^{12}CO(3–2) EMISSION IN SPIRAL GALAXIES: WARM MOLECULAR GAS IN ACTION?

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ABSTRACT

Using the APEX submillimeter telescope we have investigated the ^{12}CO(3–2) emission in five face-on nearby barred spiral galaxies, where three of them are high surface brightness galaxies (HSBs) lying at the Freeman limit, and two are low surface brightness galaxies (LSBs). We have positive detections for two of three HSB spirals and nondetections for the LSBs. For the galaxies with positive detection (NGC 0521 and PGC 070519), the emission is confined to their bulges, with velocity dispersions of ~90 and ~73 km s^{-1} and integrated intensities of 1.20 and 0.76 K km s^{-1}, respectively. For the nondetections, the estimated upper limit for the integrated intensity is ~0.54 K km s^{-1}. With these figures we estimate the H_2 masses as well as the atomic-to-molecular mass ratios. Although all the galaxies are barred, we observe ^{12}CO(3–2) emission only for galaxies with prominent bars. We speculate that bars could dynamically favor the ^{12}CO(3–2) emission, as a second parameter after surface brightness. Therefore, secular evolution could play a major role in boosting collisional transitions of molecular gas, such as ^{12}CO(3–2), especially in LSBs.

Subject headings: galaxies: ISM — galaxies: spiral — galaxies: stellar content

Online material: color figure

1. INTRODUCTION

Low surface brightness galaxies (LSBs) remain among the most intriguing galaxies. Defined as galaxies having disk central surface brightness fainter than (B) 22.0 mag arcsec^{-2},[3] they are a product of low stellar density. LSBs typically have (1) large amounts of atomic gas in the form of H I (van der Hulst et al. 1993) and (2) low star formation rates (SFRs). In general they have subsolar metallicity, in agreement with the low SFRs (de Blok & van der Hulst 1998) and consequently the weak production of metals. Also, LSBs have usually large mass-to-light ratios, indicating that disk dynamics is dominated by significant amounts of dark matter halos. This is consistent with their flat rotation curves, which in many cases extend to several times the optical radii.

A key question about LSBs is what physical conditions prevent the gas from forming stars. Is this due solely to the fact that the gas is not dense enough to trigger gravitational collapse and form stars? Is the amount of molecular gas too low to ensure significant stellar formation episodes? How different is the CO-to-H_2 conversion factor $X = [N(H_2)/W(CO)]$ in LSBs compared to the value derived for high surface brightness galaxies (HSBs) in preventing their H_2 from being discovered using CO as a tracer? Several studies indicate that X is a function of metallicity (Israel 1997), and thus it should not be a surprise that in LSBs the conversion factor reaches higher values than those obtained for HSBs.

The only way to estimate the amount of molecular gas (H_2) in galaxies is to trace the CO emission. Only a small number of detections of ^{12}CO(1–0) and ^{12}CO(2–1) in LSBs have been achieved (O'Neil et al. 2000b, 2003; Matthews & Gao 2001; Matthews et al. 2005). However, a different tracer such as ^{12}CO(3–2) emitted usually by warm CO is necessary to better constrain the gas temperature and density (Dumke et al. 2001; Muraoka & Kohno 2007). Here we report on the detection of ^{12}CO(3–2) in two HSB spirals at the Freeman limit[4] from Galaz et al. (2002, 2006) and the nondetection of the same transition in another HSB and two LSBs.

The weak ^{12}CO(1–0) emission in LSBs galaxies (see references above) suggests that we search for other ^{12}CO lines better suited for warmer environments. The ^{12}CO(3–2) transition may be more easily detected, since it is excited in warm gas ($E/k = 33.2$ K; Meier et al. 2001), which is probably present in LSBs due to the lower metallicity and lack of dust which normally shield the UV radiation, preventing the excitation of lower CO transitions (10–30 K). The caveat is whether the UV radiation destroys completely the CO or allows higher energy transitions such as ^{12}CO(3–2). Because of its higher characteristic temperature and critical density ($n_{cr} \sim 2 \times 10^3$ cm^{-3}), the ^{12}CO(3–2) transition may be more sensitive to warm and/or dense gas involved in stellar formation, a key insight that could explain why most LSBs have small $M_{H_2}/M_{H\,I}$ ratios.

2. THE SAMPLE

We have observed five spirals from the sample of Galaz et al. (2002, 2006). All of them are face-on spirals, and therefore the APEX beam (of about 18″) samples their bulges. Two of the five galaxies are bona fide LSBs, with disk surface brightnesses fainter than 22.0 mag arcsec^{-2} (UGC 02921 and UGC 02081), and three are HSB spirals (NGC 0521, PGC 070519, and NGC 7589; see below for details). Four of the selected galaxies have measurable near-IR emission, and therefore they have a significant population of low-mass and/or evolved stellar populations. The criteria to choose galaxies were the following:

1. *Face-on orientation.*—This minimizes the extinction for optical observations, allowing us to identify directly the submillimeter line width with the pure gas velocity dispersion. It also minimizes the inclination bias on the estimated disk surface brightness.

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[3] Some authors define the limit as 23.0 mag arcsec^{-2}, for example Impey & Bothun (1997).

[4] Defined as $\mu_0(B) = 21.65 \pm 0.3$ mag arcsec^{-1} (Freeman 1970).

2. *The* H I *mass*.—With the aim of accounting for the atomic gas content as an additional variable, we have selected galaxies with different H I masses. The H I masses vary between 7×10^8 and 51×10^8 $M_\odot$.

Some information worth mentioning about the selected galaxies follows.

UGC 02081.—Included in the Impey et al. (1996) catalog of LSBs and studied by Galaz et al. (2002, 2006) (LSB 100), it is also in the HIPASS Catalogue (Meyer et al. 2004). It is at $cz_{\rm Hel} = 2616$ km s^{-1} and has a diameter of 23 kpc. It also exhibits a tiny bar in the central region. It has been studied in many optical and near-IR bands, but was not detected by *IRAS*. It is not a very massive galaxy in terms of its atomic gas mass (Galaz et al. 2002). Its disk central surface brightness (B) of 22.4 mag arcsec^{-2} locates this galaxy at the LSB regime. It has a small bulge of about 190 pc scale length, with colors $B - R = 1.11$ (Galaz et al. 2006). The near-IR color of the bulge is the same as for the total galaxy, meaning that the bulge stellar populations share their properties with those of the disk.

NGC 7589.—Classified as an Sa by Impey et al. (1996) (LSB 473 in Galaz et al. 2002, 2006), it has $\mu_0(B) = 21.51$ mag arcsec^{-2} and is therefore an HSB galaxy. Located at $cz_{\rm Hel} =$ 8938 km s^{-1}, it has a diameter of 36.12 kpc and has traces of a disk bar. The difference between its bulge color ($B - R =$ 2.0) and the disk color ($B - R = 1.47$) shows that this galaxy has a metal-rich bulge compared to the bulge of other spirals (Galaz et al. 2006). Its near-IR bulge color ($J - K_s = 0.81$) suggests that the bulge is more metallic than other bulges in spirals (Galaz et al. 2002) and larger in size, with a scale length of 900 pc (B band). Its H I mass of 51.29×10^8 $M_\odot$ makes it ~7 times more massive than UGC 02081. In spite of its absolute magnitude ($M_B = -19.87$ mag), the galaxy is not detected by *IRAS*.

PGC 070519.—LSB 463 in Galaz et al. (2002, 2006). This SBc galaxy ($cz_{\rm Hel} = 5244$ km s^{-1}) is about 19 kpc diameter. It has a disk central SB $\mu_0(B) = 21.7$ mag arcsec^{-2} and therefore is also an HSB galaxy. This galaxy has an absolute magnitude $M_B = -18.63$ and a color $B - R = 1.0$ in the bulge and $B - R = 0.84$ in the overall galaxy. This implies a bulge with larger metallicity compared to that of the disk (Galaz et al. 2002), for a galaxy with also a large H I mass (37.15×10^8 $M_\odot$) considering its size. It is not detected by *IRAS*. We note that it also presents a noticeable bar which appears to be clearly "melted" with the bulge.

NGC 0521.—This is the largest and brightest spiral in our sample ($M_B = -20.11$). Classified as an SBsc(r) ($cz_{\rm Hel} =$ 5018 km s^{-1}), has a diameter of ~65 kpc, twice that of the Milky Way. Its central disk surface brightness is $\mu_0(B) =$ 21.7 mag arcsec^{-2}, so it is an HSB galaxy. It has visible spiral arms and a prominent bulge with a scale length of 720 pc in the R band. The bulge is quite red ($B - R = 1.64$), with almost no difference in color with the overall galaxy (LSB 059 in Galaz et al. 2006). The near-IR color $J - K_s = 0.74$ suggests a metallic bulge. It has a large amount of H I (43.7×10^8 $M_\odot$). However, as discussed below, this is not a large amount considering the remarkable size of the galaxy. It is detected by *IRAS* in 60 and 100 μm, with fluxes of about 0.65 and 3.16 Jy, respectively. It has a noticeable nuclear bar which does not however extend too far through the disk.

UGC 02921.—An SAB(s)dm galaxy in Impey et al. (1996) [$\mu_0(B) = 23.6$ mag arcsec^{-2}], located at $cz_{\rm Hel} = 3544$ km s^{-1}), it is an LSB galaxy. It has a diameter of 21 kpc and a large H I mass (21.88×10^8 $M_\odot$). It present a tiny bar from which two spiral arms are developed.

3. OBSERVATIONS WITH APEX

For APEX observations we use the heterodyne receiver APEX-2A (345 GHz), tunable in the frequency range 279–381 GHz. The receiver noise temperature (about 60–70 K) is fairly constant over the entire tuning range. The telescope beam size at 345 GHz is ~18″. We observed the five galaxies between 2006 July and 2007 January, using the chopper wheel calibration technique (Kutner & Ulich 1981), which provides main-beam brightness temperature $T_{\rm MB}$, after dividing by the main-beam efficiency $\eta_{\rm MB} = 0.73$. The typical noise system temperature during the observation was $T_{\rm sys} \sim 150$–180 K. The total on source integration time was 2 hr on average, with a velocity resolution per channel of 0.11 km s^{-1}. We tuned the receiver to the corresponding redshifted ^{12}CO(3–2) line. Data reduction was done with the GILDAS-CLASS package;[5] for each galaxy all spectra were added and a linear baseline subtracted. The final spectrum for each galaxy was smoothed to obtain a velocity resolution of ~16 km s^{-1} and an rms noise temperature $T_{\rm rms} = 5$ mK. Therefore, the typical noise temperature *per channel* is about $5 \times (16/0.11)^{1/2} \sim 60$ mK.

Figure 1 shows final smoothed and summed spectra. Only for galaxies NGC 0521 and PGC 070519 we detected ^{12}CO(3–2) emission. A Gaussian fit was applied to each spectrum and the parameters of the fit are summarized in Table 1. Detections are defined for signals above 3 σ, where $\sigma \sim 5$ mK is the rms noise temperature. Galaxies NGC 7589, UGC 02081, and UGC 02921 do not present ^{12}CO(3–2) emissions larger than the detection threshold.

4. ANALYSIS AND DISCUSSION

Driven by the uncertainty in the CO-to-H_2 conversion factor for spirals in general, we use an approach similar to that of O'Neil et al. (2000a) to compute the H_2 masses for NGC 0521 and PGC 070519 and the corresponding upper limits for NGC 7589, UGC 02081, and UGC 02921. Therefore, we assume a ^{12}CO(1–0) to ^{12}CO(3–2) ratio of 1. This is a reasonable approach considering, for example, the ratio of about 1.2 obtained, on average, by Meier et al. (2001) for a sample of dwarf galaxies. Dumke et al. (2001) obtained similar figures, with a (3–2)/(1–0) ~ 1.3 for the centers of spirals.

CO velocity dispersions are ~89 km s^{-1} for NGC 0521 and 73 km s^{-1} for PGC 070519. Since these galaxies are face-on, the velocity width would correspond to the intrinsic velocity dispersion of the ^{12}CO(3–2) emission. In both cases, and given the similar sizes of the corresponding bulges and the antenna beam, the velocity dispersions would simply correspond to that of the CO embedded in the respective bulges. Note that the velocity dispersions are ~5–10 times larger than those typically observed for H I in the central regions of spirals (van der Kruit & Shostak 1982). We suspect that this large width is due to velocity fields induced by the bars observed in NGC 0521 and PGC 070519 (see Fig. 1). Such behavior was also observed by Dumke et al. (2001), who obtained similar values for ΔV. In Table 1 we indicate the ^{12}CO(3–2) line velocity width and also the H I velocity dispersion. We note the high value also for W(H I) in NGC 0521, indicating the presence of a strong velocity field. Note that all the other galaxies present large velocity dispersions in H I, suggesting therefore a likely large value for the velocity dispersion of their molecular gas.

From the Gaussian fits we determine the integrated intensity $I_{\rm CO} = \int T_{\rm MB} dv$, and the intensity at the peak of the emission

[5] See http://www.iram.fr/IRAMFR/GILDAS.

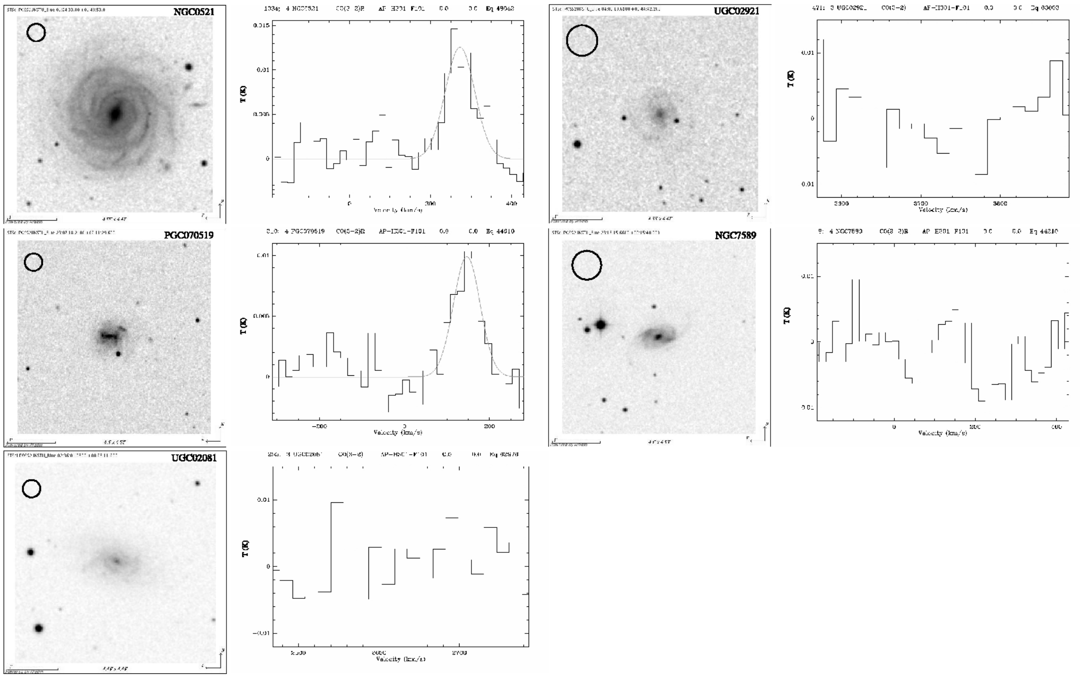

FIG. 1.—Images and spectra of galaxies observed with APEX. Images are from the SDSS (*B* filter). Spectra are centered in the ^{12}CO(3–2) rest emission. The velocity resolution was smoothed to about 16 km s^{-1} for each spectrum. The solid line for NGC 0521 and PGC 070519 spectra indicate the corresponding Gaussian fits to the line emission. The circle in each image represents the mean antenna beam size of about 18″. [*See the electronic edition of the Journal for a color version of this figure.*]

(in mK; see Table 1). Using the method of Bregman & Hogg (1988) and the formula of Sanders et al. (1986)

$$M_T(\mathrm{H_2}) = 5.82(\pi/4)d_b^2 I_{\mathrm{CO}}, \tag{1}$$

where d_b (pc) is the telescope beam diameter at the distance of the source and I_{CO} is the total CO line integrated intensity (K km s^{-1}), we estimate the H_2 mass for galaxies with positive ^{12}CO(3–2) detections (NGC 0521 and PGC 070519). For galaxies with negative detections (UGC 02081, UGC 02921, and NGC 7589) we estimate upper limits using

$$I_{\mathrm{CO}} \leq 3T_{\mathrm{MB}}\Delta v_{\mathrm{H\,I}}/\sqrt{n}, \tag{2}$$

in K km s^{-1}. We assume that $\Delta V_{\mathrm{H\,I}} \sim \langle \Delta V_{^{12}\mathrm{CO}(J=3-2)} \rangle$, the average velocity dispersion between NGC 0521 and PGC 070519, that is, 80 km s^{-1}. We think this value is more realistic than just using an arbitrarily smaller value, since UGC 02081, UGC 02921, and NGC 7589 also present bars. Thus $\sqrt{n} = \sqrt{80/16} = \sqrt{5}$, the number of channels used in the smoothed spectra. Therefore

$$I_{\mathrm{CO}} \leq \frac{3}{\sqrt{5}} T_{\mathrm{MB}} \Delta v_{\mathrm{CO}}. \tag{3}$$

For nondetections (UGC 02921, UGC 02081, and NGC 7589), we use $T_{\mathrm{MB}} = \sigma_{\mathrm{rms}} \sim 5$ mK for all the corresponding spectra. Thus, $I_{\mathrm{CO}} < 0.54$ K km s^{-1}. Using the corresponding beam diameter in pc for all galaxies, as seen at the distance of each galaxy, we obtain estimated H_2 masses for NGC 0521 and PGC 070519, and upper limits for UGC 02921, UGC 02081, and NGC 7589 (see eq. [1] and Table 1). It is worth noting that we do detect ^{12}CO(3–2) for NGC 0521 and PGC 070519, but do not detect it for NGC 7589, which is 0.2 mag arcsec^{-2} *brighter* than these two galaxies, suggesting that factors other

TABLE 1

GAUSSIAN FIT PARAMETERS FOR ^{12}CO(3–2) EMISSION IN NGC 0521 AND PGC 070519, AND UPPER LIMITS FOR NONDETECTIONS

Name (1)	T_{MB} (mK) (2)	σ_{rms} (mK) (3)	$\int T_{\mathrm{MB}}dv$ (K km s^{-1}) (4)	$M_{\mathrm{H\,I}}$ ($\times 10^8 M_\odot$) (5)	M_{H2}(18″) ($\times 10^8 M_\odot$) (6)	$M_{\mathrm{H\,I}}$(18″) ($\times 10^8 M_\odot$) (7)	$M_{\mathrm{H2}}/M_{\mathrm{H\,I}}$ (8)	Width (km s^{-1}) (9)	W(H I) (km s^{-1}) (10)
Detections:									
NGC 0521	12.7	2.9	1.20 ± 0.10	43.7	2.01	2.2	0.91	88.7	244
PGC 070519	9.8	2.5	0.76 ± 0.09	37.1	1.39	16.5	0.08	72.8	64
Nondetections:									
NGC 7589	<5	∼5	<0.54	51.3	<2.77	26.6	<0.10	∼80	183
UGC 02081	<5	∼5	<0.54	7.76	<0.25	1.1	<0.23	∼80	179
UGC 02921	<5	∼5	<0.54	21.8	<0.45	13.4	<0.03	∼80	168

NOTES.—(1) From Galaz et al. (2002, 2006) and the NED. (2) Calibrated peak main-beam brightness temperature. (3) The rms estimates are from the smoothed data with 16 km s^{-1} resolution. (4) Integrated intensity. (5) H I mass from Galaz et al. (2002) and the NED. (6) Estimated H_2 mass enclosed by the APEX main beam of 18″. Values for the last three galaxies are upper limits. (7) H I mass interpolated to the APEX main beam. (8) H_2 to H I mass ratio. (9) Velocity width of the line. For the last three galaxies the velocity width is estimated as the average values obtained for NGC 0521 and PGC 070519. (10) Velocity width for the H I line, obtained from HIPASS (Meyer et al. 2004) and HYPERLEDA (Paturel et al. 2003), clipped at 20% peak flux density. For PGC 070519 and NGC 7589, the indicated value corresponds to the mean homogenized maximum rotation velocity uncorrected for inclination.

than surface brightness must play a key role in the $^{12}CO(3–2)$ emission.

Table 1 presents H_2 masses. Note that these values are computed assuming that molecular gas is uniformly distributed through galaxies, which we know is not the case, and in all galaxies, the beam was pointed to the bulge. As shown in Table 1, H_2 masses derived from detections are $\sim 10^8\ M_\odot$. The estimated upper limit for the molecular mass in the beam size of galaxies with no detections is $\sim(3–28) \times 10^7\ M_\odot$. With these values we are able to compute the molecular-to-atomic gas mass fractions for each galaxy (again, only upper limit estimates for galaxies with no detections). The results agree with the picture that LSBs lack significant amounts of molecular gas and, in general, with small molecular-to-atomic mass ratios (below 0.08). For one case (NGC 0521) the molecular-to-atomic gas fraction appear as large as 0.9. Although surprising, this result could be anticipated given its small H I mass considering its large size. In other terms, the molecular gas content for NGC 0521 is comparable to its atomic one. Note that we do not detect $^{12}CO(3–2)$ for three but instead for two HSBs and do not detect any CO for both of the LSBs. How could one explain this puzzling picture? Although the central disk SB of these galaxies seems to play a role in the CO emission, we suspect that other factors are key in allowing such an emission. Looking in detail at the structure of the galaxies, we note that NGC 0521 and PGC 070519 have much more prominent bars really competing with the bulge emission, compared to the other three galaxies (see Fig. 1 and also figures in Galaz et al. 2006), including NGC 7589, which is 0.2 mag arcsec^{-2} *brighter* than NGC 0521 and PGC 070519. We suggest that strong velocity fields could be responsible for the molecular emission in LSBs.

5. CONCLUSIONS

We detect $^{12}CO(3–2)$ in 2 of 5 nearby spirals, using the APEX submillimeter telescope. The emission is detected for NGC 0521 and PGC 070519, both HSB galaxies lying at the Freeman limit. The other galaxies, with no detections, share similar morphology and orientation, but two are LSBs (UGC 02921 and UGC 02081) and one an HSB (NGC 7589). All of them are face-on, making the internal extinction negligible. The measured main-beam temperature CO fluxes are 1.20 K km s^{-1} for NGC 0521 and 0.76 K km s^{-1} for PGC 070519. The remaining galaxies have fluxes below 3 σ, and thus we are able only to *estimate* upper limits for their $^{12}CO(3–2)$ fluxes (<0.54 K km s^{-1}).

Measured velocity dispersions for NGC 0521 and PGC 070519 are 89 and 73 km s^{-1}, respectively, ~5–10 times typical values obtained by other authors for bulges in spirals (van der Kruit & Shostak 1982; Dumke et al. 2001). We suspect that in these cases the gas velocity field is dominated by the bar kinematics (Dumke et al. 2001). Bars are observed actually in all five galaxies, but those of NGC 0521 and PGC 070519 appear as the more prominent ones.

We compute the total H_2 mass in the main beam, obtaining 2×10^8 and $1.4 \times 10^8\ M_\odot$ for NGC 0521 and PGC 070519, respectively. The corresponding molecular-to-atomic gas fraction is about 0.9 and 0.08. The high value for NGC 0521 is probably due to its low H I density, and to the assumption that the H I is uniformly distributed over the whole galaxy optical size. In fact, in spirals one expects that the H I is mostly distributed along the disk.

Overall, we have shown that $^{12}CO(3–2)$ emission could be intense for some galaxies at the SB "Freeman limit." Moreover, such an emission could be "dynamically boosted" by bars, helping to warm the CO and allowing the $^{12}CO(3–2)$ transition at 33 K above the ground level. Although we have no detections of $^{12}CO(3–2)$ for the LSBs in this sample, we speculate that many LSBs could present $^{12}CO(3–2)$ emission given some dynamical conditions that warm the gas (or make it denser). We speculate that many LSBs with no $^{12}CO(1–0)$ or $^{12}CO(2–1)$ emission could have instead $^{12}CO(3–2)$ emission thanks to the poor UV shielding favored by the low metallicity and low dust content, allowing a higher gas temperature. This emission, which in principle could be small, may be largely amplified by secular processes which warm the gas.

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