From Z-Machines to ALMA: (Sub)millimeter Spectroscopy of Galaxies
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From 20 cm - 1μm: Measuring the Gas and Dust in Massive Low Surface Brightness Galaxies

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Abstract. Archival data from the IRAS, 2MASS, NVSS, and FIRST catalogs, supplemented with new measurements of HI, are used to analyze the relationship between the relative mass of the various components of galaxies (stars, atomic hydrogen, dust, and molecular gas) using a small sample of nearby (z<0.1) massive low surface brightness galaxies. The sample is compared to three sets of published data: a large collection of radio sources from the UGC having a radio continuum intensity >2.5 mJy; a smaller sample of low surface brightness galaxies; and a collection of NIR low surface brightness galaxies. Overall, our sample properties are most similar to the NIR comparison samples in regard to color, gas, stellar, and dynamic mass ratios, etc. Based off the galaxies' FIR/1.4 GHz ratio, it appears likely that at least one of the 28 galaxies studied harbor AGN.

1. Introduction

Low surface brightness (LSB) galaxies are typically defined as the class of galaxies with measured central surface brightness at least one magnitude fainter than the night sky ($\mu_B(0) \geq 23.0$ mag arcsec^{-2}). Within the LSB population, the most intriguing subclass is that of the massive LSB galaxies. These are objects with diffuse, low surface brightness disks, but total magnitudes and masses that make them among the largest galaxies known.

No consensus definition for a MLSB galaxy exists. However, using the prototypical system Malin 1 as an example, MLSB systems can be classified as those LSB galaxies with $M_{HI} > 10^{10}$ $M_\odot$ and $W_{20} > 450$ km s^{-1}. Considerable work has been done recently to identify MLSB systems (O'Neil, et.al 2004a; O'Neil, van Driel, & Schneider 2006), as the combination of their high mass and LSB disks make massive LSB galaxies an excellent test bed for stellar formation and evolution theories.

2. The Sample

To better understand their properties, we undertook a data mining survey to explore the NIR, FIR, and 1.4GHz properties of a sample of massive LSB galaxies. The sample of 28 galaxies was chosen randomly from the UGC LSB galaxy sample first described in Bothun, et.al (1985). All of the galaxies in this sample had previously measured B magnitudes, velocities, and HI masses. However, once the project was underway it was discovered that the HI information of 7 of the galaxies had not been published and the data was unavailable. As a re-

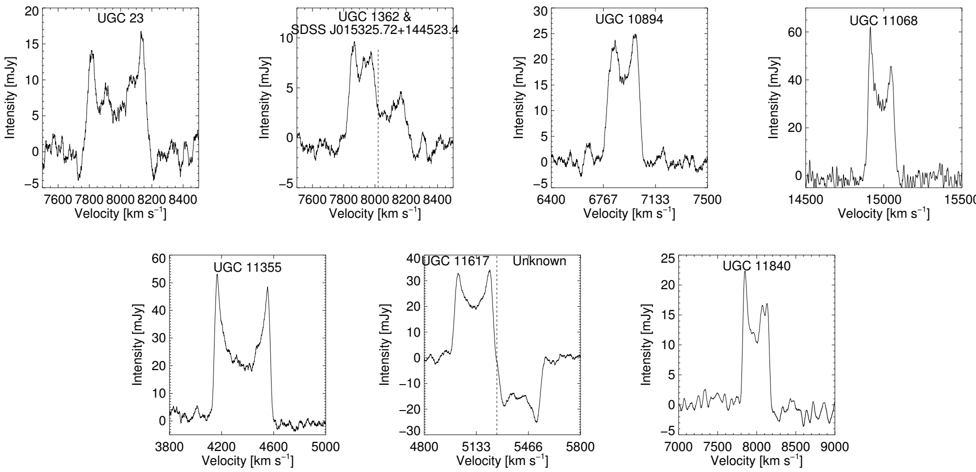

Figure 1. HI spectra measured with the GBT, smoothed to 30 km s-1 resolution. The vertical lines mark the right edge of the flux measured for the UGC 01362 and UGC 11617. Both of these spectra contain more than one galaxy.

sult, we obtained new HI measurements of these seven galaxies using the Robert C. Byrd Green Bank Telescope (GBT). Spectra for the new HI detections are given in Figure 1, and the results are summarized in Table 1. Note that our measurements found a catalog error for the radial velocity of UGC 11068.

3. Results

Archival data from the IRAS FIR, 2MASS NIR, NVSS 1.4 GHz, and FIRST 1.4 GHz catalogs, supplemented with new and previous measurements of HI, B, and $D_{25,B}$ and were used to analyze the relationship between the relative mass of the various components of galaxies (stars, atomic hydrogen, dust, and molecular gas - Condon, et.al 1998; Becker, White, & Helfand 1995; O'Neil, et.al 2004a; 2004b; NED; Table 1). The sample is compared to three sets of published data. The first

Table 1. HI properties of galaxies observed with the GBT

Galaxy	Velocity [km s^{-1}]	W_{20} [km s^{-1}]	M_{HI} [10^9 $M_\odot$]	M_{dyn} [10^{11} $M_\odot$]	D_{25} [$''$]
UGC 00023	7976	420	5.37	3.20	78
UGC 01362	7924	218	2.19	49.1	126
UGC 10894	6906	271	5.67	1.07	84
UGC 11068	14982	206	37.7	3.99	84
UGC 11355	4359	462	6.07	1.80	72
UGC 11617	5116	276	4.23	.574	54
UGC 11840	7990	380	8.20	3.20	54

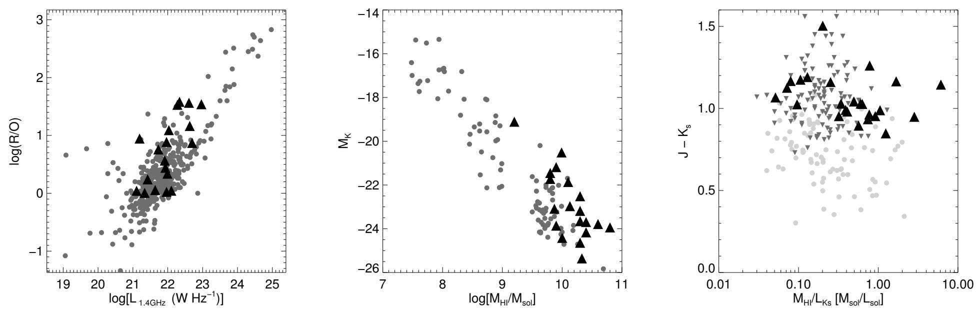

Figure 2. (Left) Ratio of the optical to radio luminosity as a function of the radio continuum luminosity. Our data set (dark triangles) is compared here the much larger Condon, Cotton, & Broderick (2002) collection of radio sources (light circles). (Middle) K_s absolute magnitude as a function of HI mass comparing our data set (dark triangles) with the collection of LSB galaxies from Galaz, et.al (2002) (light circles). Although our galaxies are more massive, the trend is consistent with that of Galaz, et.al. The difference between the J band and Ks band luminosity as a function of the HI gas fraction illustrates that our higher mass sample (dark triangles) may be more evolved than the Galaz, et.al (2002) collection (light circles). Our sample appears to be more consistent with the galaxy collection of Monnier-Ragaigne, et.al (2002) (light upside-down triangles).

sample is the Condon, Cotton, & Broderick (2002) collection of radio sources from the UGC having a radio continuum intensity >2.5 mJy (Figure 2). As with the Condon, Cotton, & Broderick data, the ratio of the radio continuum to the optical luminosity is approximately proportional to the luminosity of the radio continuum for our sources. We also compared our sample with the collection of late-type galaxies (including LSB galaxies) assembled by Galaz, et.al (2002). Although our data is consistent with the trend of Ks band luminosity versus the HI mass seen with the Galaz data (Figure 2), it is clear that our sample contains galaxies of considerably more mass. A similar trend is observed using J band magnitude against the HI mass (not shown). However, the plot of J−Ks color against H 1 mass (Figure 3) shows a significant difference between these two data sets. This suggests that our more massive set of galaxies may be more evolved than those of Galaz, et.al. For further comparison, a collection of NIR LSB galaxies assembled by Monnier-Ragaigne, et.al (2002) is also plotted on Figure 3, and our data is more consistent with that collection. The difference between the two samples (Galaz, et.al and Monnier-Ragaigne, et.al) is unclear, with the one exception that the Monnier-Ragaigne, et.al sample was chosen from the (2MASS) NIR while the Galaz, et.al sample was chosen from the optical. This may have induced a bias within the Monnier-Ragaigne, et.al sample toward galaxies with an older stellar population.

One of the goals of this project was to identify massive LSB galaxies which harbor AGN. Using the galaxies' spectral index as measured from the 25 and 60 μm fluxes (Table 2), we found only two galaxies with errors small enough to properly classify them. Both of these galaxies (UGC 00023 & UGC 12289) have α <1.2, indicating AGN may be present. in Table 2, the following galaxies had no reliable measurements Using the galaxies' measured q-value (the FIR/1.4 GHz emission ratio), however, we find seven galaxies with errors small enough for classification. Of these, only one (UGC 01922) has $q < 1.8$ indicating it harbors an AGN. Notably, UGC 00023 and UGC 12289 have $q=2.5\pm0.2$ and 2.6 ± 0.2. As the q-value has been shown previously to be a more reliable indicator of AGN activity in galaxies, it is likely that of the sample only UGC 01922 can definitively be classified as an AGN. As UGC 01922 also has the largest bulge-to-disk ratio in the sample, this result is perhaps not unexpected.

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References

Becker, R.H., White, R.L., & Helfand, D.J. 1995, ApJ, 450, 559

Bothun, G.D., Beers, T. C., Mould, J. R., & Huchra, J. P. 1985 AJ 90, 2487

Condon, J.J., Cotton, W.D., & Broderick, J.J. 2002 AJ 124, 675

Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693

Galaz, G., Dalcanton, J., Infante, L., & Treister, E. 2002 AJ 124, 1360

Impey, C. & Bothun, G. 1989 ApJ 341, 89

Monnier-Ragaigne, D., van Driel, W., Balkowski, C., Schneider, S.E., Jarrett, T.H. & O'Neil, K. 2002 A&SS 281, 145

O'Neil, K., van Driel, W., & Schneider, S. 2006, in preparation

O'Neil, K, Bothun, G., van Driel, W. & Monnier-Ragaigne, D. 2004 A&A 428, 823

O'Neil, K & Schinnerer, E. 2004b ApJL 615, 109

Schombert, J. 1998 AJ 116, 1650

Table 2. AGN measurements of galaxies. Cells with (†) indicate an AGN may be present. AGN classification from optical spectra taken from Schombert (1998); Impey & Bothun (1989). No data in the column indicates that a measurement could not be made.

Galaxy	q	α	Optical?	Galaxy	q	α	Optical?
UGC 00023	2.5 (0.2)	0.8 (0.4)†	...	UGC 00189	...	...	...
UGC 01362	...	...	...	UGC 01922	1.5 (0.1)†	2.9 (1.6)	Y†
UGC 02299	...	...	...	UGC 02588	...	...	...
UGC 02796	...	...	...	UGC 03119	2.3 (0.1)	...	...
UGC 03308	...	...	...	UGC 04144	2.2 (0.1)	2.5 (3.1)	...
UGC 05440	2.0 (0.2)	-0.4 (0.9)	...	UGC 06124	...	0.6 (1.8)	...
UGC 06968	...	-1.8 (1.5)	Y†	UGC 07598	2.1 (0.2)	0.8 (0.9)	...
UGC 08311	...	0.4 (1.7)	...	UGC 08644	...	1.0 (6.8)	...
UGC 08904	...	...	...	UGC 10894	...	-1.3 (5)	...
UGC 11068	...	...	...	UGC 11355	...	-1.1 (5)	...
UGC 11396	...	0.7 (0.9)	...	UGC 11617	...	...	...
UGC 11840	...	...	...	UGC 12021	...	...	...
UGC 12289	2.6 (0.2)	0.8 (0.4)†	Y†	[OBC 97] PO6-1	...	...	...
LSBC F582-2	...	1.9 (4)	...	Malin 1	...	...	Y†