Star Formation in Massive Low Surface Brightness Galaxies

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Abstract. Massive low surface brightness galaxies have disk central surface brightnesses at least one magnitude fainter than the night sky, but total magnitudes and masses that show they are among the largest galaxies known. Like all low surface brightness (LSB) galaxies, massive LSB galaxies are often in the midst of star formation yet their stellar light has remained diffuse, raising the question of how star formation is proceeding within these systems. HI observations have played a crucial role in studying LSB galaxies as they are typically extremely gas rich. In the past few years we have more than quadrupled the total number of massive LSB galaxies, primarily through HI surveys. To clarify their structural parameters and stellar and gas content, we have undertaken a multi-wavelength study of these enigmatic systems. The results of this study, which includes HI, CO, optical, near UV, and far UV images of the galaxies, will provide the most in depth study done to date of how, when, and where star formation proceeds within this unique subset of the galaxy population.

INTRODUCTION

Although Low Surface Brightness (LSB) galaxies, those objects with a central surface brightness at least one magnitude fainter than the night sky, are now well established as a real class of galaxies with properties distinct from the High Surface Brightness (HSB) objects that define the Hubble sequence, considerable uncertainty still exists as to both the range of their properties and their number density in the z$\leq$0.1 Universe. As LSB galaxies encompass many of the 'extremes' in galaxy properties, gaining a firm understanding of LSB galaxy properties and number counts is vital for testing galaxy formation and evolution theories, as well as for determining the relative amounts of baryons that are contained in galaxy potentials compared to those that may comprise the Intergalactic Medium, an issue of increasing importance in this era of precision cosmology.

The 'traditional' (but erroneous) perception of LSB galaxies is that they are like young dwarf galaxies: low mass, fairly blue systems, with relatively high M_{HI}/L_B values and low metallicities. In practice, however, LSB disk galaxies are now known to have a remarkable diversity in properties, including very red objects, galaxies with near-solar luminosity, and high M_{HI} ($\geq 10^{10}$ $M_\odot$) systems. LSB galaxies also include Malin 1 – the largest disk galaxy known to date. While none of these results contradict the idea that the average LSB galaxy is less evolved than the average HSB galaxy, they do show that we have not yet come close to fully sampling the LSB galaxy parameter space. In addition, it should be emphasized that there may still be large numbers of LSB galaxies with properties beyond our present detection limits.

Here we discuss an ongoing project to determine the properties of LSB galaxies at the massive end of the spectrum. The galaxies described herein all have $M_B \leq -18$ and $M_{HI} \geq 10^9 M_\odot$. Thus while the galaxies are not all as impressive as Malin 1, none of the galaxies could be considered dwarf systems and quite a few may indeed be some of the largest and/or most massive galaxies known.

HOW MANY ARE THERE?

Since the discovery of Malin 1 [1] a number of papers have been published describing the discovery of massive LSB systems [e.g. 2, 3, 4, 5, 6]. Yet until a few years ago the total number of massive LSB galaxies known was only ~18. A recent HI survey of known galaxies without known HI properties by O'Neil et al. [7] doubled the total number of massive LSB galaxies known (~35).

Following up from the O'Neil et al. [7] survey, O'Neil et al. [8] have undertaken to observe the 21-cm lines of all galaxies listed in the HyperLEDA catalog with a high probability of being massive LSB systems [8]. In all 257 galaxies were observed using the Arecibo, Nançay, and Green Bank radio telescopes. Of these 144 galaxies had unambiguous detections, and 20 fall into the category of very massive LSB galaxies ($M_{HI} \geq 10^1 0$ $M_\odot$ and/or $W_{20,uncorrected} \geq 400$ km s^{-1}).

OPTICAL MORPHOLOGY

The general appearance of massive LSB galaxies shows a prominent central bulge surrounded by distinct yet diffuse spiral arms (Figure 1). Overall the galaxies are typically less amorphous than their less massive counterparts, presumably due to the higher gravitational potential at their cores, but are still less well defined than their high surface brightness counterparts.

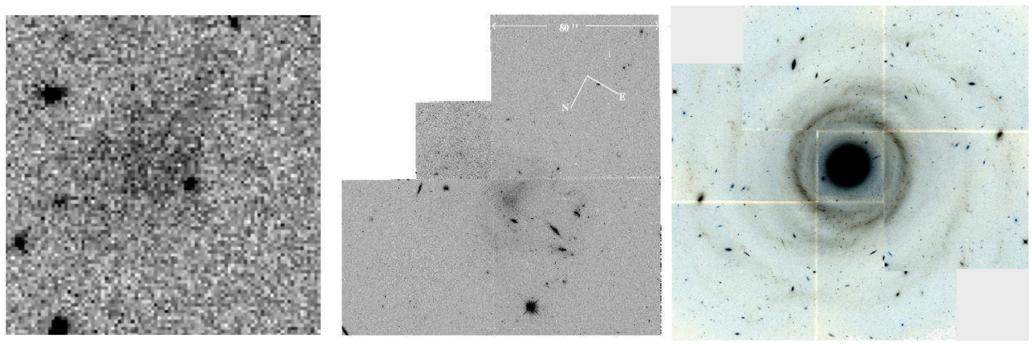

FIGURE 1. Optical images of three LSB galaxies. Listed from left to right, and also in order of increasing HI mass, the galaxies are [OBC97] P02-4, UGC 12695, and UGC 06614.

ATOMIC GAS – HI

As mentioned earlier, the HI mass of LSB galaxies covers the full spectrum from $< 10^8$ $M_\odot$ through $> 10^{10}$ $M_\odot$. As an example, Figure 2 shows the distribution of HI mass for the sample of galaxies observed by O'Neil et al. [8]. Note that in this case the galaxies were chosen to lie away from the dwarf galaxy realm and so the fall-off in the distribution at the low mass end of the figures is purely a selection effect. The same Figure also shows the mass distribution of sources with surface brightness, showing no trends toward higher (or lower) surface brightness galaxies having higher HI masses.

STAR FORMATION – Hα AND UV LIGHT

A number of studies have been done on looking at the star formation rates in LSB galaxies [e.g. 9, 12, 13, 14]. Overall, the massive LSB galaxies appear to be forming stars at a rate similar to that of their higher surface brightness counterparts. What is intriguing, though, is the finding of [9] which showed their sample to have higher fractions of diffuse Hα gas than their high surface brightness counterparts (Figure 3), showing a high fraction of the ionizing photons in massive LSB galaxies lie outside the density-bounded HII regions.

To investigate the phenomenon of star formation in massive LSB galaxies further, we have obtained GALEX UV images of number of these systems. Figure 4 shows a few of the galaxies observed for this program. In agreement with the Hα study, the Figure shows indications of star formation which do not appear to be contained solely to the various star forming 'knots' seen in the optical images.

DUST – THE INFRARED

Recently Hinz et al. [16] obtained Spitzer observations of five low surface brightness galaxies, two of which are massive LSB systems (Figure 5 – UGC 06614 and Malin 1 are the massive LSB galaxies which were studied). Stellar emissions, hot dust, and aromatic molecules were detected from all observed galaxies with uncorrupted data (the 24 μm data from one galaxy was unusable). At the 70μm and 160μm wavelengths, where cool dust would be found, only two of the galaxies were detected, with the strength of the dust emission apparently dependent on the existence of bright star forming regions.

MOLECULAR GAS – CO

Detection of molecular gas in LSB galaxies has been notoriously difficult. In spite of attempts at detecting CO on LSB galaxies for more than 20 years [e.g. 17, 18, 19] the first detection was only 8 years ago [20]. Since then a handful of CO detections have been made [See 7, and references therein], and in all cases the detections have been in massive LSB systems. However, comparing the LSB galaxy CO results with surveys of high surface brightness galaxies shows the 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 (Figure 6).

CONCLUSIONS

In summary, we clearly have a large number of known LSB galaxies which are fairly massive, and this number is growing rapidly as more as more searches are undertaken. As a result it is finally becoming feasible to look at the galaxies as a class rather than just as individuals, and to try and apply what we learn to galaxy formation

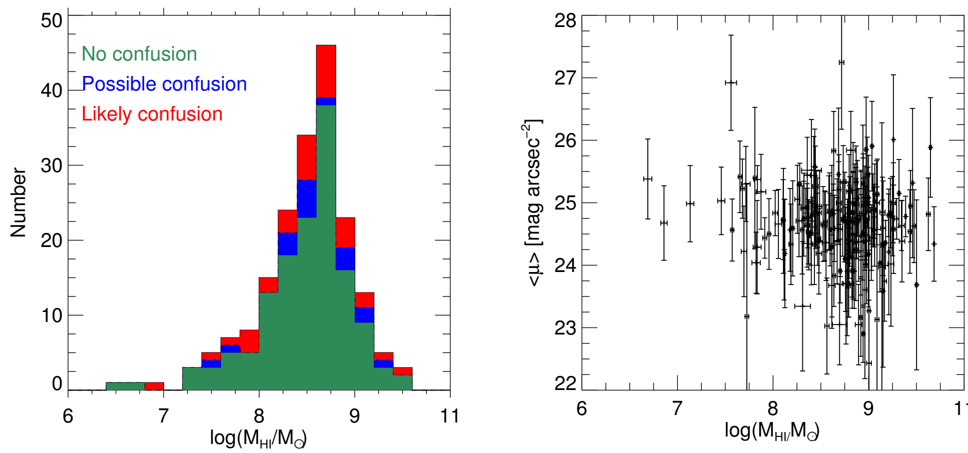

FIGURE 2. Distribution of HI mass for the O'Neil et al. [8] survey. Note that observations of the galaxies marked as 'confused' in the left plot likely picked up more than one galaxy in the telescope beam, rendering these detection highly suspect. On the right the HI mass is plotted against average surface brightness for the galaxies.

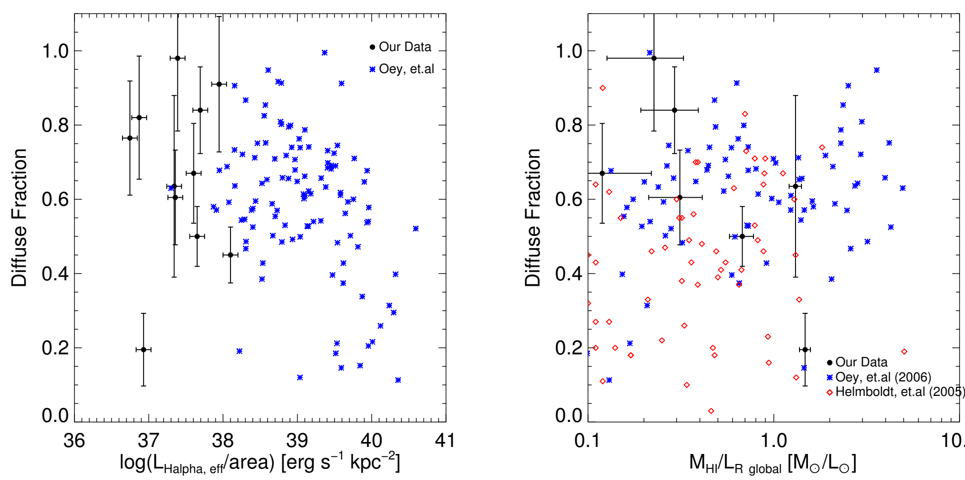

FIGURE 3. Luminosity surface brightness (luminosity/area) (left) and gas mass-to-luminosity ratio (right) plotted against the diffuse Hα sample for the sample of O'Neil et al. [9] ("Our Data") and that of Oey et al. [10] and Helmboldt et al. [11].

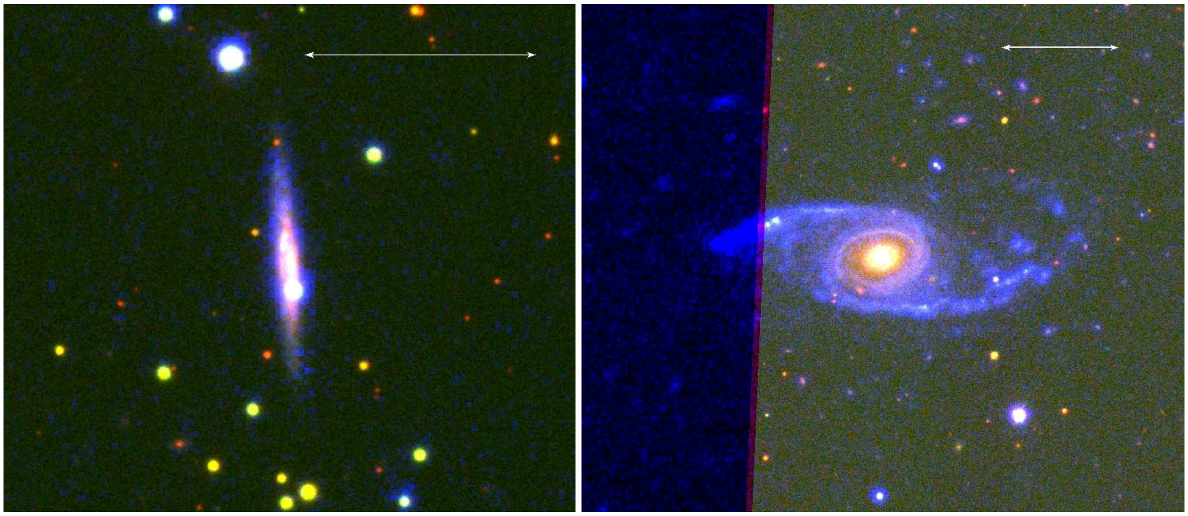

FIGURE 4. False color images showing UGC 04144 (left) and UGC 06968 (right). The red and green image colors are the i and g bands from the Sloan Digital Sky Survey [15] while the blue image band is from Galex NUV images.

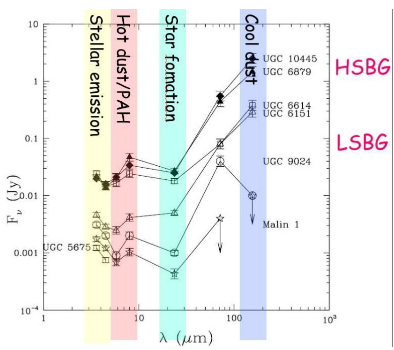

FIGURE 5. SEDs of all the galaxies in Hinz et al. [16] showing the IRAC and MIPS data points. The high surface brightness galaxy data are shown with filled symbols, while the LSB galaxy data are shown with open symbols. The arrows represent 3σ upper limits at 70 and 160 μm.

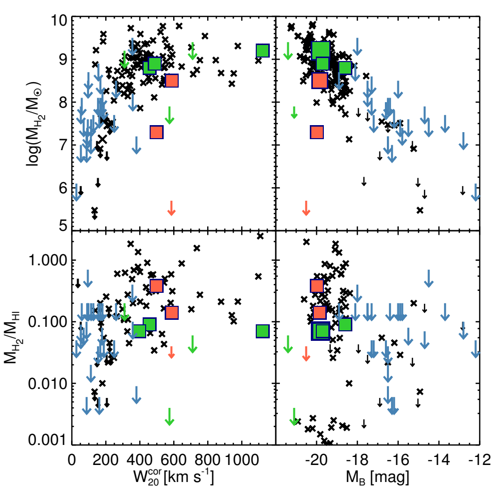

FIGURE 6. Inclination corrected HI velocity widths versus H_2 mass (top left) and the H_2-to-HI mass ratio (bottom left). At right is the absolute B magnitude versus H_2 mass (top right) and the H_2-to-HI mass ratio (bottom right). The red, blue and green symbols are LSB galaxies and the black symbols are taken from various studies of the CO content in HSB spiral galaxies. An arrow indicates only an upper limit was found. See O'Neil et al. [7] for further information on this figure.

and evolution theories.

One interesting theory on the formation of massive LSB galaxies that was recently put forth is the idea that massive LSB galaxies formed as the result of the collision of two galaxies [21]. This theory can clearly explain a number of the massive LSB systems we have seen. such as UGC 06614 and possibly Malin 1. But it cannot explain all of the galaxies which we have found as the theory requires the galaxies *not* be undergoing any recent large star formation episodes, in clear contradiction to many of the galaxies in out surveys.

THE <2 GHZ RADIO FUTURE FOR MASSIVE LSB GALAXIES

Over the next five years or so we clearly need to continue our HI surveys of the Universe to find and identify massive LSB galaxies. To perform this searches we need both a large aperture telescope (for surface brightness sensitivity) and also a high bandwidth to allow for searching a larger volume of the Universe at a given time. The AGES survey (http://www.naic.edu/∼ages) should provide just such a dataset, and we are looking forward to seeing the final survey results.

Looking farther to the future the surveys which will be possible with, e.g. the Square Kilometer Array will allow for an increase in the number of known massive LSB galaxies by factors of 100s or more while simultaneously providing not only the total flux of the galaxy but information on the gas distribution of the galaxy and its nearby neighbors. This level of information and sensitivity should revolutionize the field.

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