Stars, Gas and Dust in Galaxies: Exporing the Links
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Gas, Stars and Baryons in Low Surface Brightness Galaxies

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Abstract. Recent surveys have discovered hundreds of low surface brightness galaxies in the local (z < 0.1) Universe. Plots of the surface brightness distribution (the space density of galaxies plotted against central surface brightness) show a flat distribution from the bright-end cutoff of 21.65 through the current observational limit of 25.0 B mag arcsec^{-2}. As *no* trend is seen to indicate the size or mass of galaxies decreases with decreasing central surface brightness, it is likely that a significant percentage of the baryon content in the universe is contained in these diffuse systems. In this paper I briefly review the known properties of low surface brightness galaxies, and describe some current theories on the baryonic mass fraction of low surface brightness systems and their consequences.

1. Why Study Low Surface Brightness Galaxies?

Recent surveys by O'Neil, et al. (1997a, 1997b, 2000, 2001) have discovered hundreds of low surface brightness (LSB) galaxies 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 distribution from 21.65 through the current observational limit of 25.0 B mag arcsec^{-2} (Figure 1a). LSB systems therefore numerically dominate the galaxy population of the local universe. Additionally, as no trend is seen to indicate the size or mass of galaxies decreases with decreasing central surface brightness, it is likely that a significant percentage of the baryon content in the universe is contained in these diffuse systems.

2. LSB Galaxy Sizes

Contrary to a the often held belief that LSB and dwarf galaxies are synonymous, no correlation is seen between the central surface brightness of the galaxies in the O'Neil, *et.al.* samples and either total magnitude or total (gas) mass (Figure 1b). Galaxies do not become preferentially smaller with lower surface brightness. Instead, LSB galaxies occupy the same luminosity space as their HSB counterparts.

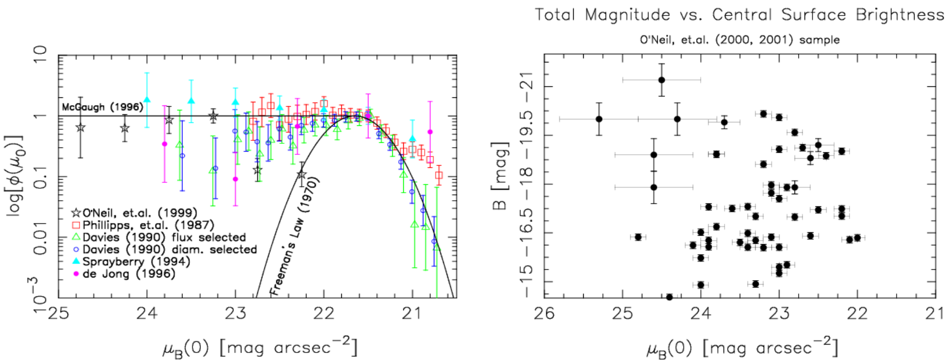

Figure 1. (a) The number density of galaxies in the local Universe, with ϕ normalized to 1. (b) Total magnitude versus central surface brightness for a sample of LSB galaxies.

3. The Mass-to-Luminosity Ratio of LSB Galaxies

A subset of the O'Neil, *et.al.* (1997a, 1997b, 2000, 2001) LSB galaxies have rotational velocities $\geq$ 200 km s^{-1} and total luminosities at least an order of magnitude below L$_*$. As such they represent extreme departures from the standard Tully-Fisher relation. In fact, the sample does not appear to have any significant correlation between velocity widths and absolute magnitudes, with only 40% of the galaxies falling within the 1σ LSB Tully-Fisher relation (Figure 2a). Unless the percentage of dark matter in these systems is unusually high, this may indicate the galaxies do not lie in the same evolutionary state as galaxies with lower gas content. Another possible interpretation, though, is found by thinking of the Tully-Fisher relation as a baryonic versus total mass relationship (i.e. McGaugh, *et.al.* 2000). In this case it can be seen that putting the LSB galaxies onto the baryonic Tully-Fisher relation is akin to increasing the galaxies baryonic mass-to-light ratios (Figure 2b).

Additional support for increasing the baryonic mass-to-light of LSB galaxies can be found by looking at the rotation curves of LSB galaxies. In a recent paper, Swaters, *et.al* (2000) has shown that the baryonic to dark matter ratio (M_b/M_{DM}) of LSB galaxies can be made to mimic to that of HSB galaxies (as opposed to being dark matter dominated even in the central regions) if M_b/L is allowed to range from $1M_\odot/L_\odot$ through $10M_\odot/L_\odot$ (or even higher).

One method for increasing M_b/L in LSB galaxies is to allow the galaxies to have an initial mass function (IMF) which produces primarily low mass stars. This can be brought about by assuming the low density inherent in LSB systems (often well below the Kennicutt criterion for star formation, i.e. van Zee, *et.al* 1998; de Blok, McGaugh, & van der Hulst 1996) affects the IMF in such a way as to prevent large scale production of stars with mass greater than $2M_\odot$. In addition to putting the LSB systems back on the baryonic Tully-Fisher relation, a preferentially low mass IMF can also explain the red, gas-rich LSB galaxies found by O'Neil, Bothun & Schombert (2000) as well as the non-detection of

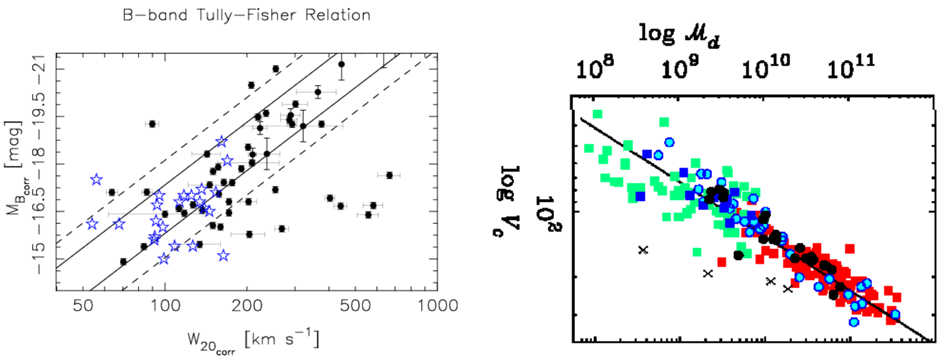

Figure 2. (a) A Tully-Fisher plot for a sample of LSB (circles) and late-type (stars) galaxies. The solid and dashed lines are the 1σ and 2σ fits to the Tully-Fisher relation of Zwaan, *et.al* (1995). The LSB galaxy data is from O'Neil, Bothun, & Schombert (2000) and the late-type galaxies are from Matthews & Gallagher (1998). (b) The Tully-Fisher relation plotted as baryonic disk mass versus rotational velocity, from McGaugh, *et.al* (2000). The crosses represent four of the outlying galaxies from the LSB galaxy Tully-Fisher relation shown in (a).

significant numbers of red giant stars in a HST study of three nearby dE LSB systems by O'Neil, Bothun & Impey (1999).

4. The (Potential) Baryonic Contribution of LSB Galaxies

It was shown (above) that the number density of LSB galaxies is at least equal to that of HSB galaxies, and that the mass-to-luminosity ratio of LSB galaxies is the same, or potentially much higher than, their HSB counterparts. With these two ideas in mind, then, we can do a rough calculation of the baryonic contribution of LSB galaxies to the local universe. (All the estimates for baryon density are adapted from are from Fukugita, Hogan, & Peebles 1998).

First, assume $L \times \frac{M}{L}$ remains constant with decreasing central surface brightness. Then assume the number density of galaxies ($\phi[\mu_B(0)]$) is constant out to 26.0 B mag arcsec^{-2}, where it cuts off (i.e. we have seen at least a sampling of all the galaxies in the local Universe). In this case, LSB galaxies contribute 9 times the baryon density of HSB galaxies. The total contribution of disk and irregular galaxies ($\rho_{disk+Irr}$) to the local baryon density is then $0.0084\, h_{70}^{-1}$, and LSB galaxies potentially contribute 40% all baryons in the local Universe.

We can now retain the assumption that $L \times \frac{M}{L}$ remains constant with decreasing central surface brightness, but assume $\phi[\mu_B(0)]$ does not cut-off until 30.0 B mag arcsec^{-2}. Here, $\rho_{LSB} = 17 \times \rho_{HSB}$, $\rho_{disk+Irr} = 0.016\, h_{70}^{-1}$, and LSB galaxies could contribute 75% all baryons in the local Universe.

Finally, we must recall the arguments if the last two sections, and consider the case where $L \times \frac{M}{L}$ increases to 6 times its value between 22.0 B mag arcsec^{-2}

and 24.0 B mag arcsec^{-2}, at which point it again remains constant. To be conservative, again assume that we have seen a sampling of all the galaxies in the Universe (i.e. $\phi[\mu_B(0)]$ cuts-off at 26.0 B mag arcsec^{-2}). For this scenario, $\rho_{LSB} = 22 \times \rho_{HSB}$, $\rho_{disk+Irr} = 0.020\, h_{70}^{-1}$, and LSB galaxies could contribute 97% all baryons in the local Universe. It is now a trivial step to allow $\phi[\mu_B(0)]$ to remain constant only to 26.5 B mag arcsec^{-2}, and thereby show that LSB galaxies contribute 100% of all the baryons in the local Universe.

Clearly something is wrong. Recent studies (i.e. Fukugita, Hogan, & Peebles 1998) have shown that all the baryons previously perceived to be 'missing' from the local Universe can be found in the form of ionized gas. Yet their accounting assumed LSB galaxies to be low mass objects, an assumption which has since been shown to be incorrect. We are now faced with the dilemma that instead of our observational counts showing an under density of baryons in the local Universe when compared with theoretical predictions, we have a clear over density. At this point all assumptions – in the theoretical models, in determining the ionized gas contribution, and in determining the space density and baryonic content of LSB galaxies – must be re-evaluated and re-tested, so that an accurate picture of the local baryonic content can be determined.

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