×10^{3}	$<2.57\times10^{10}$
0458-020	2.039	CO3-2	NRAO	54.4	0.650	1.04×10^{4}	$<4.71\times10^{11}$
0528-250	2.811	CO3-2	NRAO	69.9	0.290	1.49×10^{4}	$<3.62\times10^{11}$
0735+178	0.425	CO3-2	NRAO	78.4	0.387	1.85×10^{3}	$<1.80\times10^{11}$
0738+313	0.222	CO1-0	NRAO	65.5	0.193	9.30×10^{2}	$<2.52\times10^{10}$
0742+318	0.192	CO1-0	NRAO	63.9	0.208	8.01×10^{2}	$<2.06\times10^{10}$
0827+2421	0.525	CO3-2	JCMT	21.8	0.983	2.32×10^{3}	$<4.54\times10^{10}$
0850+440	0.163	CO1-0	NRAO	64.0	0.121	6.77×10^{2}	$<9.24\times10^{9}$
0952+179	0.238	CO1-0	NRAO	68.1	0.421	1.00×10^{3}	$<6.60\times10^{10}$
0955+326[e]	0.005	CO1-0	NRAO	53.9	6.226	1.96×10^{1}	4.39×10^{8}
0955+326[f]	0.005	CO2-1	NRAO	27.0	9.482	1.96×10^{1}	1.67×10^{8}
1049+616	0.225	CO1-0	NRAO	65.7	0.149	9.47×10^{2}	$<2.01\times10^{10}$
1157+014	1.944	CO2-1	NRAO	81.0	0.201	9.82×10^{3}	$<3.18\times10^{11}$
1229-021	0.395	CO1-0	NRAO	74.8	0.323	1.71×10^{3}	$<1.25\times10^{11}$
1229-021	0.395	CO3-2	NRAO	25.0	1.745	1.71×10^{3}	$<7.49\times10^{10}$
1327-206[g]	0.018	CO1-0	NRAO	54.6	1.696	7.03×10^{1}	1.51×10^{9}
1327-206[h]	0.018	CO2-1	CSO	31.5	3.460	7.03×10^{1}	1.03×10^{9}
1328+30	0.692	CO3-2	CSO	34.1	0.582	3.13×10^{3}	$<8.73\times10^{10}$

TABLE 1, cont'd

Source	z_{abs}	Trans'n	Telesc.	Beam (″)	I^{i}_{mb} (K km/s)	D_{Mpc}	Molec. Mass[j] $M_\odot$
1331+170	1.776	CO5-4	CSO	33.5	0.579	8.88×10^{3}	$<1.53\times10^{11}$
1331+170	1.776	CO4-3	NRAO	37.3	1.225	8.88×10^{3}	$<4.00\times10^{11}$
1331+170	1.776	CO2-1	NRAO	74.5	0.375	8.88×10^{3}	$<4.90\times10^{11}$
1332+552	0.374	CO1-0	NRAO	75.6	0.143	1.61×10^{3}	$<5.23\times10^{10}$
1511+102	0.437	CO1-0	NRAO	79.0	0.213	1.90×10^{3}	$<1.04\times10^{11}$
1517+239	0.738	CO4-3	CSO	26.9	0.506	3.36×10^{3}	$<5.03\times10^{10}$
1602+178	0.739	CO4-3	NRAO	23.3	0.961	3.36×10^{3}	$<7.19\times10^{10}$
1700+518	0.288	CO1-0	NRAO	69.1	0.151	1.22×10^{3}	$<3.23\times10^{10}$
1704+607	0.092	CO1-0	NRAO	60.1	0.109	3.77×10^{2}	$<2.74\times10^{9}$
1704+608	0.222	CO1-0	NRAO	65.5	0.327	9.30×10^{2}	$<4.27\times10^{10}$
1704+608	0.364	CO1-0	NRAO	73.2	0.200	1.57×10^{3}	$<6.65\times10^{10}$
1946+769	2.845	CO3-2	NRAO	70.5	0.130	1.51×10^{4}	$<1.65\times10^{11}$
2020-370	0.029	CO2-1	CSO	31.9	0.527	1.16×10^{2}	$<4.19\times10^{8}$
2136+141	2.139	CO3-2	NRAO	56.2	0.351	1.09×10^{4}	$<2.74\times10^{11}$
2348-011	2.616	CO7-6	CSO	32.0	0.273	1.37×10^{4}	$<7.11\times10^{10}$

a) Linewidth=180km/s; b) Linewidth=185km/s;
c) Linewidth=393km/s; d) Linewidth=139km/s;
e) Linewidth=342km/s; f) Linewidth=252km/s;
g) Linewidth=347km/s; h) Linewidth=300km/s;

i) To calculate integrated intensity for non-detections:
1) linear fit to continuum used to calculate rms/channel;
2) 300 km/s linewidth used;
3) 3σ upper limit used.

j) Parameters used to calculate molecular mass:
1) $H_o = 75$; 2) $\mu = 4.344\times10^{-24}$ g/H_2;
3) $q_o = 0.5$; 4) $\alpha = 2.5\times10^{20}$ cm^{-2}/(K km s^{-1}).

Figure 1. Molecular Mass vs. z is plotted for the QSO absorption line systems in this work (filled circles), ultraluminous FIR galaxies (crosses), radio galaxies (open circles), radio quiet QSOs (stars), damped Ly-α systems (open squares) & the Milky Way (MW). Arp 220, F10216+4724 & 1643+4631A are plotted as triangles. The lines correspond to detection limits of the specified telescopes & bandpasses. See "Summary of Results" for further details.