First Detection of CO in a Low Surface Brightness Galaxy [1]

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ABSTRACT

We report on the first attempts at searching for CO in red low surface brightness galaxies, and the first detection of molecular gas in a low surface brightness ($\mu_B(0)_{obs} >$ 23 mag arcsec^{-2}) galaxy. Using the IRAM 30m telescope, CO(1-0) and CO(2-1) lines were searched for in four galaxies – P06-1, P05-5, C05-3, & C04-2. In three of the galaxies no CO was detected, to T$_{MB}$ ~1.8mK (at the 3σ level). In the fourth galaxy, P06-1, both lines were detected. Comparing our findings with previous studies shows P06-1 to have a molecular-to-atomic mass ratio considerably lower than is predicted using theoretical models based on high surface brightness galaxy studies. This indicates the N(H$_2$)/$\int T(CO)dv$ conversion factor for low surface brightness galaxies may currently be consistently underestimated by a factor of 3 - 20.

Subject headings: galaxies: individual: (P06-1, P05-5, C05-3, C04-2) – galaxies: ISM – galaxies: evolution

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1. Introduction

Recently it has become clear that there exists a large population of low surface brightness (LSB) galaxies which previously had escaped detection (e.g. Impey et.al. 1988; Schombert et al. 1992; Morshidi-Esslinger, Davies, & Smith 1999; O'Neil, Bothun, & Cornell 1997a; O'Neil, Hauser, & Bothun 2000). The importance of LSB galaxies in the local universe is emphasized by studies showing that the majority of the galaxies in the local universe are LSB galaxies. Realizing then that most galaxies are optically diffuse, it becomes important to understand these systems if we wish to understand galaxy formation and evolution as a whole. This study is made difficult, though, by the lack of data on LSB galaxies. In particular, in spite of the importance of LSB galaxies there is at the present time little information about the molecular ISM in these systems.

To date four studies have been undertaken to look for CO in low surface brightness systems. The first two studies – Schombert et al. (1990) and de Blok & van der Hulst (1998) – focused on galaxies with $(B-V) \leq 0.6$ and achieved 3σ detection limits of T_{MB}=8.4 – 24.3 mK (with the NOAO 12m telescope and the JCMT). The next two studies (Knezek 1993; Braine, Herpin, & Radford 2000) were of giant LSB systems. In all four cases no CO was detected. A fifth, very recent, study by Matthews (2000) is also well worthy of mention. This study was designed to look for CO in late-type, edge-on galaxies. CO was detected for a sample of galaxies, a subset of which, if de-projected from their edge-on orientation, may be LSB systems.

The recent discovery of red $(B-V \geq 1)$ LSB galaxies (O'Neil et al.1997b) has brought the idea of searching for molecular gas in LSB systems back to the forefront. As red colors should be indicative of reasonably high metallicities and therefore should insure against CO depletion (for example, as is seen in low metallicity dwarf galaxies), it seemed worthwhile to make a fifth attempt at CO detection in these diffuse systems.

2. Observations

Our targets were chosen from the catalogs of O'Neil, Bothun, & Schombert (2000) (OBS hereafter). In an attempt to insure against any anti-correlation (or correlation) between the galaxies' H I and CO content (i.e. Kenney & Young 1989) the total H I mass and mass-to-luminosity ratios of the chosen galaxies vary widely, from 1 – 75 $\times$ 10^8 $M_\odot$ of HI and 1.3 – 4 $M_\odot$(HI)/$L_\odot$(B). Additionally, as mentioned above, to insure against CO depletion the four galaxies have $(B-V) \geq 1$.

We observed the CO(1–0) and (2–1) rotational transitions with the IRAM 30m telescope in the period from June 24 to 28, 2000. Table 1 lists the adopted positions (determined using the digitized Palomar sky survey plates) and heliocentric velocities (adopted from the measured 21-cm values of OBS) for our target sources. The beams were centered on the nuclei of each galaxy. Pointing was checked every hour and was found to be better than $5''$,and focus was checked every 3–4 hours. For each source both transitions were observed simultaneously with two receivers in each band. To each receiver we connected a 256 channel filter bank with channel width 1 MHz, (670 km s^{-1} bandwidth, 2.6 km s^{-1} resolution at 3mm). For the source [OBC97] P06-1, which was known to have a wide HI line (OBS) we used two 512 channel filter banks with 1 MHz wide channels, as well as two sections of the auto-correlator of width 510 MHz and resolution 1.25 MHz. We observed using the wobbling secondary with a maximal beam throw of $240''$. The image side band rejection ratios were measured to be $>$ 30 dB for the 3 mm SIS receivers and $>$ 12 dB for the 1.3 mm SIS receivers. The data were calibrated using the standard chopper wheel technique (Kutner & Ulich 1981) and are reported in main beam brightness temperature T_{MB}. Typical system temperatures during the first two days of our observations were 200 and 450 K in the 3 mm and 1.3 mm band respectively. During the last two days the weather conditions deteriorated and no useful 1.3 mm data were obtained under these conditions.

3. Results

3.1. The Detection

One of the galaxies observed, [OBC97] P06-1, had a clear detection with both the J(1-0) and J(2-1) lines, providing the first detection of molecular gas in a LSB galaxy (Figure 1). The observed main beam brightness temperature was 3.2$\pm$0.6 and 5.3$\pm$1.1 mK, after smoothing to 40 km s^{-1} (for the J(1-0) and J(2-1) lines, respectively). This corresponds to an integrated flux density of 0.95 $\pm$ 0.22 and 1.1 $\pm$ 0.33 K km s^{-1}. (Errors for the flux density are computed from the rms error of the main beam brightness temperature and an assumed 40 km s^{-1} error for the velocity width.)

The IRAM J(1-0) beam-width is only 22″, considerably smaller than both the 3.6′ Arecibo beam used in the H I observations of OBS and the optical diameter (d_{27}) of 61.5″ reported by O'Neil, et al.(1997a) (Table 2). It is therefore worthwhile to consider whether or not the IRAM beam has captured the majority of the observable CO. As this is the first detection of CO in a LSB system, we are forced to turn to studies mapping the CO distribution in HSB spiral galaxies. In 1989, using 2.6-mm CO emission observations of more than 200 galaxies, Young & Knezek (1989) (hereafter YK89) concluded the average CO extents of spiral galaxies are typically one-half the optical radius. If P06-1 follows this trend, the J(1-0) beam only covers approximately 50% of the total surface area of CO while the J(2-1) line is reduced to measuring only 12% of the total CO emission. In agreement with this idea is the comparison of H I to CO velocity widths done by Tutui & Sofue (1999), which put our measured velocity width at 66% of the predicted value. As the rotation curves of LSB galaxies can be found to be more slowly rising than their HSB counterparts (i.e. de Blok, McGaugh, & van der Hulst 1996; van Zee et al. 1997; Swaters, Madore, & Trewhella 2000), this may be an indication that the beam has not fully encompassed the galaxy. It is therefore quite possible that we have only measured roughly 1/2 of the total CO(1-0) and 1/10 of the CO(2-1) emission of P06-1.

3.2. The Non-Detections

In three of the four observed galaxies, [OBC97] C04-2, [OBC97] C05-3, & [OBC97] P05-5, no CO was detected, with 3σ non-detection limits ranging from T_{MB}=1.5 – 3.9 mK (Figure 2 & Table 2). These detection limits are factor of 6 – 7 smaller than the recent work done by de Blok & van der Hulst (1998) and Schombert et al. (1990). It is interesting to note, though, that the integrated intensity limits of our observations are only slightly smaller than in the de Blok & van der Hulst (1998) sample due to the narrower velocity widths of their sample. It should also be noted that the optical size of these galaxies, 36″, 24″, and 30″diameters for C04-2,C05-3, and P05-5, respectively, indicates that the majority of each galaxy was enclosed by the IRAM beam (for the J(1-0) observations).

4. H_2 in LSB Galaxies

The observed integrated CO flux of the four galaxies can be converted into an H_2 mass by assuming a value of $N(H_2)/\int T(CO)dv = 3.6\times10^{20}cm^{-2}/(Kkms^{-1})$ (see below for a discussion on the conversion factor). Assuming the J(1-0) value is a more accurate measurement for P06-1 (as the beam size at 115GHz samples a larger part of the galaxy), this gives $M_{H_2} = 11\times10^8\ M_\odot$, or $M_{H_2}/M_{HI} = 0.2$. Comparing our results with those of other spiral galaxies indicates P06-1 to have a molecular-to-atomic gas ratio near the low end of the observed values (i.e. YK89). This is surprising as the red color of P06-1 ($B-V = 1$) typically would indicate a much higher value of M_{H_2}/M_{HI} (see below).

For the non-detections, the 33σ (J(0-1)) M_{H_2}/M_{HI} limits range from 0.09 to 0.6. Comparing this with our measured values for P06-1 shows the non-detection limits to lie from 1/2 – 3 times the detected M_{H_2}/M_{HI} value of P06-1. Taking into account the relatively high inclination of P06-1 (i=60°) compared with most of the other LSB galaxies which have been observed (i_{typ}=33°) makes it plausible that only slightly more sensitive CO studies could considerably increase the number of CO detections in LSB systems. This argument is supported further by the recent discovery of CO in a number of edge-on, late-type galaxies by Matthews (2000).

Using the detected CO lines to estimate the H_2 content of P06-1 and the other galaxies studied in our survey is a highly uncertain process. No molecular line is ideally suited for the determination of $N(H_2)$, as it depends on knowing the CO $\leftrightarrow$ H_2 conversion factor $X=N(H_2)/\int T(CO)dv$, having a galaxy which is fairly homogeneous in temperature and density (at least for the CO molecule), and understanding the optical thickness of the system. Additionally, in low metallicity systems (as LSB galaxies appear to be), CO emission is a poor tracer of molecular mass (i.e. YK89; Braine & Combes 1992; Mihos, Spaans, & McGaugh 1999 – hereafter MSM). To allow for comparison between our findings and the work of Schombert et al. (1990) and de Blok et al. (1998) we adopt the value given by Sanders et al. (1986) of $X = N(H_2)/\int T(CO)dv = 3.6\times10^{20}\ cm^{-2}/(Kkms^{-1})$ derived from observing high luminosity IRAS galaxies, albeit with the warning that our H_2 calculations are for comparison only, and could easily be off by a factor of 10 (or more!) (i.e. de Blok & van der Hulst 1998; MSM).

It should be noted that we are comparing the *measured* values of CO, without accounting for the considerably smaller beam size used for the CO measurements (11″ and 22″) than for the HI measurements (3.6′). If the CO extent is 1/2 the optical radius of these galaxies, as is found by YK89, then our comparison is accurate for the non-detections but low for P06-1. As this is the first detection of CO in a LSB galaxy, though, there is no way of determining whether the findings of YK89 hold for these systems.

5. Discussion

Assuming a Salpeter-like IMF, near-IR observations by Bell et al. (1999) of red LSB galaxies indicate they should have metallicities in the $\sim$Z$_\odot$ range. When combined with a theoretical study of the molecular ISM in LSB galaxies (MSM), this indicates the CO intensity of the red LSB galaxies should be above 1.0 K km s^{-1} (for the J=1–0 transition). (It should be noted that the Bell et al. (1999) paper accurately predicts the values found by YK89 in their observations of HSB spiral galaxies.) The MSM paper also provides a prediction of the observed M$_{H_2}$/M$_{HI}$ for Z$_\odot$ galaxies ranging from 1 – 3, depending on the structure of the galaxies' ISM. For the three non-detections in our sample, both the observed $\int T(CO)dv$ and M$_{H_2}$/M$_{HI}$ fall well short of the predicted value. Our one detection, though, matches the predicted $\int T(CO)dv$ value well but has a M$_{H_2}$/M$_{HI}$ value a factor of 6 – 20 too small.

A number of factors may be contributing to the discrepancy between our observe values (and upper limits) and those predicted by both MSM and Bell et al. (1999):

1. If the CO extent is considerably larger than the beam size, our observed values could be underestimated. It is doubtful, though, that this idea plays much of a role. Even if the observed $\int T(CO)dv$ value of P06-1 is half the actual value, this could only increase M$_{H_2}$/M$_{HI}$ by a factor of 2, and would most likely increase it by considerably less. Additionally, the three non-detections have optical (d$_{27}$) sizes of less than 36″, insuring that most of each galaxy would fit within the beam.

2. If the metallicity of the LSB galaxies is considerably lower than that predicted by Bell et al. (1999), the galaxies will have fewer dust grains to drive molecule formation, resulting in lower than average molecular content. Additionally, low metallicity results in a low UV attenuation. This implies that the H$_2$ (which is strongly self-shielding) would not be much affected by the lower metallicity, while the CO would more readily be destroyed (i.e. Schombert et al. 1990). Thus X, the H$_2$ to CO ratio, would increase. For our observed galaxies,the theoretical predictions of MSM show that decreasing the metallicities to Z=0.3Z$_\odot$ will both increase X by a factor of $\sim$2 and decrease M$_{H_2}$/M$_{HI}$ by 5. Simultaneously, $\int T(CO)dv$ is reduced to 0.1 – 0.3 K km s^{-1} (depending on the galaxies' central surface brightness). With these values the upper limits on $\int T(CO)dv$ for C04-2 and C05-3 could readily fall onto the values predicted by MSM for M$_{H_2}$/M$_{HI}$ and could come considerably closer to their predicted $\int T(CO)dv$ values. The upper limits of P05-5, though, are still short of the predicted M$_{H_2}$/M$_{HI}$ value by a factor of 3.

   Attempting to match P06-1 into MSM's predictions through lowering its metallicity also has problems. As the predicted and observed values of $\int T(CO)dv$ match, lowering the galaxy's metallicity to 0.3Z$_\odot$ can allow the predicted and observed M$_{H_2}$/M$_{HI}$ values to match, but the observed $\int T(CO)dv$ value is then too high by a factor of 10.

3. The third factor which should be considered is the homogeneity of the ISM. MSM show that the galaxies with 'clumpier' ISM have higher values of X than their homogeneous counterparts, as the denser regions are better shielded from the background interstellar radiation field.

4. The last item to consider in these calculations is the efficiency of the galaxies in converting atomic hydrogen into molecular hydrogen. If the velocity dispersion of LSB galaxies is higher than in their high surface brightness counterparts, the formation and growth of molecular clouds could be adversely affected. This would result in lower molecular content in LSB systems. This idea is supported by the fact that the one LSB galaxy which has been detected in CO also has the highest HI gas mass (and presumably the highest total mass) of any LSB galaxy in this study.

As can be seen from the above arguments, no one parameter can readily account for both the observed $\int T(CO)dv$ values/limits and for the low M_{H_2}/M_{HI} values which are observed both in this project and in previous searches for CO in LSB galaxies. If MSM's prediction for $\int T(CO)dv$ is correct, then we are handed a dilemma – either the four galaxies observed in this project are homogeneous, in which case one of the galaxies (P06-1) has a metallicity 10 times that of the other three galaxies, in spite of their similar colors, or the galaxies have a clumpy structure and their metallicities are similar and all are a factor of 3 – 10 times fainter than that predicted by Bell et al. (1999). In the latter case the models of MSM predict that P06-1 has considerably more high density regions than the other three homogeneous galaxies.

Assuming the MSM values for $\int T(CO)dv$ are correct, at least to within a factor of $\sim$3 (to account for possible variations in the HI$\rightarrow$H$_2$ conversion rate), we have to face the issue that the previously used value of N(H$_2$)/$\int T(CO)dv$ is low by a factor of 3 – 20. due to the large number of uncertainties in X, it is quite likely that this interpretation is correct, at least to some degree. It should be emphasized, though, that such a high value of X may be indicative of a different evolutionary path or processes in LSB galaxies.

Clearly there are still a large number of questions yet to be answered about these systems before a true understanding of their stellar structure and evolution can be found. Perhaps the most important issue is a determination of the metallicities of the red LSB galaxies so that more accurate comparisons between these objects and the models of MSM can be obtained. Regardless, though, two facts seem to be clear from our CO observations. First, the observed CO flux intensities of LSB galaxies are well below predictions made which assume LSB and HSB galaxies to evolve in an identical fashion. Second, even the higher CO/H$_2$ conversion factor used by Schombert et al. (1990) and de Blok et al. (1998) is most likely too low by a factor of at least two, resulting in higher than previously believed limits on M_{H_2} in LSB galaxies.

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Table 1
Observed Sources

Source	α(J2000) h m s	δ(J2000) ° ′ ″	v_{Hel} km s^{-1}	$\mu_B(0)$	$\mu_{B_c}(0)$	$B-V$	v_{20} km s^{-1}	M_{HI} $\times 10^8 M_\odot$	i °	d$_{27}$ ″
C04-2	08 23 29.3	21 36 45	5168	24.0	24.2	1.3	103	4.2	31	35
C05-3	08 27 44.4	20 28 50	12940	23.9	24.0	1.2	130	26.	20	24
P05-5	23 19 34.8	08 45 41	3177	24.4	24.6	1.2	71	0.6	37	28
P06-1	23 23 32.6	08 37 25	10882	23.2	24.2	0.94	430	74.	66	62

Information taken from OBS, O'Neil, Bothun, & Cornell (1997a), and O'Neil et al. (1997b)

Table 2
Line Parameters

Source	Transition CO	T$_{MB}$ (mK)	$\int T_{MB} dv$ (K km s^{-1})	M_{H_2} $\times 10^8 M_\odot$	$\frac{M_{H_2}}{M_{HI}}$	v$_{Hel}$ (km s^{-1})	Width (km s^{-1})
C04-2	1–0	< 0.5[a]	< 0.096[b]	< 2.3[c]	< 0.55	–	(103)
C05-3	1–0	< 0.6[a]	< 0.14[b]	< 2.2[c]	< 0.086	–	(130)
P05-5	1–0	< 0.7[a]	< 0.12[b]	< 0.11[c]	< 0.18	–	(71)
	2–1	< 1.3[a]	< 0.21[b]	< 0.047[c]	< 0.078	–	(71)
P06-1	1–0	3.2 ± 0.6[d]	0.95	11.[c]	0.15	10904[e]	302[f]
	2–1	5.3 ± 1.2[d]	1.14	3.2[c]	0.043	10903[e]	216[f]

[a]For non-detections, T$_{MB}$ is the 1σ r.m.s. noise smoothed to a resolution of 40 km s^{-1}.

[b]Non-detection limits are $I_{CO} = 3T_{MB}\frac{v_{HI}}{\sqrt{N}}$ (N = the number of channels).

[c]$M_{H_2} = 5.82\left[(\pi/4)\, d_b^2 I_{CO}\right]$ (Assumes $N(H_2)/\int T(CO)dv = 3.6 \times 10^{20}\ cm^{-2}/(Kkms^{-1})$.)

[d]T$_{MB}$ was computed as $\int T_{MB} dv$ divided by width.

[e]Velocity of central line channel.

[f]Width is given by number of channels above 3σ noise level.

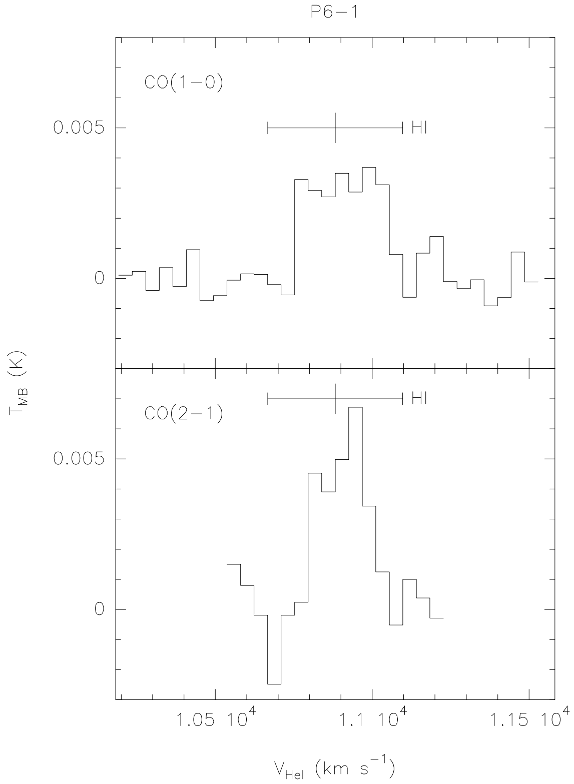

Fig. 1.— IRAM 30m CO(1–0) and (2–1) spectra for the low surface brightness galaxy P06-1. The data have been smoothed to a resolution of about $40\,\mathrm{km\,s^{-1}}$. The horizontal bar indicates the extent of HI as measured by O'Neil et al. (2000).

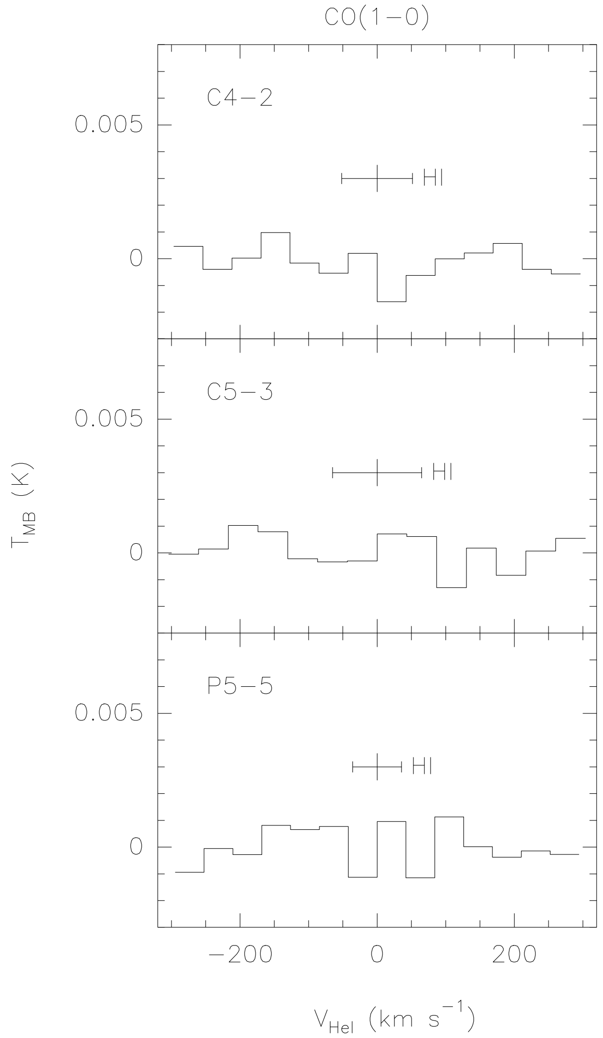

Fig. 2.— IRAM 30m CO(1–0) spectra for three low surface brightness galaxies where we derived upper limits on the CO(1–0) line strength. The data have been smoothed to a resolution of about $40\,\mathrm{km\,s^{-1}}$and are plotted as offsets from their heliocentric velocities listed in Table 1. The horizontal bar indicates the extent of HI as measured by O'Neil et al. (2000).