The Morphology, Color, and Gas Content of Low Surface Brightness Galaxies

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Abstract. Recent surveys have discovered hundreds of low surface brightness galaxies, systems with central surface brightness fainter than 22.0 B mag arcsec$^{-2}$, in the local universe. Plots of the surface brightness distribution – that is, the space density of galaxies plotted against central surface brightness – show a flat space density distribution from the canonical Freeman value of 21.65 through the current observational limit of 25.0 B mag arcsec$^{-2}$. It is therefore extremely important to understand these diffuse systems if we wish to understand galaxy formation and evolution as a whole. This talk is a review of both the known properties of low surface brightness galaxies and of popular theories describing the formation and evolution of these enigmatic systems.

1. Introduction

The importance of low surface brightness (LSB) galaxies in the local universe has recently been emphasized in a study by O’Neil & Bothun (2000) which has extended the known distribution of galaxies in the local universe. Their result is a flat surface brightness distribution function from the Freeman value of 21.65 ± 0.30 to the survey limit of 25.0 B mag arcsec$^{-2}$, more than 10σ away (Figure 1a). This indicates that the majority of the galaxies, and potentially the majority of the baryons in the local universe, are contained in gravitational potentials only dimly lit by the embedded galaxy. Realizing that most galaxies are optically diffuse, then, it becomes extremely important to understand these systems if we wish to understand galaxy formation and evolution as a whole. With this in mind I wish to undertake a brief review both of our current understanding of LSB galaxy properties as well as a review of some popular ideas behind the formation of these enigmatic systems.

2. What We (think) We Know about LSB Galaxies

LSB galaxy colors: Contrary to what was first believed, the colors of LSB galaxies range across the entire high surface brightness (HSB) galaxy spectrum, including what may be the bluest galaxy known (UGC 12695, with $U-I = -0.2$) as well as some fairly red systems ($B-V > 1.0$) (Figure 1b) (O’Neil, et.al. 1997a, 1997b, 1998). Although currently it appears that LSB galaxy colors do not quite extend into the extremely red colors found in some HSB galaxies, this
Figure 1. (a) The number density of galaxies in the local universe, with $\phi$ normalized to one (O’Neil & Bothun 2000). (b) A representative sample of LSB galaxy colors, from O’Neil, et.al. (1997b).

is likely due more to small number statistics rather than to an actual lack of extremely red LSB systems.

**Gas-to-luminosity ratio of LSB galaxies:** The gas-to-luminosity ratio ($M_{HI}/L_B$) of LSB galaxies spans an extremely large range, from fairly low ($M_{HI}/L_B = 0.1 M_\odot/L_\odot$) through what may be the highest $M_{HI}/L_B$ galaxies known ([OBC97] N9-2, $M_{HI}/L_B = 46 M_\odot/L_\odot$). Additionally, if any trend can be seen between the galaxies’ color and gas content it is that there may be an increase in their $M_{HI}/L_B$ with redder color (Figure 2a) (O’Neil, Bothun, & Schombert 2000, OBS from now on).

**Tully-Fisher relation:** Although previous studies have shown LSB galaxies to follow a slightly broadened version of the standard Tully-Fisher (T-F) relation defined by HSB galaxies (Zwaan, et.al. 1995), a recent study of over 40 LSB galaxies found no significant correlation between LSB galaxy velocity widths and absolute magnitudes, with only 40% of the sample falling within $1\sigma$ of the previously defined LSB T-F relation (Figure 2b). At the least, then, there is a significant population of LSB galaxies which do not adhere to the T-F relation (OBS).

**Rotation curves:** The rotation curves of LSB galaxies have been shown to rise more slowly than similar HSB galaxies Using ‘standard’ values for the stellar mass-to-luminosity ratio, as taken from HSB galaxies ($\Upsilon = 1 – 3$), this leads to the conclusion that many LSB galaxies have a baryonic mass fraction up to $3 \times$ less than HSB galaxies with the same velocity width (i.e. Swaters, et.al. 2000; Van Zee, et.al. 1998; de Blok & McGaugh 1997).

3. **What Are LSB Galaxies?**

**The faded version of HSB galaxies?** No. LSB galaxies often have both very blue colors and very low metallicities ($B-V < 0.2, Z < 0.01Z_\odot$), precluding the
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Figure 2. (a) Color versus mass-to-luminosity ratio for a variety of galaxy types (from OBS). (b) Galaxies from the sample of OBS. The solid and dashed lines are the 1σ and 2σ fits to the LSB galaxy T-F relation of Zwaan, et.al. (1995).

possibility that LSB galaxies are primarily composed of an old stellar population. As a caveat, though, it should be noted that a number of very red LSB galaxies have now been found, and these could be faded HSB galaxies. If this is correct, though, all other LSB galaxies (i.e. those which do not have extremely red colors) would have to be explained, as well as why there are two separate populations of LSB galaxies (O’Neil, et.al. 1997a, 1997b).

“Stretched out” HSB galaxies? No. Current theories describing LSB galaxies as extending further into their dark matter haloes than similar HSB galaxies predict that LSB galaxies will follow either a universal T-F relation or one which is unique at each \( \mu(0) \). These theories therefore cannot account for the galaxies of OBS which fall well off the T-F relation, with no correlation between \( \mu(0) \) and residual error. Additional problems with the models can (depending on which models are considered) include: difficulty matching the observed shape of LSB galaxy rotation curves; inability to allow for high gas fraction, red LSB galaxies, (i.e. Dalcanton, et.al. 1997; McGaugh & de Blok 1998; Avila-Reese & Firmani 2000; McGaugh 1999).

A completely new type of galaxy? No. Although this idea could justify ignoring LSB galaxies when determining theories of galaxy formation and evolution, no evidence has been seen for LSB galaxies to be anything but a continuation of the HSB galaxy spectrum. There is a smooth transition between LSB and HSB galaxies in surface brightness and complete overlap in LSB and HSB galaxy colors, scale lengths, mass, luminosity, etc. (i.e. Bell & de Blok 2000; O’Neil, et.al. 1997a, 1997b).

Galaxies with a different stellar population? Maybe. Although this is not a popular idea, as having an IMF which depends on galaxy properties (i.e. surface density) adds complication to models of galaxy evolution, this theory has not yet been disproved. The gas density of LSB galaxies is typically at or below the nominal threshold for star formation, as set by the Toomre criterion (i.e.
Van Zee, et.al. 1998; de Blok, McGaugh, & Van der Hulst 1996). With this in mind, it would be surprising if LSB galaxies' IMF was not at least somewhat affected by their low density. Additionally, recent HST WFPC-2 studies of three nearby LSB dE galaxies failed to find evidence for a significant number of red giants (< 13 per 10 pc$^2$, as opposed to the 100s per 10 pc$^2$ typically found in HSB galaxies (O'Neil, et.al. 1999)). Using these two ideas – the low gas density and the lack of evidence for significant numbers of giant branch stars – we can construct a toy model wherein no stars greater than $2M_\odot$ are allowed to form. When this is done, not only are LSB galaxy colors, gas fractions, etc. readily matched, but it is also remarkably easy to form both red and blue galaxies which do not follow the canonical T-F relation (see OBS). Additionally, the addition of a large number of small stars to any galaxy dramatically increases the galaxy's stellar mass-to-luminosity ratio ($\Upsilon_\star$) and can dramatically decrease the total amount of dark matter needed in LSB systems (Swaters, et.al. 2000; OBS). Although these models are admittedly extremely oversimplified, they pave the way for further studies into this idea, and currently appear to be the best theory going.

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