Astron. Astrophys. 330, 63–66 (1998)

ASTRONOMY
AND
ASTROPHYSICS

A sensitive search for CO emission from faint blue galaxies at $z \sim 0.5$

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Received 18 September 1997 / Accepted 19 September 1997

Abstract. We have obtained sensitive upper limits on the CO J=2-1 and CO J=3-2 emission lines for five faint blue galaxies with redshifts $z \sim 0.5$ using the IRAM 30 m telescope. These observations would have been able to detect the luminous infrared galaxy IRAS F10214+4724 if it were located at this redshift and unlensed. However, they are not sensitive enough to detect the prototype starburst galaxy M82 or the HII galaxy UM448 if they were located at this redshift. Our upper limits for the CO emission are consistent with between 19% and 66% of the total galactic mass being in the form of molecular hydrogen, and thus shed little light on the ultimate fate of these galaxies.

Key words: galaxies: compact – galaxies: formation – galaxies: ISM – galaxies: starburst – radio lines: galaxies

1. Introduction

A large population of faint blue galaxies at moderate redshifts was first identified by Tyson (1988). These galaxies are puzzling both because of their large space density (30 times that of ordinary bright galaxies, Lilly et al. 1991; Babul & Rees 1992) and their lack of obvious bright counterparts in the local universe. Recent studies have provided us with a detailed look at a sample of these galaxies at $z = 0.1 - 0.6$ (Koo et al. 1994, 1995; Guzman et al. 1996). The galaxies have star formation rates of 1-20 $M_\odot$ yr^{-1} (Koo et al. 1995), comparable to the total star formation rates of present day disk galaxies (Kennicutt 1983). However, they are very compact, with half-maximum diameters of only 2-4 kpc (Koo et al. 1994). Although their blue luminosities are also comparable to local field galaxies ($M_B \sim -21$), their total masses are estimated at only $1 - 5 \times 10^9$ $M_\odot$, much smaller than the typical masses of normal elliptical or spiral galaxies ($\sim 10^{11}$ $M_\odot$) (Guzman et al. 1996). These observations suggest the galaxies are dwarf galaxies near their peak luminosity after undergoing a major burst of star formation. Since star formation is intricately linked with the presence of molecular gas in the local universe, these galaxies are likely to contain significant amounts of molecular gas to provide the fuel for the observed starbursts.

The detection of CO at z = 2.28 in the luminous infrared galaxy IRAS F10214+4724 (Brown & Vanden Bout 1991; Solomon et al. 1992) has stimulated numerous searches for CO emission from galaxies at moderate to high redshifts (Wiklind & Combes 1994b; Evans et al. 1996). However, these searches were less successful than expected, and only highly amplified objects have been detected: the Cloverleaf quasar at z = 2.56 (Barvainis et al. 1994) and BR1202-0725 at z = 4.69 (Ohta et al. 1996; Omont et al. 1996). Recently, Scoville et al. (1997) reported the detection of the first non-lensed object at z = 2.394, the weak radio galaxy 53W002. The derived molecular mass is so high (7.4×10^{10} $M_\odot$ with a standard CO-to-H_2 conversion factor, and even more if the metallicity is low) that it constitutes between 30 and 80% of the total dynamical mass, depending on the unknown inclination. The lensing that can amplify CO emission to a level that is detectable with current instruments can also be produced by galaxy clusters. A search for CO emission from four giant arcs in clusters has been reported by Casoli et al. (1996), and they detected one of them at z = 0.725. Another sensitive technique for probing the cold molecular interstellar medium at high redshifts is via absorption lines (e.g. Combes & Wiklind 1996). Four systems have been detected in more than a dozen molecules in absorption with z between 0.25 and 0.9 (Wiklind & Combes 1994a, 1995, 1996a, 1996b).

In this paper, we present the results of a survey for CO emission from five faint blue galaxies at redshifts $z \sim 0.5$ selected from the sample of Koo et al. (1995). This survey differs from previous surveys in targeting galaxies with known star formation rates, as opposed to damped Lyman α systems (Wiklind & Combes 1994b) or distant radio galaxies (Evans et al. 1996). Unfortunately, as in previous surveys, we have achieved only upper limits to the CO emission from our target objects.

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Table 1. CO upper limits for faint blue galaxies

Galaxy	RA(1950) ($h\ m\ s$)	DEC(1950) ($^{o\ \prime\ \prime\prime}$)	z	ΔV (km s^{-1})	time (hr)	$\sigma(2-1)$ (mK)	$\sigma(3-2)$ (mK)	$I_{CO}(3-2)$ (K km s^{-1})	$L_{CO}(3-2)$ (K km s^{-1} pc^2)
SA57-1501	13:05:43.9	29:24:59	0.4993	143	9.3	2.2	3.7	0.42	2.6×10^9
SA57-7042	13:05:03.2	29:34:26	0.5250	273	2.4	6.3	10.8	1.69	1.1×10^{10}
SA57-10601	13:06:25.0	29:39:39	0.4384	101	1.8	5.3	5.5	0.52	2.8×10^9
SA57-17731	13:06:15.5	29:50:47	0.6612	242	3.9	3.7	5.9	0.87	7.4×10^9
Herc-1-13088	17:19:04.4	50:04:00	0.4357	106	4.3	6.8	9.7	0.95	5.1×10^9

Temperatures are given in the main beam scale

2. Observations and data reduction

2.1. Observations

Of the 17 galaxies in the Koo et al. (1995) sample of faint blue galaxies, nine have redshifts such that the CO J=2-1 and J=3-2 lines are accessible with the IRAM receivers. Three of these nine galaxies are somewhat more extended than the other six and indeed appear non-stellar in ground-based optical observations (Koo et al. 1995). We excluded these three galaxies from our sample on the grounds that they may be somewhat more massive objects, akin perhaps to small spiral galaxies. Observations of five of the remaining six galaxies were obtained with the IRAM 30 m telescope in two separate observing runs in January 1996 and June 1997. The sixth galaxy, SA57-5482, was not observed due to time constraints. The half-power beam width is 17$''$ at 2–mm and 12$''$ at 1.3–mm. We used the 2– and 1.3–mm SiS receivers to observe both lines simultaneously. The receivers were all used in single sideband mode, and the typical system temperatures were 250-500 K for the 2–mm receiver and 350-700 K for the 1.3–mm receiver, in T_A^* scale (or, on average, 600 K and 1200 K in T_{MB} scale, respectively). The backends were essentially two 1MHz-filter-banks, of 512 channels each, and in addition an auto-correlator; the spectra have been smoothed to 10 km s^{-1} resolution. The observations were made using a nutating secondary with a beam throw of 1.5$'$. The pointing was checked every two hours and the pointing accuracy was estimated to be 3$''$ rms.

2.2. Data reduction and analysis

The spectra were first inspected, and any spectrum showing baseline curvature or other artifacts was discarded. The remaining spectra were averaged together, weighted by their rms noise. A first order baseline was removed from each average spectrum, and the spectra were smoothed to a resolution of 10 km s^{-1} to produce the final spectra (Fig. 1). The final temperatures (and rms noise in Table 1) have been converted to the T_{MB} temperature scale (η_{MB} = 0.45 at 230 GHz, 0.59 at 150 GHz).

Upper limits to the integrated CO intensity were derived using the rms noise measured from the CO spectra and the velocity widths obtained from measurements of optical emission lines (Koo et al. 1995). We adopt as the 3σ upper limit to the CO intensity

$$I_{CO} \le \frac{3\sigma\Delta V}{\sqrt{N_{chan}}}\ \ \mathrm{K\ km\ s^{-1}}$$

(Wiklind & Combes 1994b), where σ is the rms noise in K measured in our 10 km s^{-1} channels, ΔV is the velocity width of the CO line, here taken to be the full-width half-maximum of the optical lines, and $N_{chan} = \Delta V/10$ km s^{-1} is the number of channels in the velocity width. The CO luminosity for a source at high redshift is given by

$$L_{CO} = 23.5 I_{CO}\Omega_B \frac{D_L^2}{(1+z)^3}\ \ \mathrm{K\ km\ s^{-1}\ pc^2}$$

where Ω_B is the area of the main beam in square arcseconds and $D_L = (c/H_o q_o^2)[q_o z + (q_o - 1)(\sqrt{1+2q_o z} - 1)]$ is the luminosity distance in Mpc (Wiklind & Combes 1994b). We adopt q_o = 0.5 and H_o = 70 km s^{-1} Mpc^{-1} in this paper. Table 1 gives the position, redshift, and velocity width obtained from the optical emission lines (Koo et al. 1995), as well as the integration time, the rms noise for each line, and the CO integrated intensity and CO luminosity calculated from the CO J=3-2 upper limit.

3. Discussion

Our upper limits to the CO flux are comparable to the best upper limits in the literature for moderate to high redshift objects. For example, the detections of CO J=3-2 emission at high redshift are 6.7 Jy km s^{-1} for IRAS F10214+4724 (Radford et al. 1996) and 8.1 Jy km s^{-1} for the Cloverleaf (Barvainis et al. 1994), while our 3σ upper limits range from 2 to 8 Jy km s^{-1}. If our galaxies had comparable CO fluxes to IRAS F10214+4724 or the Cloverleaf quasar, we would have detected them with our observations. In addition, if we assume the amplification due to lensing is a factor of 10 in the two high redshift galaxies, their CO luminosities L_{CO} (converted to our cosmology) are 8.9×10^9 and 1.3×10^{10} K km s^{-1} pc^2, respectively. Thus, we would have detected either of these two galaxies, unlensed, at a redshift of $z \sim 0.5$.

Since these faint blue galaxies are thought to be distant counterparts to HII galaxies, we should also compare our upper limits with CO observations of nearby dwarf galaxies. The CO J=1-0 luminosities of the starburst galaxy M82 and the HII galaxy UM448 are both $L_{CO} \sim 5 \times 10^8$ K km s^{-1} pc^2 (calculated from

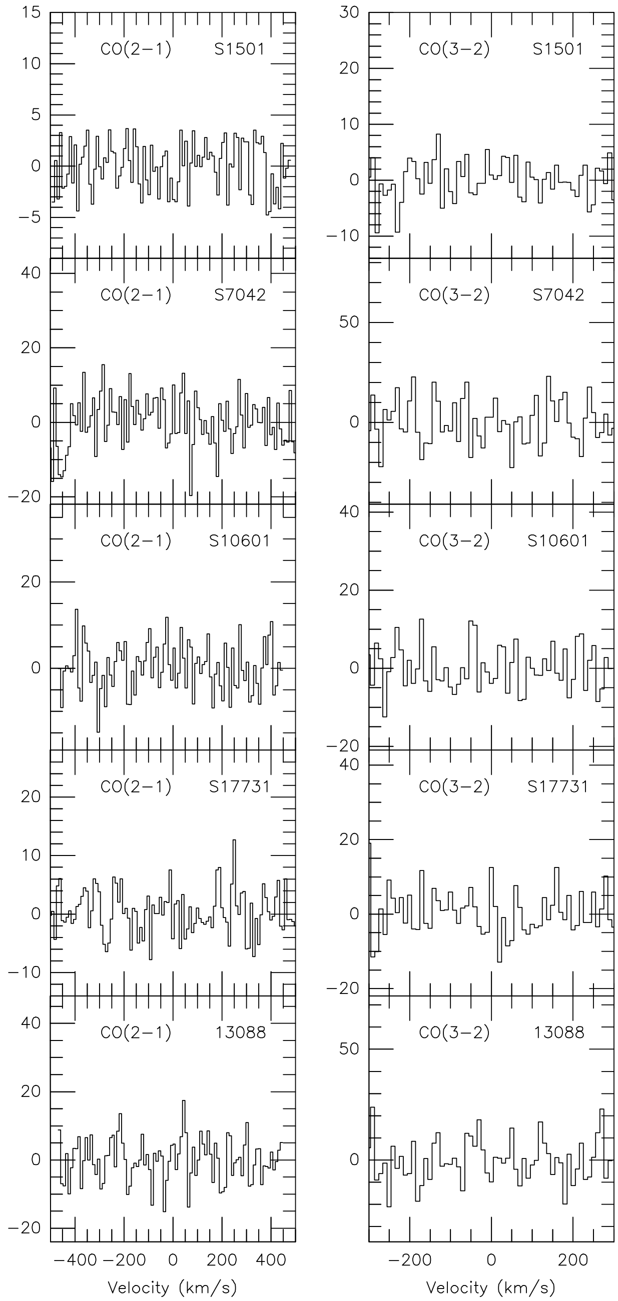

Fig. 1. ^{12}CO J=2-1 and J=3-2 spectra for the five faint blue galaxies. The observed CO transition is marked in each spectrum. The temperature scale is T_{mb} in mK and the velocity resolution is 10 km s^{-1}. No galaxies were detected.

Young et al. 1995; Sage et al. 1992). Unfortunately, our best upper limits are still a factor of 4-8 larger than the luminosities of these nearby dwarf galaxies, and so we would not have detected M82 or UM448 at $z \sim 0.5$.

For galaxies in the local universe with near-solar metallicities and normal rates of star formation (i.e. not starburst galaxies), the mass of molecular hydrogen gas is related to the CO luminosity in the J=1-0 line by $M_{H_2} = 4.8 L_{CO}$ M$_\odot$ (i.e. Solomon et al. 1987). Since we have observed the CO J=2-1 and J=3-2 lines, we must consider the excitation of the gas in estimating molecular gas masses. In galactic nuclei, the three transitions have similar strengths (Braine & Combes 1992; Güsten et al. 1993), while in the disks of spiral galaxies, the J=2-1/1-0 ratio is typically 0.5-0.7 (Braine & Combes 1992; Sakamoto et al. 1994) and the 3-2/2-1 ratio is 0.7 (Wilson et al. 1997). Given the compact and starburst nature of these systems, we will assume that the three lowest CO line ratios have equal strengths, in which case our CO J=3-2 observations give the best upper limit to the molecular mass. If in fact these galaxies are more like normal spirals in their excitation, our gas masses will be underestimated by a factor of about two.

Table 2. Comparison of virial and gas masses

Galaxy	M_{vir} 10^9 M$_\odot$	M_{H_2} 10^9 M$_\odot$
SA57-1501	17	<3.2
SA57-7042	60	<14
SA57-10601	8.4	<3.4
SA57-17731	48	<8.9
Herc-1-13088	9.2	<6.1

The CO-to-H_2 conversion factor is known to depend on the metallicity of the galaxy (Wilson 1995) and is also expected to be different in the unusual conditions present in a starburst galaxy. The metallicities of these galaxies are estimated to be ~ 0.7 solar (Guzman et al. 1996), which implies a roughly normal CO-to-H_2 conversion factor (Wilson 1995). Assessing the impact of the starburst environment is more difficult, although Solomon et al. (1997) suggest that the conversion factor is roughly four times smaller in luminous infrared galaxies than in normal spirals. To take into account the intense star formation in these galaxies, we will calculate the H_2 mass using $M_{H_2} = 1.2 L_{CO}$ M$_\odot$; note that this may underestimate the gas masses by up to a factor of four if the star formation environment is relatively normal.

Table 2 compares the upper limits to the gas masses with the virial masses of the galaxies. The virial masses were calculated as in Guzman et al. (1996), and then scaled up by a factor of 4 to account for possible underestimate of the total mass of the galaxy using the optical data (see discussion in Guzman et al. 1996). (These virial mass estimates will be even more uncertain if these objects are predominantly disk-like rather than spheroidal systems, as assumed in the calculation.) Since the radii of our galaxies have not been measured, we adopt the average effective radius R_e = 0.96 kpc (converted to our cosmology) measured for seven faint blue galaxies by Koo et al. (1994). Table 2 shows that, even with our conservative assumptions, which increase the total mass of the galaxy and decrease the gas mass, our upper limits are consistent with the faint blue galaxies containing between 19% and 66% of their total mass in the form of molecular gas. Depending on how much gas they can retain to fuel later star formation episodes, these galaxies may either be the progenitors of present day dwarf elliptical galaxies (if most of the gas is lost in the current burst, Koo et al. 1995) or HII galaxies (if a significant fraction of their gas survives the current burst). Unfortunately, these observations provide no constraint on the interesting question of whether or not these galaxies still contain large quantities of molecular gas.

4. Conclusions

We have obtained sensitive upper limits on the CO J=2-1 and CO J=3-2 emission lines for five faint blue galaxies with redshifts $z \sim 0.5$ for which accurate redshifts and linewidths had been determined previously from optical observations. Our upper limits are comparable to the best upper limits published for moderate to high redshift objects in the literature, and are sensitive enough to have detected the luminous infrared galaxy IRAS F10214+4724 if it were located at this redshift and unlensed. However, our sensitivity is insufficient to detect either the prototype starburst galaxy M82 or the HII galaxy UM448 if they were located at this redshift. Our upper limits for the CO emission are consistent with these galaxies containing between 19% and 66% of their total mass in the form of molecular hydrogen. Since whether these galaxies will evolve into dwarf ellipticals or retain enough gas to burst again as HII galaxies depends on their ability to retain gas during the observed burst of star formation, our observations are unable to provide any useful information on the ultimate fate of these galaxies.

Acknowledgements. The research of C.D.W. is supported by a grant from NSERC (Canada).

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