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Is the initial mass function of low surface brightness galaxies dominated by low-mass stars?

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ABSTRACT

The rotation curves of low surface brightness (LSB) galaxies suggest that they possess significantly higher mass-to-light (M/L) ratios than their high surface brightness counterparts, indicating that LSB galaxies may be dark matter dominated. This interpretation is hampered by the difficulty of disentangling the disc and dark halo contributions from the disc dynamics of LSB galaxies. Recently, Fuchs has attempted such a disentanglement using spiral arm density wave and swing amplification theory, allowing an independent measurement of the disc mass; this work suggests that LSB discs are significantly more massive than previously believed. This would considerably reduce the amount of matter required in the dark haloes in fitting the rotation curves. Interestingly, the high mass-to-light ratios derived for the discs appear inconsistent with standard stellar population synthesis models.

In this paper, we investigate whether the high M/L ratios for the Fuchs LSB discs might be understood by adopting a very 'bottom heavy' initial mass function (IMF). We find that an IMF with a power-law exponent of around $\alpha = 3.85$ (compared with the standard Salpeter IMF, $\alpha = 2.35$) is sufficient to explain the unusually high M/L ratios of the Fuchs sample. Within the context of the models, the blue colours $[(B - R)_0 < 1.0]$ of the sample galaxies result from being metal-poor ($[\mathrm{Fe/H}] = -1.5 \sim -1.0$) and having undergone recent ($\sim$1–3 Gyr ago) star formation.

Key words: stars: luminosity function, mass function – galaxies: fundamental parameters – galaxies: stellar content.

1 INTRODUCTION

Low surface brightness (LSB) galaxies have a wide range of properties, being termed 'LSB' only by virtue of their extrapolated central surface brightness being fainter than $\mu_B(0) = 21.65 \pm 0.30$ mag arcsec^{-2} (Freeman 1970; see Bothun, Impey & McGaugh 1997 and Impey & Bothun 1997 for more detailed reviews of LSB galaxies).

Intriguingly, LSB galaxies appear, in general, to possess higher mass-to-light (M/L) ratios than their high surface brightness (HSB) counterparts. However, the nature of this greater mass contribution is poorly constrained due to uncertainties involved in the decomposition of baryonic disc matter (stars and gas) from the non-baryonic dark matter halo, from disc dynamics (e.g. de Blok, McGaugh & Rubin 2001). Therefore, the total baryonic mass in the disc of LSB galaxies, and its contribution to the disc dynamics, are not clear.

Recently, de Blok et al. (2001) have fitted a series of mass models to the high-resolution rotation curves of 30 LSB galaxies, assuming both core dominated (pseudo-isothermal) and cold dark matter cusp dominated [specifically, Navarro, Frenk & White 1997 (hereafter NFW) profiles] haloes for a range of assumptions concerning the stellar M/L ratios. They found that in general, the pseudo-isothermal models fit the data better than the NFW profiles, and that the maximum disc models are preferable for the fitting the inner rotation curves, albeit requiring high stellar M/L ratios.

Recently, a new constraint on the mass decomposition of LSB galaxy discs has been made by Fuchs (2002) who employs the density wave and swing amplification theory of galactic spiral arms (see also McGaugh & de Blok 1998). The technique leads to a disc mass estimate independent of traditional disc/halo decomposition of the rotation curve. He reports that for his sample of LSB disc galaxies,

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Table 1. The Fuchs (2002) sample of LSB galaxies.

Galaxy ID	$(B-R)_0$	$(B-V)_0$	$(B-I)_0$	M/L_R	μ_0
F568−1	0.79	0.62	1.32	13.0	23.76
F568−3	0.84	0.55	1.29	6.2	23.07
F568−6	–	0.63	2.26	10.3	23.60
F568−V1	0.78	0.51	1.21	14.4	23.29
UGC 128	0.69	0.51	1.09	3.1	24.22
UGC 1230	0.76	0.52	1.20	3.0	23.36
UGC 6614	–	0.72	2.32	5.8	24.85

selected for clear spiral structure, the discs possess unexpectedly high M/L ratios in the *R-band* ($M/L_R \sim 4$–16),[1] in addition to relatively blue colours [$(B-R)_0 < 1.0$]. Fuchs also found that the LSBs with higher M/L ratios have lower fractions of gas to total baryonic mass, perhaps indicating these galaxies have had a higher conversion rate of gas into stars. Furthermore, the LSB discs for which a disc mass can be independently estimated, are significantly heavier than expected for standard stellar population synthesis models (Bell & de Jong 2001; Mouhcine & Lancon 2003).

We investigate in this paper whether the high M/L ratios of the Fuchs sample can be explained by an increased contribution of low-mass stars in LSB galaxy stellar populations, i.e. through modifying the initial mass function (IMF).

2 DATA

Table 1 lists the seven LSBs from the Fuchs (2002) sample. The dereddened $B-R$ colours are from table 2 of de Blok, van der Hulst & Bothun (1995).[2] We note that McGaugh & de Blok (1997, hereafter MdB97) also used M_T for their compilation of $B-V$ and $B-I$ colours, and we also list these colours in Table 1.

In Fig. 1, we have divided the MdB97 sample of (both HSB and LSB) spiral galaxies into two groups, one group with $\mu_0 < 22.7$ and the other with $\mu_0 > 22.7$. This is a rather loose application of Freeman's law on this sample of spiral galaxies. The location of the Fuchs sample in Fig. 1 shows that his sample is, in general, fairly blue, when compared with the MdB97 sample of spiral galaxies. The galaxies F568-6 (Malin2) and UGC 6614 are clear outliers in $B-I$ colour. These two are amongst the largest LSBs known (Quillen & Pickering 1997).

3 STELLAR POPULATION MODELS

The present stellar population synthesis models are based upon the Y^2 isochrones,[3] which are computed until the onset of helium core burning (Kim et al. 2002). The models we compute are all single starbursts, characterized by a single age and metallicity. In reality, galaxies are generally composed of mixtures of stellar populations, with a range of ages and metallicities. We have deliberately used a simplified (i.e. single burst) star formation prescription for the LSB galaxies, in order to explore the importance of varying one parameter, namely the IMF. In this regard, our single-burst models approximately represent the luminosity weighted mean age and metallicity for the stellar systems in question.

[1] We have recalculated M/L_R after removing the gas mass component and listed them in Table 1.

[2] M_T in their column 8, which is corrected for Galactic extinction, is used to obtain colours.

[3] http://csaweb.yonsei.ac.kr/∼kim/yyiso.html

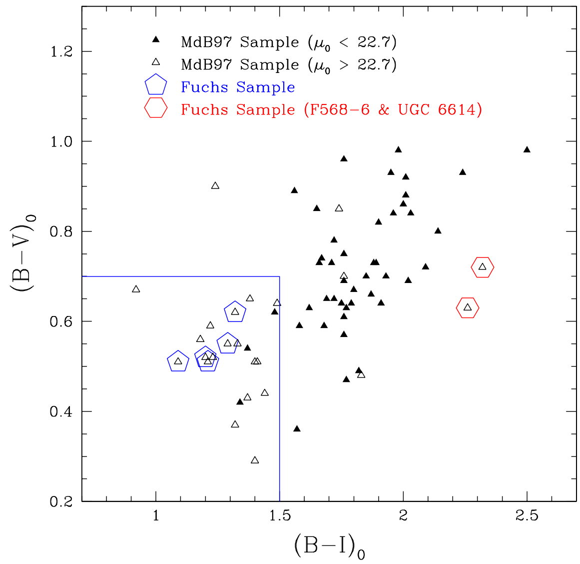

Figure 1. Colour–colour diagram of the spiral galaxies from the sample of McGaugh & de Blok (1997, MdB97). Five of the Fuchs (2002) sample of LSB galaxies are located at the blue end of the colour sequence (pentagons). The exceptions are F568-6 and UGC 6614 (hexagons; see the text).

Following our previous models (Lee, Yoon & Lee 2000; Lee, Lee & Gibson 2002), the isochrones assume $[\alpha/\mathrm{Fe}] = +0.3$, and are coupled to the post-RGB stellar evolutionary tracks of Yi, Demarque & Kim (1997). Although the latter tracks are solar-scaled, the effects of alpha-enhancements are minimal at low-metallicity ($Z < Z_\odot$) (Kim et al. 2002), which is the metallicity range of interest for our LSBs (see Section 4). Furthermore, since we employ steeper IMFs than the standard Salpeter one, the importance of post-RGB stars is reduced because of the reduced number of high-mass stars.

The investigated age range is from 1 to 14 Gyr, and the metallicities cover $-2.51 \leqslant [\mathrm{Fe/H}] \leqslant +0.39$. The colours of the horizontal-branch have been calibrated to Milky Way globular clusters (Lee et al. 2000, 2002). The stellar library of Lejeune, Cuisinier & Buser (1997, 1998) was used for the conversion from theoretical to observable quantities because of their wide coverage in stellar parameters such as temperature, surface gravity and metallicity.

The constancy and shape of the IMF is still controversial, although a number of studies are converging on the idea of a so-called 'universal' IMF (e.g. Kroupa 2002; Wyse et al. 2002; Bell et al. 2003; Chabrier 2003; Weidner & Kroupa 2004). Indeed, the possible dependence of IMF on galaxy types has been suggested by the previous studies (e.g. Portinari et al. 2004). In this paper, we explore the variation in IMF required to explain the high M/L ratios of LSB galaxies. To this end, we use the simple power-law IMF, where the number of stars (dN) in mass interval (dm) is described by

$$\mathrm{d}N \propto m^{-\alpha}\,\mathrm{d}m. \tag{1}$$

The range in α required to reproduce the unusually high M/L ratios of LSB galaxies is shown in the Figs 2–4. For simplicity, the lower-mass (M_l) and the upper-mass (M_u) ends of the IMF were fixed at 0.1 and 60 $M_\odot$, respectively.

In this paper, we define the IMF with $(\alpha, M_u, M_l) = (2.35, 0.1, 60)$ as the standard Salpeter model, although the original Salpeter (1955) IMF is only defined for the mass function of stars within the mass range 0.4–10 $M_\odot$. As a result of this simplification, there is only one free parameter, α, to describe the shape of the IMF. This enables us to explore other parameters, such as metallicity

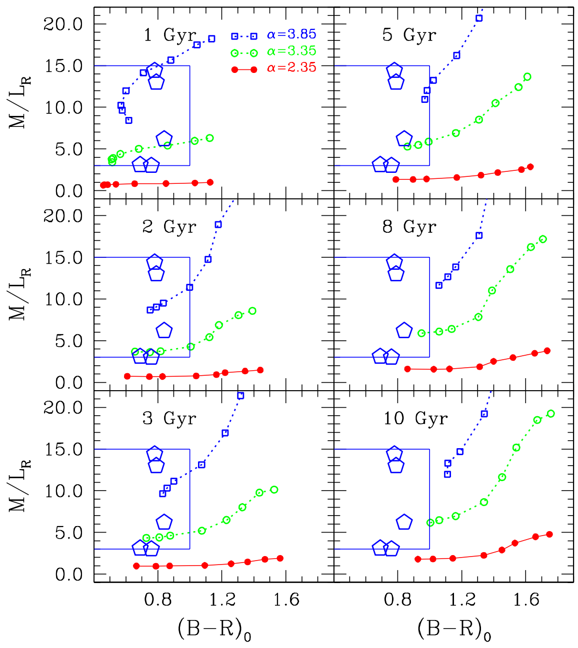

Figure 2. Our simple stellar population predictions for the $(B-R)_0$ versus M/L_R as a function of age for three IMF slopes. The solid lines with filled circles correspond to the standard Salpeter IMF with an exponent $\alpha = 2.35$. The dotted lines with open circles and open squares are $\alpha = 3.35$ and $\alpha = 3.85$ cases, respectively. At a given age and IMF exponent, the metallicity [Fe/H] is −2.51, −1.90, −1.51, −0.90, −0.49, −0.17, +0.17 and +0.39, from left to right. From the left-hand panel, it is suggested that both unusually high-M/L_R ratios and blue colours [$(B-R)_0 < 1.0$] of the Fuchs (2002) sample of LSB galaxies (large pentagons) could be satisfactorily explained by employing steeper than Salpeter IMFs with the combination of low metallicity ([Fe/H] = −1.5 ∼ −1.0) and a rather recent (∼1–3 Gyr) star formation.

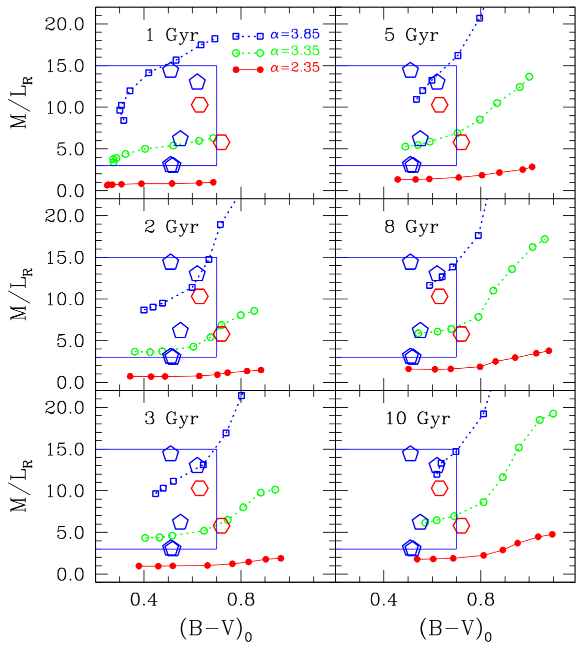

Figure 3. Similar to Fig. 2, but $(B-V)_0$ versus M/L_R diagrams. The two large hexagons are F568-6 ($M/L_R = 10.3$) and UGC 6614 ($M/L_R = 5.8$).

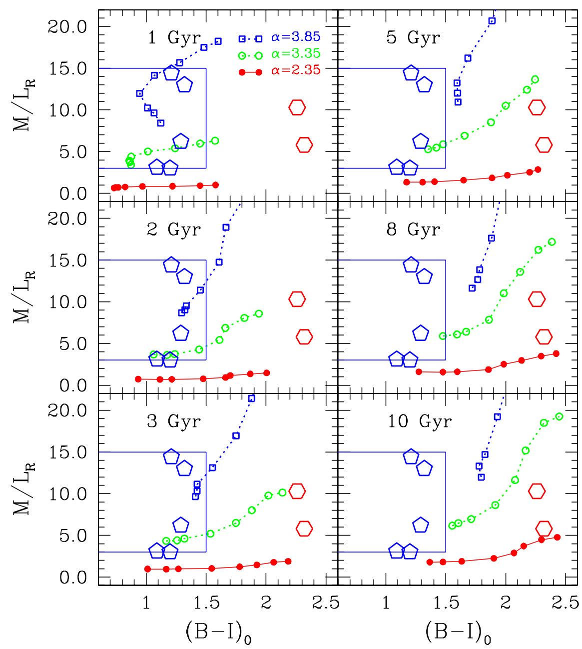

Figure 4. Similar to Fig. 2, but $(B-I)_0$ versus M/L_R diagrams. The two large hexagons are F568-6 ($M/L_R = 10.3$) and UGC 6614 ($M/L_R = 5.8$).

and age, more easily. Of course, a more realistic IMF may be of a more complicated form, but this power-law formula provides an approximation for the such IMFs.

The low-mass end of the Y^2 isochrones is given at 0.4 $M_\odot$ because of the uncertain nature of the high-density equation of state for low-mass stars. For our purposes, we linearly extrapolated the Y^2 isochrones down to 0.1 $M_\odot$.[4] For IMFs steeper than the standard Salpeter variety, the baryonic M/L ratios significantly depend upon the choice of the low-mass end. For instance, for $M/L \sim 10$, α + 4.5 is needed when the low-mass cut-off is taken at 0.4 $M_\odot$, while α + 1.5 is necessary if the low-mass cut-off is taken at 0.1 $M_\odot$.

4 RESULTS AND DISCUSSION

Figs 2–4 show our derived M/L ratios and colours for single burst populations for a range of galaxy ages and metallicities. There is a region of parameter space where a slightly steeper than normal (bottom-heavy) IMF does achieve agreement with the unusually high-M/L_R ratios of the Fuchs sample.

The blue colours of the LSBs also provide constraints upon the allowable combination of age and metallicity of the sample. The characteristic colours of $(B-R)_0 \leqslant 1.0$, for instance, require recent star formation (∼1–3 Gyr ago), when adopting the metallicity range −1.5 < [Fe/H] < −1.0, as implied by the oxygen abundance measurements of de Blok & van der Hulst (1998). This interpretation for such blue colours is generally consistent with the recent

[4] Stellar models that reach masses below 0.4 $M_\odot$ have been presented in the literature (e.g. Baraffe et al. 1998; Chabrier et al. 2000). We use a simple extrapolation rather than these more sophisticated models, but our conclusions should not be affected much by this simplification. This is because the luminosity contribution of these low-mass stars is negligible, especially in the optical band where we focus in this study. From our calculations, for instance, at [Fe/H] = −1.5 and at 3 Gyr, the mass fraction from the stars below 0.4 $M_\odot$ is 87.2 per cent, while their contribution to the total luminosity is only 7.6 per cent, in the case of $\alpha = 3.35$.

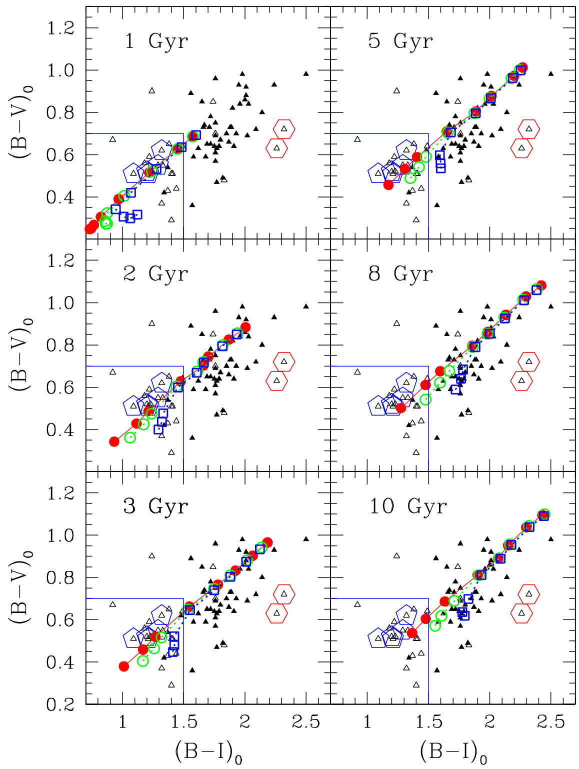

Figure 5. Our simple stellar population predictions are compared with the sample of MdB97 (see Fig. 1 for symbol description). The solid line with filled circles is for standard Salpeter IMF with $\alpha = 2.35$. The dotted lines with open circles and open squares are $\alpha = 3.35$ and $\alpha = 3.85$ cases, respectively. At the given IMF exponent, [Fe/H] is −2.51, −1.90, −1.51, −0.90, −0.49, −0.17, +0.17 and +0.39 from lower left to upper right.

study by Burkholder, Impey & Sprayberry (2001). Interestingly, Padoan, Jimenez & Antonuccio-Delogu (1997) have concluded that LSB galaxies are typically older than 7 Gyr. Their conclusions are, however, only valid where the metallicity of LSB galaxies are constrained to $Z = 0.0002$ ([Fe/H] ~ -2.0) as they stressed in their paper. This is a result of the well-known age–metallicity degeneracy that plagues integrated broad-band colours in the optical range (e.g. Worthey 1994).

Fig. 5 shows that our simple stellar population models broadly follow the colours of the MdB97 sample (both HSB and LSB spiral galaxies) in the $(B-I)_0$ versus $(B-V)_0$ plane. In order to explain their presently rather blue colours, Figs 2–5 suggest that the LSBs do need the combination of low metallicity ([Fe/H] $= -1.5 \sim -1.0$) and rather recent star formation (∼1–3 Gyr ago). The two giant LSBs (F568-6 and UGC 6614) almost certainly require an additional older, metal-rich population to explain their red colours.

A notable feature in Figs 2–5 is that the integrated colours at 1 Gyr are significantly bluer than those at 2 Gyr. This is because of the convective core overshooting phenomenon, which causes a brighter main-sequence turn-off and a longer stellar lifetime during the hydrogen burning phase (Yi 2003).

4.1 IMF variations

The adoption of a steeper-than-Salpeter IMF is easily able to explain the M/L ratios of the sample LSB disc galaxies. Is such a steep IMF plausible?

From the observed CO deficiency in LSB galaxies, Schombert et al. (1990) have suggested that star formation may be inefficient in metal-poor discs, and may take place preferentially outside the giant molecular cloud environment with an IMF operating in a suppressed high-mass mode. It is interesting to note, in this respect, that the Romanishin, Strom & Strom (1983) spectroscopy of a few nearby LSB galaxies suggests that their H II regions are significantly deficient in massive stars. Schombert et al. (1990) further proposed that the star formation that takes place in warmer, low-density H I environments could produce smaller clouds (because of initially lower cloud masses) and have an IMF which is substantially different from that in an environment of cold, dense gas. Interestingly, Waller et al. (2002) find from multiband *Hubble Space Telescope* photometry of H II regions in M33 that the IMF may depend on metallicity in the sense that the most metal-rich H II regions produce more massive than low-mass stars. This is a rather surprising result when one considers the generally favoured top-heavy IMF theory at early times when metallicity is low (e.g. Larson 1998).

If the stellar IMF of the LSB galaxies is indeed steeper than the standard Salpeter IMF, then this might imply that the following are true. (i) The LSBs must be intrinsically less luminous in the optical and in the near-infrared regime compared with HSB galaxies. This simply due to the significantly smaller number fraction of luminous stars in LSB galaxies, despite their similar masses to HSBs. (ii) This smaller number fraction of evolved stars leads naturally to less efficient chemical enrichment, and thus lower metallicity. (iii) In such a low metallicity environment, less efficient dust production may further accentuate the bluer colours of LSBs. (iv) Significant amounts of baryonic matter, in the form of low-mass stars, may reside in the discs of LSB galaxies. Depending upon the shape of the LSB luminosity function, LSBs could be major repositories of baryons in the Universe.

Another interesting issue is the gas mass fraction. LSB disc galaxies are known to be H I rich relative to their optical luminosity, when compared with HSB galaxies. The baryonic gas mass fraction is written

$$f_g = \frac{M_g}{M_g + M_*}, \tag{2}$$

where M_g is the total mass in the form of gas, and M_* is the mass in stars. The estimation of M_* is, however, now arguably quite uncertain. The f_g therefore depends upon what amounts of stellar mass one adopts, and admittedly the adoption of the standard Salpeter IMF for the M_* has been prevalent in the literature. Like our case of a steeper than the standard Salpeter IMF, if the stellar mass is indeed significantly enhanced by low-mass stars and more of the gas is locked up into these stars, then f_g should become correspondingly smaller. A hint toward this interpretation is seen in fig. 5 of Fuchs (2002). Accordingly, if the steeper than Salpeter IMF is truly the case for the LSB galaxies, then star formation scenarios at lower efficiencies may need to be reconsidered as a result of this study (e.g. van den Hoek et al. 2000).

5 SUMMARY

We have presented theoretical efforts to reproduce the relatively high mass-to-light ratios, and blue colours, of a sample of LSB galaxies by employing a significantly steeper IMF than the standard Salpeter variety. In particular, we address the unusually high M/L ratios that are based upon Fuchs' independent disc mass estimation of several LSB disc galaxies with clear spiral structure, using his density wave and swing amplification theory. We find that a 'bottom-heavy' IMF, such as $\alpha = 3.85$, is sufficient to reproduce the high M/L ratios. Moreover, we report that a combination of a relatively low metallicity ([Fe/H] = $-1.5 \sim -1.0$) and a rather recent ($\sim$1–3 Gyr ago) star formation could also successfully explain the observed blue colours of the LSB galaxies [$(B - R)_0 < 1.0$]. Although suggestive, it remains to be seen whether these simple IMF variations are justifiable, or whether more complicated processes are needed.

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