Properties of Molecular Gas in Massive Low Surface Brightness Galaxies, Including New ^{12}CO Observations of Three Malin 1 'Cousins'

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ABSTRACT

To date, the only low surface brightness (LSB) galaxies which have been detected in CO are the Massive LSB (MLSB) galaxies. In 2003, O'Neil, Schinnerer, & Hofner hypothesized that is the prominent bulge component in MLSB galaxies, not present in less massive low surface brightness galaxies, which gives rise to the detectable quantities of CO gas. To test this hypothesis, we have used the IRAM 30m telescope to obtain three new, deep CO J(1−0) and J(2−1) observations of MLSB galaxies. Two of the three galaxies observed were detected in CO – one in the J(1−0) line and the other in both the J(1−0) and J(2−1) lines, bringing the total number of MLSB galaxies with CO detections to 5, out of a total of 9 MLSB galaxies observed at CO to date. The third object had no detection to 2 mK at CO J(1−0). Comparing all MLSB galaxy CO results with surveys of high surface brightness galaxies, we find the MLSB galaxies' M_{H_2} and M_{H_2}/M_{HI} values fall within the ranges typically found for high surface brightness objects, albeit at the low end of the distribution, with the two MLSB galaxies detected at CO in this survey having the highest M_{H_2}/M_{HI} values yet measured for any LSB system, by factors of 2–3.

Subject headings: Galaxies: CO,H_2 — Galaxies: ISM — Galaxies: low surface brightness — Galaxies: spiral — Galaxies: evolution

1. Introduction

Despite more than a decade of study, the star formation processes within low surface brightness (LSB) galaxies, those objects with central surface brightness at least 1 magnitude fainter than the night sky (uncorrected for inclination), remain enigmatic. The general properties of LSB galaxies – blue colors, high gas mass-to-luminosity ratios, and low metallicities – lead to the conclusion that LSB systems are under-evolved compared to their high surface brightness (HSB) counterparts. When combined with the low gas density (typically $\rho_{\rm HI} \leq 10^{21}$ cm^{-2}) and low baryonic-to-dark matter content typical of LSB systems, the question can be raised not of why LSB galaxies are under-evolved, but instead of how LSB systems form stars at all (O'Neil, Schinnerer, & Hofner 2003, and references therein).

One of the primary methods for studying the star formation rate and efficiency in galaxies is through study of the galaxies' interstellar medium

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(ISM), and one mechanism for studying a galaxy's ISM is through observing its CO content. Until recently, all attempts at detecting CO in LSB systems had been unsuccessful (Braine, Herpin, & Radford 2000; de Blok & van der Hulst 1998; Schombert, et al. 1990), leading to speculation as to why LSB galaxies appear to lack molecular gas. However, in the past three years the first detections of CO in LSB galaxies have been made, giving the first look into the ISM of LSB systems (O'Neil, Schinnerer, & Hofner 2003; O'Neil & Schinnerer 2003; O'Neil, Hofner, & Schinnerer 2000).

While the three detections to date of CO gas in LSB galaxies are of considerable importance, it is clear further study is paramount to understand LSB systems – knowing the CO content of only three LSB galaxies does not provide enough information to understand the molecular gas content of LSB systems as a whole. To aid in our understanding, we undertook CO observations of three additional LSB galaxies, with properties similar in most respects to the properties of the LSB galaxies with detected CO. The results of those observations are described herein.

2. Observations

As mentioned above, the three sources observed for this project have properties similar to those of the three LSB galaxies which previously have been detected in CO. That is, all three galaxies observed fall into the category of Massive LSB (MLSB) galaxies, or 'Malin 1' cousins (named after the largest and most famous of the MLSB galaxies), with $M_{HI} \geq 10^{10}$ $M_{\odot}$, $W_{20}^{corr} \geq 450$ km s^{-1}, $M_B \leq -18.5$, and $D_{25} \geq 50$ kpc. A complete description of the previously known properties of all MLSB galaxies observed at CO, including those observed for this paper are given in Table 1.

The CO J(1–0) and J(2–1) rotational transitions of the galaxies were observed using the IRAM 30m telescope in the period from 7-8 March, 2003. Table 2 lists the adopted positions (determined using the digitized Palomar sky survey plates and accurate to 2-3″) and heliocentric velocities (O'Neil, et al. 2004) for our target sources. The beams (22″ at 110 GHz) were centered on the nucleus of each galaxy. This resulted in a coverage of the inner 14, 27, and 24 kpc for UGC 04144, UGC 05440, and UGC 06124, respectively. Pointing and focus were checked every hour and pointing was found to be within the telescope limits (better than 2″). For each source both transitions were observed simultaneously with two receivers. Both back ends were set using with 510 MHz bandwidth and 1.25 MHz resolution, resulting in an unsmoothed resolutions of 3.36 and 1.68 km s^{-1} for the 3mm and 1mm observations, respectively. For data reduction, the lines were smoothed to 26.9 km s^{-1} resolution. Each target was observed on-source for a total of 66 minutes.

All observations used the wobbling secondary with the maximal beam throw of 240″. The image side band rejection ratios were measured to be > 30dB for the 3 mm SIS receivers and > 12dB 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 observations were 170–190K and 350–450K in the 3 mm and 1.3 mm band, respectively. All data reduction was done using CLASS – the Continuum and Line Analysis Single-dish Software developed by the Observatoire de Grenoble and IRAM (Buisson, et al. 2002).

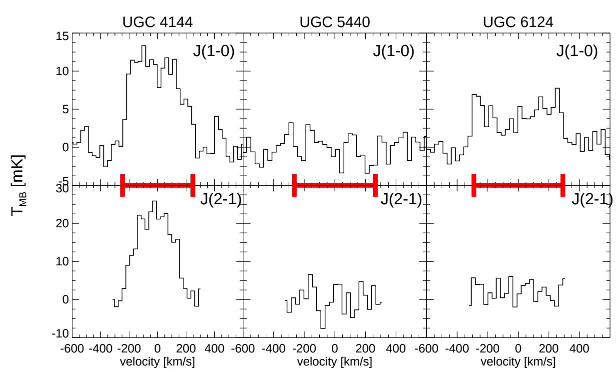

Fig. 1.— IRAM 30m CO J(1−0) and J(2−1) spectra for UGC 04144, UGC 05440, and UGC 06124. The data have been smoothed to a resolution of 26.9 km s^{-1}. The horizontal bars indicate the extent of the observed (uncorrected) H I velocity widths (at 20% the peak HI intensity) as given by O'Neil, et al. (2004).

TABLE 1

KNOWN PROPERTIES OF MLSB GALAXIES OBSERVED IN CO

Name	Type	$\mu_{\rm B}(0)$ [mag arcsec^{-2}]	M$_B$ [mag]	D$_{25}$ [kpc]	i [°]	$\log(\frac{M_{HI}}{M_\odot})$	v$^{\rm HI}_{\rm HEL}$ [km s^{-1}]	w$^{\rm HI}_{\rm 20,obs}$ [km s^{-1}]	Neighbors[a]
				Observations from this paper					
UGC 04144	Sc	24.4[1,b]	-20.0	42	83	9.9[1]	9795[1]	494[1]	1
UGC 05440	Sd	25.7[1,b]	-20.5	96	65	10.8[1]	18932[1]	531[1]	0
UGC 06124	S	26.0[1,b]	-19.9	81	82	10.3[1]	13970[1]	583[1]	0
				Previous Detections					
UGC 01922	S?	... [c]	-19.8	59	38	10.33[1]	10894[1]	1120[1,d]	2
UGC 12289	Sd	23.3	-19.7	57	22	10.13[1]	10160[1]	488[1]	2
[OBC97] P06-1	Sd	23.2	-18.6	29	70	9.87	10882	458	1
				Previous Non-detections					
UGC 06968	Sc	... [c]	-21.1	48	71	10.30	8232	574	3
LSBC F582-2	Sbc	... [c]	...	41	66	9.99	7043	310	1
Malin 1	S	26.4	-21.4	240	20	10.6	24733	710	0

NOTE.—Unless otherwise noted, properties are from O'Neil, Schinnerer, & Hofner (2003) and references therein.
[a]The number of galaxies within a 750 kpc/2,000 km s^{-1} radius, as found with NED. [b]A measured $\mu_B(0)$ for this galaxy is not available. The central surface brightness is defined as $\langle\mu_{\rm B}\rangle = {\rm m_{pg}} + 5\log{\rm (D)} + 8.89 - 0.26$, where m_{pg} is the photographic magnitude from the UGC, D is the diameter in arcmin, 8.89 is the conversion from arcmin to arcsec, and 0.26 is an average conversion from m$_{pg}$ to m$_B$ (Bothun, et al. 1985).
[c]The classification of this galaxy as an LSB galaxy is from Schombert (1998).
[d]The velocity width for UGC 01922 uncorrected for inclination is 690 km s^{-1}(Giovanelli & Haynes 1985).

References. — [1]O'Neil, et al. (2004);

TABLE 2

PARAMETERS FOR IRAM OBSERVATIONS

Name	RA [J2000]	DEC [J2000]	σ^{1-0}_{rms}† [mK]	σ^{2-1}_{rms}† [mK]
UGC 04144	07:59:27.3	07:26:30.0	3.4	2.0
UGC 05440	10:05:35.9	04:16:45.0	1.7	3.4
UGC 06124	11:03:39.5	31:51:30.0	2.0	2.6

NOTE.—†R.m.s. estimates are from the smoothed data (26.9 km s^{-1} resolution).

3. Results

Two of the three galaxies observed, UGC 04144 and UGC 06124, were detected in CO while the third galaxy, UGC 05440, was not detected, with an upper limit of $f_{CO(1-0)} < 0.82$ K km s^{-1}and M$_{H_2}$ < $10^{9.2}$M$_\odot$(Figure 1). Due to its distance (v$_{HEL}$=18932 km s^{-1}), the upper M$_{H_2}$ limit placed on UGC 05440 was too high for any significance. However, the limit placed on M$_{H_2}$/M$_{HI}$ is low for a galaxy of its luminosity. Table 3 lists the CO properties of all three objects, as determined by our observations. For comparison with previous studies (O'Neil, Schinnerer, & Hofner 2003, and references therein) we used a standard CO $\leftrightarrow$ H$_2$ conversion factor (X) of N(H$_2$)/ $\int$ T(CO)dv = 3.6×10^{20} cm^{-2}/(K km s^{-1}) adopted from Sanders, et al. (1986). As discussed in O'Neil, Hofner, & Schinnerer (2000), this assumption does not include dependence based on the structure of the ISM, metallicity, etc. A discussion of any errors which may arise due to this assumption can be found in O'Neil, Schinnerer, & Hofner (2003).

Of the three galaxies observed, UGC 04144 is the most nearby, making it unsurprising that UGC 04144's J(1−0) flux is considerably higher than that found for the other galaxies. However, it is notable that both UGC 04144 and UGC 06124 have M$_{H_2}$/M$_{HI}$ values considerably higher than is found for the other MLSB galaxies with CO detections. Before these observations, the average value of M$_{H_2}$/M$_{HI}$ for the MLSB galaxies was 0.08. In contrast, UGC 06124 has M$_{H_2}$/M$_{HI}$ = 0.14 and UGC 04144 has M$_{H_2}$/M$_{HI}$ = 0.38. Comparing these galaxies with the other MLSB galaxies observed, both those with and without CO detections, shows very little differences in their properties. All galaxies observed have similar morphologies (Sc/Sd), colors (from U through K – NED[1]), H I masses, and total (dynamic) masses. Two of the MLSB galaxies have both 1.4 GHz continuum and IRAS detections – UGC 04144 (f$_{1.4GHz}$=4.7 mJy, f$_{60\mu m}$=0.40 Jy) and UGC 01922 (f$_{1.4GHz}$=38.5 mJy), f$_{60\mu m}$=0.33 Jy (Condon, et al. 1998; Beichman, et al. 1988; Moshir, et al. 1992), but UGC 01922 has M$_{H_2}$/M$_{HI}$ of only 0.07. Similarly, the number of neighboring galaxies does not seem to alter the quantity of molecu-

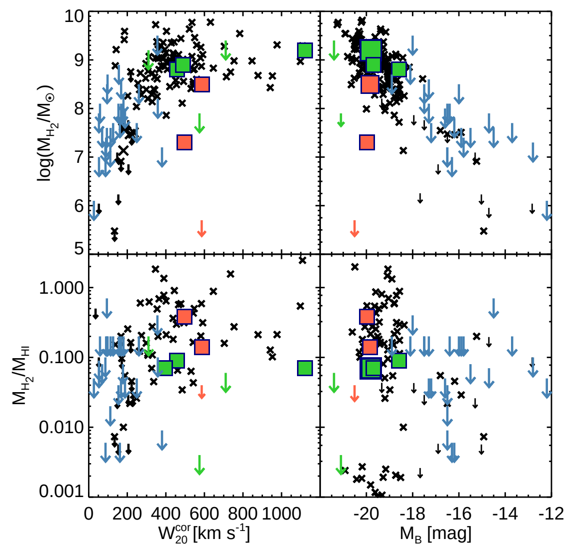

Fig. 2.— Inclination corrected H I velocity widths versus H$_2$ mass (top left) and the H$_2$-to-H I mass ratio (bottom left). At right is the absolute B magnitude versus H$_2$ mass (top right) and the H$_2$-to-H I mass ratio (bottom right). The red symbols are LSB galaxies from this survey, the green symbols are MLSB measurements from previous surveys (O'Neil, Schinnerer, & Hofner 2003; O'Neil, Hofner, & Schinnerer 2000), the blue are previous LSB (lower mass) measurements (O'Neil, Hofner, & Schinnerer 2000; Braine, Herpin, & Radford 2000; de Blok & van der Hulst 1998; Schombert, et al. 1990), and the black symbols are taken from various studies of the CO content in HSB spiral galaxies (Casoli, et al. 1996; Boselli, et al. 1996; Tacconi & Young 1987) and from the (Matthews & Gao 2001) study of extremely late-type, edge-on spiral galaxies. An arrow indicates only an upper limit was found. Note that only 5 MLSB galaxies are shown in the plots on the right, as the absolute magnitude of LSBC F582-2 is not known.

[1]NED is the NASA Extragalactic Database, available online at http://nedwww.ipac.caltech.edu/

lar in within these galaxies. UGC 04144 has one nearby neighbor (NGC 02499, at a distance of 350 kpc and Δv=185 km s^{-1}), while UGC 06124 has no galaxies within a 750 kpc/2,000 km s^{-1} radius (Table 1).

The single quantity which does appear to distinguish UGC 04144 and UGC 06124 from the other MLSB galaxies observed is their high inclination (i=83° and 82° for UGC 04144 and UGC 06124, respectively, versus i=22°, 38°, and 70° for the other three galaxies with CO detections). However, the error for the inclination measurements is 5–10°, making the inclination of UGC 04144/UGC 06124 comparable to that of [OBC97] P06-1 (i=70°), UGC 06968 (i=71°). As a result, while it is possible the high inclination angle has contributed to the higher M_{H_2}/M_{HI} values seen for UGC 04144 and UGC 06124, it is unlikely this is the only explanation. Follow-up H I and CO imaging should help resolve this question.

4. Conclusions – Molecular Gas in LSB Galaxies

With the results in this paper we have added two more measurements of molecular gas in LSB galaxies, bringing the total number of detections up to five, out of a total of nine MLSB (and 37 LSB galaxies of any type). Figure 2 compares the findings in this paper with all other LSB galaxy CO studies and with a sample of measurements from a variety of other galaxy studies. These include 'standard' HSB disk galaxy studies (Boselli, et al. 1996; Casoli, et al. 1996), dwarf galaxy studies (Tacconi & Young 1987), and a study of extreme late-type spiral galaxies (Matthews & Gao 2001). In all cases a conversion factor of $N(H_2)/\int T(CO)dv = 3.6 \times 10^{20}$ cm^{-2}/(K km s^{-1}) was used to allow ready comparison between the results.

As can be seen in Figure 2, both the detected CO and upper limits placed on the non-detections (and by inference H_2 detections and upper limits) for LSB galaxies fall within the ranges typically found for high surface brightness objects. (The one exception to this, UGC 06968, is described in detail in O'Neil, Schinnerer, & Hofner 2003.) Using the data from Casoli, et al. (1996), Boselli, et al. (1996), and Tacconi & Young (1987) gives $\langle M_{H_2}/M_{HI}\rangle$=0.51±0.78 for all HSB galaxies and $\langle M_{H_2}/M_{HI}\rangle$=0.53±0.80 for HSB galaxies with $M_B < -18.5$. These numbers, though, are skewed due to the presence of a few galaxies with $M_{H_2}/M_{HI} > 1$. Looking instead at the median value for the HSB galaxies with $M_B < -18.5$ is $\langle M_{H_2}/M_{HI}\rangle_{median}$=0.27. The MLSB galaxies with CO detections have M_{H_2}/M_{HI}=0.07 – 0.5, with $\langle M_{H_2}/M_{HI}\rangle_{median}$=0.09, within the range of the values for the HSB galaxies, albeit a bit lower. As no correction has been made to the MLSB galaxy data to account for surveying only the central 10-25 kpc of each galaxy for CO, the fact that the MLSB galaxies' M_{H_2}/M_{HI} appears to be somewhat lower than that found for the HSB galaxies cannot be considered significant.

It is also clear from Figure 2 that the only LSB galaxies which have been detected at CO are the massive LSB galaxies. Unlike their less massive counterparts which often have little or no central concentration of matter, the higher gravitational potential at the center of MLSB galaxies typically results in a dense central bulge. O'Neil, Schinnerer, & Hofner (2003) speculate that it is within this high density region that the star formation history of massive LSB galaxies most readily mimics that of HSB galaxies, resulting in an overall higher star formation rate, and producing the molecular gas detected. This speculation is given considerable more weight with our most recent observations. Previously, detection of molecular gas in LSB galaxies seemed like an impossible task, with the first CO detection occurring only after 10 years of searching. Yet in this paper we described observing only three LSB galaxies and detecting CO in two of the three – a 67% detection rate. As all three sources were chosen using the criteria described in O'Neil, Schinnerer, & Hofner (2003) – LSB galaxies with high dynamical masses, $M_B < -19$, and large central bulges – it would appear O'Neil et al.'s speculation has merit. The high detection rate shows we are now able to reliably find CO gas within the central region of MLSB galaxies.

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ratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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Table 3

Properties of All MLSB Galaxies Observed in CO

Galaxy	Line	$\int T_{MB}dv$† [K km s^{-1}]	v_{HEL} [km s^{-1}]	Width [km s^{-1}]	$\log(M_{H_2}/M_\odot)$‡	M_{H_2}/M_{HI}
		Observations from this paper				
UGC 04144	1−0	3.56	9797	430	7.3	0.38
UGC 04144	2−1	7.17	9763	429	9.0	0.20
UGC 05440	1−0	<0.50	···	···	<5.7	···
UGC 05440	2−1	<0.59	···	···	<5.6	···
UGC 06124	1−0	1.72	13940	517	8.5	0.14
UGC 06124	2−1	<0.78	···	···	<7.9	···
		Previous Detections				
UGC 01922[1]	1−0	1.38	10795	404	9.2	0.07
UGC 01922[1]	2−1	2.96	10802	403	8.9	0.04
UGC 12289[1]	1−0	1.16	10162	200	9.0	0.07
UGC 12289[1]	2−1	0.69	10185	201	8.2	0.01
[OBC97] P06-1[2]	1−0	0.95	10904	302	8.8	0.09
[OBC97] P06-1[2]	2−1	1.14	10903	216	8.3	0.03
		Previous Non-detections				
UGC 06968[1]	1−0	<0.21	···	···	<7.9	<0.004
UGC 06968[1]	2−1	<0.58	···	···	<7.8	<0.003
LSBC F582-2[2]	1−0	<0.54	···	···	<9.2	<0.2
Malin 1[2]	1−0	<0.15	···	···	<9.4	<0.06
Malin 1[2]	2−1	<0.35	···	···	<8.7	<0.01

Note.—†Non-detection limits are $I_{CO} < 3T_{MB}\frac{v_{HI}^{20}}{\sqrt{N}}$ (N = the number of channels, T_{MB} is the 1σ rms main beam temperature).
‡As described in Section 3, conversion to M_{H_2} was done using $N(H_2)/\int T(CO)dv = 3.6 \times 10^{20}$ cm^{-2}/(K km s^{-1})

References. — [1]O'Neil, Schinnerer, & Hofner (2003); [2]O'Neil, Hofner, & Schinnerer (2000);