DEEP CO OBSERVATIONS OF FOUR LSBS

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Abstract

Low surface brightness galaxies (LSBs) are an important species of extragalactic object, differing from "normal" HSB galaxies in that their stellar disks are very diffuse (see Bothun, Impey, and McGaugh 1997). LSBs are typically HI-rich galaxies, ranging in size from giants (e.g. Malin 1) to dwarfs. One explanation for their LSB nature has been that LSBs could have negligible current star formation rates and probably negligible past star formation. This interpretation is supported by the fact that while HI-rich, the gas surface densities of LSBs are observed to be below the Toomre threshold for star formation over most of their gas disks (van der Hulst et al. 1993). However, Martin & Kennicutt (2001) note there are examples of globally subcritical galaxies in which star formation is actually quite vigorous (e.g. NGC 2403 and M33). This star formation likely reflects sporadic star formation in regions of these galaxies that have had their gas densities increase above the Toomre threshold. Could such sporadic star formation been characteristic of LSBs and could some LSBs show evidence for this?

We used the University of Arizona Steward Observatory (formerly NRAO) 12m to perform deep CO(1 – 0) observations of three LSBs (47–211, N09–2, and N10–4) selected on the basis of their O–E colors as measured off the POSS I. By picking LSBs with redder O–E colors, we hoped to select galaxies with an older population of stars and possibly a history of previous star formation, despite their globally subcritical nature. In addition to these three galaxies, we also observed the LSB P06-1 which was the only unambiguous LSB galaxy previously detected in CO(1 – 0) (O'Neil, Hofner, and Schinnerer 2000).

Our observations had single channel 3σ detection limits of $T_{MB} \approx 1 - 4$ mK (the deepest observations were on P06-1, the shallowest on N09-2). No CO was detected in any of the targeted LSBs. These null detections can be used to establish lower limits on the molecular gas content of these LSBs and rough limits on the level of previous star formation. The non-detection of P06-1 suggests the previous CO detection in P06-1 may have been spurious, although the former detection was in both CO(1 – 0) and CO(2 – 1).

Our Motivation

• Low Surface Brightness galaxies (LSBs) are the most common kind of galaxy in local space and have very low rates of star formation which are likely tied to the physical conditions of their ISM.

• **Since star formation occurs in molecular clouds, the physical conditions of any molecular gas in LSBs is very important to understanding their evolution.**

• However, little is known about molecular gas in LSBs except that it has not been easy to find:

- **Only one previous study has detected CO in a galaxy** that was a confirmed LSB.
  - O'Neil, Hofner, & Schinnerer 2000) detected **one LSB (P06-1) out of four** observed in CO.

The Goal

Any additional detection of CO in LSBs would be helpful in determining the environment of their ISM.

Selecting LSBs likeliest to have Molecular Gas

• LSBs are among the bluest non-Starburst galaxies known, despite their very low current star formation rates (Bothun *et al.* 1997).

- de Blok (1999) speculated LSBs were blue because most of their light is dominated by a few young stars in active star formation regions. According to de Blok, **roughly 20% of LSBs should be quiescent and as such should appear quite red.**

• **Redder LSBs are likely to have higher metallicities than their bluer counterparts.**

- O'Neil, Hofner, & Schinnerer (2000) successfully found CO in a red LSB from O'Neil, Bothun, & Cornell (1997) [hereafter OBC].

• However, few large LSB surveys have also obtained the colors of LSBs.

- **We obtained colors for previously identified LSBs** through cross-identification with the Minnesota Automated Plate Scanner Catalog of the Palomar Observatory Sky Survey (POSS I).

Our Approach: The reddest LSBs on the POSS I are possibly the most likely to have significant molecular gas … pick these galaxies and observe them in CO.

Our Observations

• **Telescope**: University of Arizona Steward Observatory (UASO) 12m telescope.

• **Dates**: 2001 February 18 to 21.

• **Targets**: We targeted the positions given by O'Neil, Bothun, and Schombert (2000) for N09-2, N10-4, and P06-1 and Dickey (1997) for 47-211. (See Table 1)

• **Frequencies and Bandpasses**:

- Our bandpasses were **centered on the CO (1–0) transition** redshifted to the observed HI spectral line redshifts.
- We only observed the CO(1–0) transition because the necessary integration times for the CO(2–1) transition were too great
- Each receiver was connected to a 256 channel filterbank with a channel width of 2 MHz (corresponding to 5.2 km/s resolution) with a **total bandwidth of 512 MHz** (or 1331 km/s at 115 GHz).

• **Notes**:

- Calibration was done via vane (chopper) calibration.
- Pointing and focus of the UASO 12m was checked roughly **every 90 minutes**. Typical point accuracy is ~5 arcseconds.
- Observed system temperatures ranged from 180 to 470K with a median value of 225K (mean of 250K).
- 2 bad channels throughout observations which were flagged.
- Weather was clear throughout the run.

Data Reduction

• **Producing the Final Spectra**

- A **main beam efficiency of 0.84** is assumed.
- **Each 90 second scan was fit with a linear baseline** over channels not within the velocity limits of the previously observed HI distribution.
- **Baselined spectra for each object were co-added produce the final spectra (presented in Figure 4).** Total integration times varied from 162 minutes (for N09-2) to 900 minutes (for P06-1).
- ***No CO was detected, even in P06-1, which was previously observed in CO(1-0) and CO(2-1) by O'Neil, Hofner, & Schinnerer (2000)!***

• **Estimating Upper Limits on Molecular Gas Content**

- We estimate T_{rms} using channels outside the velocity limits of previously observed HI distribution.
- We estimate for the amount of molecular hydrogen using*:

$$N(H_2) < 3.6\times10^{20}\,cm^{-2}\left[3T_{rms}\sqrt{\delta v \Delta V_{HI}}\right]$$

* ***Need justification?*** See Schombert *et al.* (1990) and Sanders *et al.* (1986). Yes, the value of χ (the conversion factor between I_{CO} and N_{H2}) is quite uncertain in LSBs…remember, this is only an estimate!

Table 1: The Observed LSBs

Object	α (J2000)	δ (J2000)	O	O–E	cz (km/s)	Δv_{HI} (km/s)	σ (mK)	I_{CO} (K km/s)	M_{H_2} (M_{solar})	M_{HI} (M_{solar})	M_{H_2}/M_{HI}
N10-4	11:58:52.2	20:58:39.0	21.70	2.72	7478	80	1.616	<0.099	$<3.58\times10^8$	9.78×10^8	<0.366
N09-2	10:20:21.9	28:07:54.0	21.77	1.42	7746	118	3.714	<0.276	$<1.07\times10^9$	1.08×10^{10}	<0.100
47-211	16:01:56.2	15:42:42.0	22.22	3.24	10423	261	1.196	<0.132	$<9.48\times10^8$	1.73×10^9	<0.548
P06-1	23:23:32.6	8:37:25.0	17.41	1.00	10882	430	1.121	<0.159	$<1.25\times10^9$	7.41×10^9	<0.168

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P06-1: How'd We Miss It?

• **The most likely reason for our non-detection of P06-1 is the fact that we did not go deep enough.**

- Our limiting T_{rms}=1.121 mK corresponds to a flux limit of **S_ν~0.027 Jy**
- O'Neil, Hofner, & Schinnerer (2000) [hereafter OHS] used the IRAM 30m, which means their T_{MB} = 3.2mK for P06-1 corresponds to **S_ν=0.014 Jy**.
- This is supported by the fact that **our upper limit on the molecular mass of P06-1 is 1.2×10⁹ solar masses** versus the detected amount of **1.1×10⁹ solar masses reported by OHS.**

• **However our non-detection of P06-1 is still important…**

- Young & Knezek (1989) show that most spirals have CO extents of roughly half their optical diameters. OHS note the IRAM 30m beamwidth of 22" is considerably smaller than the optical diameter of 61".5. **OHS therefore concluded they were likely missing up to 50% of the CO content of this galaxy.**
- The UASO 12m beamwidth is 56" in size. Therefore **we should have (barely) a 1σ detection of P06-1 if it had twice the CO content reported by OHS.**

Key Result from P06-1 Observation

Since we did not detect P06-1, this suggests CO (at least in P06-1) is not as extended in LSBs as in HSB spirals.

Conclusions

• **Our method of selecting LSBs likely to have detectable molecular gas content is unproven due to the lack of detections.**

• Mihos, Spaans, & McGaugh (1999) model the ISM in galaxies as a function of surface brightness, metallicity, and density structures…

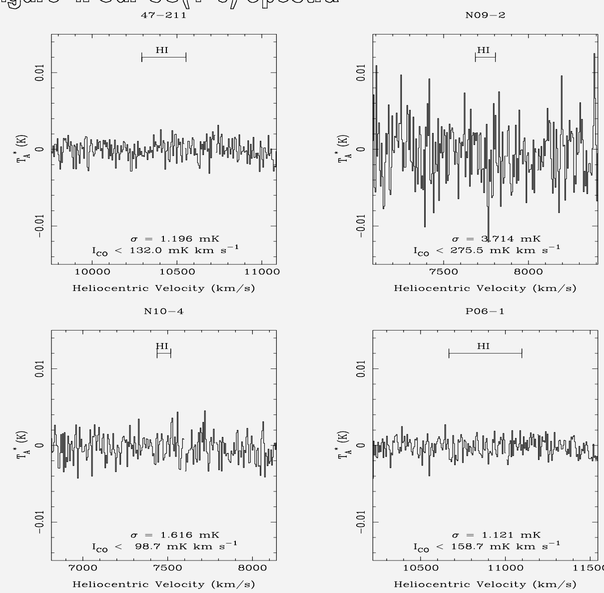
- Given our surface brightnesses of 23 to 24 mag arcsec^{-2} and metallicities typical of LSBs ($Z\sim0.3Z_{solar}$) they predict $I_{CO}\sim0.1$ to 1.0 K km/s, overlapping with our detectable limits (see Table 1). For higher metallicities I_{CO} should be 15 - 100 K km/s, far too high!
- **If their model is to be correct, our inability to detect these galaxies suggests they have extremely low metallicities, less than 0.1 solar!**

• The non-detections may allow us to place upper limits on the molecular gas content of these galaxies (see Table 1) assuming the "standard" $N(H_2)/I_{CO}$ ratio…which is very debatable:

- Given our surface brightnesses of 23 to 24 mag arcsec^{-2} and $Z\sim0.3Z_{solar}$ the model of Mihos, Spaans, & McGaugh (1999) suggest variations in χ leading to up to 7x more (or 6x less) H_2 in these galaxies than our estimates.
- The value of χ is inversely related to metallicity, thus the extremely low metallicities implied by our low I_{CO} limits would lead to high χ and thus a **significant amount of molecular gas that could be hidden in LSBs despite the fact that CO is rare in LSBs.**

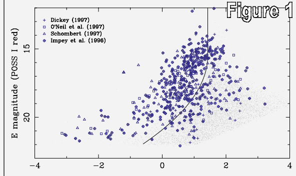
• More pending…

Figure 4: Our CO(1–0) Spectra



LSBs on the POSS I

Figure 1



• Over 65% of LSBs on the POSS I lie blueward of the bluest 10% of "normal" APS galaxies (indicated by the dark curving vertical line), **including those "red" (in B-V) LSBs from OBC!**

Why LSBs Appear Blue on the POSS I

• In the APS Catalog of the POSS I galaxy colors are determined from the integrated Blue (O) and Red (E) magnitudes down to the plate limit.

• The **Blue emulsions exhibit deeper limiting surface brightnesses** than the Red emulsions.

- This difference in limiting surface brightness has little effect on the colors of high surface brightness galaxies (like those in the RC3).
- However, LSBs from OBC have systematically lower POSS I fluxes than implied by their reported B and V magnitudes **(see Figure 2)**.
- **Figure 3** shows these differences lead to **lower surface brightness objects having bluer colors on the POSS I.**

Key Point

LSBs with red POSS I colors are likely to have extremely red B–V colors and thus potentially higher metallicities and molecular gas content.

Figure 2

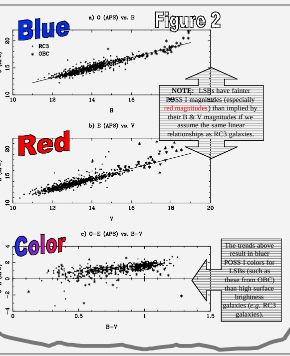


Figure 3