DO LOW SURFACE BRIGHTNESS GALAXIES HOST STELLAR BARS?

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Abstract

With the aim of assessing if low surface brightness galaxies host stellar bars, and study the dependence of the occurrence of bars as a function of surface brightness, we use the Galaxy Zoo 2 dataset to construct a large volume-limited sample of galaxies, and segregate the galaxies as low and high surface brightness in terms of their central surface brightness. We find that the fraction of low surface brightness galaxies hosting strong bars is systematically lower than the one found for high surface brightness galaxies. The dependence of the bar fraction on the central surface brightness is mostly driven by a correlation of the surface brightness with the spin and the gas-richness of the galaxies, showing only a minor dependence on the surface brightness. We also find that the length of the bars shows a strong dependence on the surface brightness, and although some of this dependence is attributed to the gas content, even at fixed gas-to-stellar mass ratio, high surface brightness galaxies host longer bars than their low surface brightness counterparts, which we attribute to an anticorrelation of the surface brightness with the spin.

Keywords: galaxies: fundamental parameters — galaxies: general — galaxies: spiral — galaxies: statistics — galaxies: structure

1. INTRODUCTION

Low surface brightness galaxies (LSBs) are faint galaxies that emit less light per unit area than a typical bright spiral galaxy. The term LSB typically refers to disk galaxies with $B$-band central surface brightnesses fainter than $\mu_0(B) \geq 22.7$ mag arcsec$^{-2}$ (Freeman 1970). In this paper we adopt the commonly used criterion $\mu_0(B) \geq 22.0$ mag arcsec$^{-2}$ (Impey et al. 2001; Boissier et al. 2003; Zhong et al. 2008) to define our sample of LSBs. Despite some of them being intrinsically bright, due to their faint central surface brightness, they were difficult to detect, but in the last two decades a large amount of research has enlightened our understanding of this kind of galaxies. Although intrinsically faint, observational studies by Impey & Bothun (1997) and O'Neil & Bothun (2000) suggest that a significant fraction of the galaxy population are LSBs, making these galaxies the major recipients of baryonic matter in the Universe. In general, the span range of physical parameters of LSBs is the same as the conventional Hubble sequence and are not restricted to be low mass dwarf galaxies (McGaugh et al. 1995). The main difference between LSBs and their high surface brightness (HSB) counterparts is their low stellar surface mass density that produces the low surface brightness that characterizes them. The typical rotation curve of LSBs do not rise as steeply as the rotation curves of HSBs of similar luminosity (de Blok et al. 2001; Swaters et al. 2010), but they are surprisingly flat and extend to large radii implying that they are strongly dark matter dominated at all radii, with mass models indicating that the dark matter halos of LSBs are less dense than those of HSBs (de Blok & McGaugh 1996, 1997; de Blok et al. 2001).

In the literature, LSBs are regarded as unevolved galaxies due to their low star formation rates (van der Hulst et al. 1993; van Zee et al. 1997; Wyder et al. 2009; van den Hoek et al. 2000; Schombert et al. 2011), their high gas fractions for their stellar masses, and high HI total masses (Burkholder et al. 2001; O’Neil et al. 2004; Huang et al. 2014) and low metallicities (de Blok & van der Hulst 1998a,b; Kuzio de Naray et al. 2004), which suggest that these kind of galaxies follow different evolutionary tracks than HSBs.

The existence of LSBs is usually explained as this kind of galaxies being formed in high angular momentum dark matter halos. If the specific angular momentum of baryons is conserved and set equal to that of the dark matter halo (Fall & Efstathiou 1980), then the disk scalelength is regulated by the dark matter halo spin. In this way, the low surface brightness, which is a direct consequence of the low stellar mass density of the disk, is specified by the $\lambda$ spin parameter of the dark matter halo, making LSBs
systems from the high tail of the galaxy spin distribution (Dalcanton et al. 1997; Jimenez et al. 1998; Mo et al. 1998; Jimenez et al. 2003), with $\lambda > 0.05$ (Boissier et al. 2003; Kim & Lee 2013). In this context, LSBs are galaxies with sparse disks embedded in dark matter halos which are dynamically dominant at all radii, hence expected to be stable against disk instabilities (Ostriker & Peebles 1973; DeBuhr et al. 2012; Yurin & Springel 2015; Algorry et al. 2016).

Mihos et al. (1997), through analytic arguments and numerical experiments, found that LSBs are stable against both local and global disk instabilities. On a work entirely focused on the formation and evolution of bars in LSBs, Mayer & Wadsley (2004) using high-resolution simulations of LSBs embedded in cold dark matter halos including models with dominant gaseous components, find that the halo-to-disk mass ratio within the disk radius is the main factor determining if a galaxy is able to develop a bar. For their LSBs models with $\lambda \sim 0.065$, a high baryonic fraction of 10 per cent is required in order to grow bars, which is more than double the baryon fraction estimated for LSBs (Hernandez & Gilmore 1998). Mayer & Wadsley (2004) also report that when LSBs are able to form bars, their typical sizes are smaller than the halo scale radius and both, gaseous and stellar bars evolve into forming bulge-like structures in a few gigayears.

If LSBs are galaxies formed in halos with high values of the spin parameter, the result by Long et al. (2014) directly applies to them. Using numerical simulations of isolated galaxies, they demonstrate that the growth of stellar bars in spinning dark matter halos is strongly suppressed, with the bar growth in strength and size being increasingly quenched in systems with $\lambda \geq 0.03$, because the angular momentum transfer from the disk to the halo is reduced. In this same line, Cervantes-Sodi et al. (2013) (henceforth CS+13), using a volume limited sample of galaxies from the Sloan Digital Sky Survey (SDSS), and using an order of magnitude estimate for the spin parameter (Hernandez & Cervantes-Sodi 2006), found that the fraction of galaxies hosting strong bars was a strong function of $\lambda$, with strong bars preferentially found in galaxies with low to intermediate values of the spin parameter, while weak bars presented systematically high values of $\lambda$.

With LSBs expected to be stable against bar formation, it is not surprising to find that bars are rare in LSBs. In the study by McGaugh & Bothun (1994), of 36 LSBs only one shows features of a strong bar, and form Impey et al. (1996) catalog, of 516 only 19 are classified as barred galaxies. More recently, Honey et al. (2016) found that of a sample of 856 LSB galaxies extracted from the SDSS, only 8.3 per cent have bars, and through a near-infrared image study, they conclude that the range of bar parameters such as bar length and ellipticities are similar to those found in HSBs.

In the present work, we select a large volume-limited sample of galaxies from the SDSS, with visual classification from the Galaxy Zoo 2 project, to study the fraction of barred galaxies as a function of central surface brightness, with the aim of establishing if the bar fraction is different between LSBs and HSBs, if the difference is due entirely on the surface brightness of the galaxies, and if the length of the bars detected on both samples is statistically different. The sample description is detailed in Section 2, our general results and discussion are presented in Section 3. Lastly, we summarize our general conclusions in Section 4.

2. DATA

The sample of galaxies used in the present study comes from the Galaxy Zoo 2 project. The Galaxy Zoo 2 (GZ2; Willett et al. 2013) is an on-line citizen science project where morphological classification of 304 122 galaxies drawn from the Sloan Digital Sky Survey Data Release 7 (SDSS DR7) were conducted. Like an extension of its predecessor, the Galaxy Zoo (Lintott et al. 2008, 2011), the classification was conducted following a multi-step decision tree, containing 13 classification tasks and 36 possible answers guiding the volunteers in order to classify each galaxy by providing a composite color image (in the $g$, $r$ and $i$ bands) for the galaxies in the sample.

Given that the present work focuses on barred disk galaxies, we look for galaxies classified as disk galaxies viewed face-on for a direct identification of the bar. We impose a strict classification criterion requesting a minimum of 20 votes for each relevant task; ie, disk, smooth, face-on. To classify a galaxy as a disk, face-on system we request a vote fraction $\geq 0.6$ (ie, $p_{\text{disk}} \geq 0.6$, $p_{\text{not edgeon}} \geq 0.6$), and to identify barred galaxies we adopt the threshold $p_{\text{bar}} \geq 0.6$; with all other galaxies regarded as unbarred ones. A similar threshold of $p_{\text{bar}} = 0.5$ was adopted by Masters et al. (2012), where they showed it to be reliable to identify strong bars; in this sense we regard weakly barred galaxies as unbarred, and our barred fraction refers to strongly barred galaxies exclusively. We restrict our analysis to a volume-limited sample with $0.02 < z < 0.04865$ and absolute magnitude $M_r < -19.7$.

All photometric data was extracted from the SDSS DR7 (Abazajian et al. 2009) and corrected using the standard Galactic extinction corrections (Schlegel et al. 1998) and a small $k$-correction (Blanton & Roweis 2007). Stellar masses were obtained from the MPA/JHU SDSS database. Our final sample consist of 10 430 face-

1 http://www.mpa-garching.mpg.de/SDSS/
on disk galaxies segregated into 7,851 unbarred and 2,579 barred galaxies.

To define our subsample of LSBs we use the relation by Zhong et al. (2008) to find the central surface brightness, given by

$$\mu_0 = m + 2.5 \log_{10} \left( 2\pi a^2 \right) + 2.5 \log_{10} (q) - 10 \log_{10} (1 + z)$$ \hspace{1cm} (1)

where $m$ is the apparent magnitude, $a$ is the disk scale length (in arcsec), $q = b/a$ is the axis ratio and $z$ is the redshift. The third and fourth term of Equation 1 are due to the correction by inclination and cosmological dimming effects. Once estimated $\mu_0$ in the $r$ and $g$ bands, we make use of the transformation equation by Smith et al. (2002) to get $\mu_0$ in the $B$-band:

$$\mu_0(B) = \mu_0(g) + 0.47(\mu_0(g) - \mu_0(r)) + 0.17.$$ \hspace{1cm} (2)

Having estimated the central surface brightness on the $B$-band, we are now able to define our subsample of LSBs as those with $\mu_0(B) \geq 22.0$, resulting in a total of 4,484 galaxies.

To study the joint dependence of the bar fraction on $\mu_0(B)$ and the gas mass fraction $M_{\text{HI}}/M_*$, we use estimates of HI mass from a recently published catalog by Teimoorinia et al. (2017) who provide $M_{\text{HI}}/M_*$ for half a million galaxies in the SDSS, obtained by applying an artificial neural network based on a sample of $\sim$13,000 SDSS galaxies with H I mass detections from the Arecibo Legacy Fast Arecibo L-band Feed Array (ALFALFA). This H I estimate shows no systematic trend with parameters such as stellar mass, color or star formation rate. When using this estimate, our sample is reduced to 8,865 galaxies.

Finally, to explore if the length of the bars found in LSBs is different to that measured on HSBs, we use the Hoyle et al. (2011) catalog, that provides bar lengths for a total of 3,150 galaxies. As part of the GZ2 project, bar lengths are measured by volunteers though a Google maps interface, by drawing a line extending the length of the bar in question, requiring at least 3 measurements per galaxy. By matching our sample with this catalog we obtain a total of 1,686 galaxies with $L_{\text{bar}}$ measurements, of them 1,362 have H I mass estimates from Teimoorinia et al. (2017).

Figure 1 shows random example images of LSBs and HSBs with and without bars in our sample.

### 3. RESULTS

The fraction of barred galaxies as a function of the limited redshift range of our sample is presented in Figure 2, where error bars denote the estimated 1σ confidence intervals based on the bootstrapping resampling method. This convention will be kept in all subsequent figures. The bar fraction for the whole sample is 25%, in good agreement with Lee et al. (2012), who report...
24% of the galaxies in their sample presenting strong bars. We remind the reader that in the present work, we focus exclusively on strong bars, given that weak bars are not resolved in this redshift range (Masters et al. 2011). This is not an issue regarding strong bars as we did not find any dependence of the bar fraction on the size of the galaxies in pixels. For HSBs the bar fraction is close to 30%, also in good agreement with previous works (Eskridge et al. 2000; Laurikainen et al. 2004; Marinova & Jogee 2007; Lee et al. 2012). As can be appreciated from the figure, the bar fraction for LSBs is only 20%, systematically lower than the value estimated for HSBs. The difference of the bar fraction for LSBs and HSBs is due to the dependence of $f_{\text{bar}}$ on the central surface brightness, as can be appreciated in Figure 3 top panel, that shows the dependence of $f_{\text{bar}}$ on $\mu_0(B)$, with the vertical line denoting the value that segregates LSBs to the left and HSBs to the right. The corresponding figure using the natural SDSS photometric $r$-band surface brightness is presented in Figure 3 bottom panel, with the same general trend, an increase of $f_{\text{bar}}$ with increasing $\mu_0(r)$.

As mentioned in the introduction, this dependence of the bar fraction on the surface brightness was already pointed out by several works using more limited samples (McGaugh & Bothun 1994; Honey et al. 2016), and predicted by CS+13 in the case LSB represent the tail of high spinning galaxies in the general galaxy population. To test this hypothesis, we used the model proposed by CS+13 to estimate the spin parameter $\lambda$ as defined by Peebles (1971) $\lambda = LE^{1/2}/GM^{5/2}$, where $E$ is the total energy, $M$ the mass, and $L$ the angular momentum of the configuration. The model by CS+13 includes a dark matter halo with a truncated isothermal density profile responsible for establishing a rigorously flat rotation curve along the whole disk, and a disk with an exponential surface density profile of the form $\Sigma(r) = \Sigma_0 e^{-r/R_d}$, with $\Sigma_0$ the central surface density and $R_d$ the disk scalelength. Circular velocities ($V_d$) are assigned through a Tully-Fisher relation (Pizagno et al. 2007) and a disk-to-halo mass ratio ($f_d$) is adopted following the prescription by Gnedin et al. (2007) to finally express $\lambda$ as:

$$\lambda = \left(\frac{\sqrt{2}}{G}\right) f_d R_d V_d^2 M_d^{-1}$$

For a detailed description of the model, we refer the
reader to CS+13. Figure 4 top panel clearly shows an anticorrelation between $\mu_0(B)$ and $\lambda$, confirming our hypothesis that LSBs form in high spinning systems. In this sense, the increase of $f_{\text{bar}}$ with increasing $\mu_0(B)$ is a natural outcome, given the previous result by CS+13. In the same figure we include isocontours that denote regions of constant $f_{\text{bar}}$ obtained by dividing the parameter space into 10 x 10 bins, applying a spline kernel to get a smooth transition, and requiring at least 5 galaxies per bin to estimate the bar fraction. A clear trend of increasing $f_{\text{bar}}$ with decreasing $\lambda$ is noticeable with no dependence on $\mu_0(B)$ at fixed $\lambda$. From this figure is apparent that the dependence of $f_{\text{bar}}$ on $\mu_0(B)$ comes from the marked correlation between $\mu_0(B)$ and $\lambda$. For completeness we show in Figure 4 bottom panel the bar fraction as a function of $\lambda$, recovering the same behavior reported by CS+13 (see their figure 1b), with a decrease of the bar fraction with increasing $\lambda$. This result is encouraging given that in the sample used in the present work the bar identification is made by amateur citizen scientists, while in the sample employed by CS+13 the classification is preformed by professional astronomers (Lee et al. 2012).

As several studies have previously pointed out (Masters et al. 2012; Oh et al. 2012; Skibba et al. 2012; Cervantes-Sodi et al. 2013; Gavazzi et al. 2015), the bar fraction is a strong function of stellar mass, with increasing $f_{\text{bar}}$ as $M_*$ increases. Likewise, LSBs tend to be less massive than their HSBs counterparts (Galaz et al. 2011), which could explain why $f_{\text{bar}}$ is lower for LSBs. In Figure 5a, we explore the co-dependence of the bar fraction on $\mu_0(B)$ and $M_*$. The first thing to notice on the figure is a general increase of $\mu_0(B)$ with increasing $M_*$. Secondly, for galaxies with $M_* > 10^{10.75}$, the isocontours denoting constant $f_{\text{bar}}$ show a strong dependence on stellar mass, while almost no dependence on $\mu_0(B)$. For less massive galaxies, a co-dependence with $\mu_0(B)$ appears, with $f_{\text{bar}}$ decreasing with increasing central surface brightness. This kind of bimodality has already being detected, for instance Nair & Abraham (2010) showed that the bar fraction presents a minimum at $M_* \sim 10^{10.2}$, a bimodality which is also seen in the stellar population.

The fraction of barred galaxies is also sensitive to color, $f_{\text{bar}}$ being highest for red galaxies (Nair & Abraham 2010; Masters et al. 2011; Lee et al. 2012; Oh et al. 2012). Figure 5b shows that $f_{\text{bar}}$ depends exclusively on $u-r$ and is independent of $\mu_0(B)$ for red galaxies with $u-r > 2$, but for blue galaxies the dependence of $f_{\text{bar}}$ on $\mu_0(B)$ is noticeable, stressing the presence of the aforementioned bimodality.

Using samples of galaxies from the SDSS with H I gas mass estimates from ALFALFA (Giovanelli et al. 2005), Masters et al. (2012) and Cervantes Sodi (2017) showed the inhibiting effect gas has in the formation of bars. Using the H I mass estimate from Teimoorinia et al. (2017), we explore in Figure 5c the co-dependence of $f_{\text{bar}}$ on $\mu_0(B)$ and $M_{\text{HI}}/M_*$, finding that, for galaxies fainter than $\mu_0(B) = 21.0$ mag arcsec$^{-2}$, at fixed $M_{\text{HI}}/M_*$ there is almost no dependence on $\mu_0(B)$. This figure indicates that the dependence of $f_{\text{bar}}$ on the surface brightness of the galaxies is mostly driven by the correlation present between surface brightness and gas richness. In this
sense, given that LSBs are intrinsically gas-rich galaxies (Minchin et al. 2004; Pustilnik et al. 2011; Du et al. 2015), the low fraction of barred LSBs is at least partially driven by the inhibiting effect the gas has in the formation of bars (Masters et al. 2012; Cervantes Sodi 2017), which is more evident in LSBs than in HSBs given that they present a wider range of $M_{\text{HI}}/M_*$ values. Figure 5c also shows that for galaxies brighter than $\mu_0(B) = 21.0$ mag arcsec$^{-2}$, surface brightness may play a role in the likelihood of galaxies hosting bars, even for gas-rich systems.

Finally, Figure 5d shows a clear correlation between the $\lambda$ spin parameter and the gas mass fraction, as previously reported by Cervantes-Sodi & Hernández (2009); Huang et al. (2012). From the contours almost entirely perpendicular to the distribution of points in the plane, we can conclude that the dependence of $f_{\text{bar}}$ with $\lambda$ is as strong as the dependence of $f_{\text{bar}}$ with the gas fraction. Considering that at fixed $\lambda$ (Figure 4a) and $M_{\text{HI}}/M_*$ (Figure 5c), the bar fraction is independent of $\mu_0(B)$, we conclude that the dependence of $f_{\text{bar}}$ on $\mu_0(B)$ is driven by these other two co-dependences.

Given that we also count with bar length measurements from Hoyle et al. (2011), we explored the dependence of the bar length ($L_{\text{bar}}$), normalized to the optical size of the galaxy defined as two times the $r$–band Petrosian radius 90 ($2r_{p,90}$), on $\mu_0(B)$ (6 top panel), finding a clear trend of increasing bar size with increasing $\mu_0(B)$.

In Figure 5c we learned that the low fraction of
barred LSBs is mostly driven by the large gas mass fraction of this type of galaxies. Taking into account the results obtained through numerical experiments by Villa-Vargas et al. (2010) and Athanassoula et al. (2013), where bars are prevented to form in gas-rich galaxies, and in the cases where they are able to form, they form later and are weaker than in gas-poor galaxies, the increase of bar length with increasing surface brightness observed in Figure 6 top panel, could be due to the trend between $\mu_0(B)$ and $M_{\text{HI}}/M_*$, and not directly attributed to the the surface brightness. To disentangle this dependence of the bar length with $\mu_0(B)$ and $M_{\text{HI}}/M_*$, we turn to Figure 6 middle panel, where we show the normalized bar length as a function of $M_{\text{HI}}/M_*$ for the full sample (black solid line) as well as for the case of the sample segregated in HSBs and LSBs (purple and blue lines respectively). As expected, as we move from gas-poor to gas-rich systems, the bar length decreases for all cases, the full sample as well as for the HSBs and LSBs considered separately. Interestingly, at fixed gas-mass fraction, the HSBs have systematically longer bars than the LSBs, indicating that the bar length is not independent of surface brightness. We also explored the dependence of the bar length on $\lambda$ in Figure 6 lower panel, finding a steadily decrease of the bar length with increasing spin, with HSBs having again, systematically longer bars than their LSBs counterparts.

4. CONCLUSIONS

We compiled a large volume-limited sample of galaxies drawn from the SDSS-DR7, and studied the dependence of the bar fraction on the surface brightness of galaxies. We find that the fraction of galaxies hosting strong bars among LSBs ($\sim 20\%$) is systematically lower than the fraction found for HSBs ($\sim 30\%$), a natural consequence derived from the dependence of $f_{\text{bar}}$ with $\mu_0(B)$ found in the present work, with the fraction of barred galaxies increasing with increasing central surface brightness.

By exploring the co-dependence of the bar fraction with $\mu_0(B)$ and other physical parameters of the galaxies in the sample, such as stellar mass, color, and gas-to-stellar mass fraction, we conclude that the increase of $f_{\text{bar}}$ with increasing $\mu_0(B)$ is mostly driven by an anti-correlation of $\mu_0(B)$ with $\lambda$ and $M_{\text{HI}}/M_*$. In this sense, the low bar fraction of LSBs is primarily due to their H I gas-richness when compared with their HSBs counterparts, and the inhibiting effect the gas has in the formation of bars, as previously pointed out by numerous works (Masters et al. 2012; Cervantes Sodi 2017; Kim et al. 2017), plus the fact that LSBs are high spinning galaxies, making their disks more sparse and less self-gravitating, and hence less prone to global instabilities, a result in accordance with the previous result by CS+13.
While the presence of bars in galaxies seems to be fairly independent of the surface brightness of galaxies at a fixed \( M_{\text{HI}}/M_\star \), the bar length shows a stronger correlation with \( \mu_0(B) \) than with \( M_{\text{HI}}/M_\star \), and at fixed gas-to-stellar mass ratio, HSBs have systematically larger bars than LSBs, a trend in good agreement with the theoretical results by Mayer & Wadsley (2004), who found that the bars formed in simulated LSBs are shorter than the ones formed in HSBs and that these bars quickly evolve to pseudobulges. This correlation between the normalized bar length and \( \mu_0(B) \) is mostly driven by the anticorrelation between \( \mu_0(B) \) and \( \lambda \), with decreasing bar length with increasing \( \lambda \), showing only a minor dependence on \( \mu_0(B) \) at fixed \( \lambda \). Our result concerning the bar length goes in line with the findings by CS+13, who reports that weak bars are preferentially hosted by high spinning galaxies (LSBs), while strong bars are more commonly found in galaxies with low-to-intermediate values of \( \lambda \) (HSBs).

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