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Authors: Bing-Qing Zhang, Hong Wu, Wei Du, Pin-Song Zhao, Min He and Feng-Jie Lei

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Full Text

Preamble

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Low Surface Brightness Galaxies Selected by Different Model Fitting

Bing-Qing Zhang[1],[2], Hong Wu[1],[2],[3], Wei Du[1], Pin-Song Zhao[1], Min He[1], and Feng-Jie Lei[1]

[1] Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China; hwu@bao.ac.cn, bqzhang@bao.ac.cn
[2] School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, China

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Abstract

We present a study of low surface brightness galaxies (LSBGs) selected by fitting the images of all galaxies in the α.40 SDSS DR7 sample with two kinds of single-component models and two kinds of two-component models (disk+bulge): single exponential, single Sérsic, exponential+de Vaucouleurs (exp+deV), and exponential+Sérsic (exp+ser). Under the criteria of B-band disk central surface brightness $_{0}$,disk $>$ 22.5 mag arcsec^{-2} and axis ratio b/a $>$ 0.3, we selected four non-edge-on LSBG samples from each of the models which contain 1105, 1038, 207, and 75 galaxies, respectively. There are 756 galaxies in common between LSBGs selected by exponential and Sérsic models, corresponding to 68.42% of LSBGs selected by the exponential model and 72.83% of LSBGs selected by the Sérsic model; the rest of the discrepancy is due to the difference in obtaining $_{0}$ between the exponential and Sérsic models. Based on the fitting, in the range of 0.5 $\leq$ n $\leq$ 1.5, the relation of $_{0}$ from the two models can be written as MATH_0 . The LSBGs selected by disk+bulge models (LSBG_{2comps}) are more massive than LSBGs selected by single-component models (LSBG_{1comp}), and also show a larger disk component. Though the bulges in the majority of our LSBG_{2comps} are not prominent, more than 60% of our LSBG_{2comps} would not be selected if we adopt a single-component model only. We also identified 31 giant low surface brightness galaxies (gLSBGs) from LSBG_{2comps}. They are located in the same region in the color–magnitude diagram as other gLSBGs. After comparing different criteria for gLSBG selection, we find that for gas-rich LSBGs, M $> 10^{10}$ M is the

best criterion to distinguish between gLSBGs and normal LSBGs with bulge.

Key words: catalogs – galaxies: spiral – galaxies: bulges – methods: data analysis – methods: statistical

1. Introduction

Low surface brightness galaxies (LSBGs) are galaxies whose central surface brightness of the disk component is at least one magnitude fainter than the sky brightness (Impey & Bothun 1997). Studies show that LSBGs are under-evolved because they generally have sparse Hα emission (Pickering et al. 1997; Huang et al. 2014), low star formation rate (SFR), low SFR surface density (van der Hulst et al. 1993; Galaz et al. 2011; Lei et al. 2018, 2019), and low metallicity (McGaugh & Bothun 1994; Liang et al. 2010). They are rich in neutral hydrogen (H I) gas (de Blok et al. 1996; Burkholder et al. 2001; O'Neil 2004; Du et al. 2015), but have little CO molecules (O'Neil et al. 2003; Honey et al. 2018), indicating that they have low efficiency in converting H I gas to H_2 molecules (Cao et al. 2017).

LSBGs are mostly late-type disk-dominated galaxies (McGaugh & Bothun 1994; de Blok et al. 1995). O'Neil et al. (1997) show that around 80% of the galaxies in their LSBG sample are well-fitted by an exponential profile. As it is appropriate to fit LSBGs with a single disk model, many authors have done so (O'Neil et al. 1997; Du et al. 2015).

However, McGaugh et al. (1995b) claim that a small but significant subset of LSBGs has B/D 1 (bulge-to-disk ratio), and Pahwa & Saha (2018) show that about 40% of the galaxies in their LSBG sample have bulges. This kind of LSBG that has a bulge at its center will be lost if only a single disk model is adopted. Two approaches have arisen: one is to perform a bulge+disk decomposition to obtain the central surface brightness of the disk component (Pizzella et al. 2008; Pahwa & Saha 2018), and another is to use the average surface brightness within the effective radius (¯) instead of central surface brightness ($_0$) to reduce the effect of luminosity concentration in the galaxy center (Greco et al. 2018; Martin et al. 2019; Tanoglidis et al. 2021). The second approach cannot obtain detailed information about the disk component, motivating us to search for LSBGs with bulges using the bulge+disk decomposition method.

In another aspect, observational technology has improved and wide-field surveys have developed considerably in the last two decades, e.g., the Sloan Digital Sky Survey (SDSS; York et al. 2000), the Dark Energy Camera Legacy Survey (DECaLS; Dey et al. 2019), and the Arecibo Legacy Fast ALFA survey (ALFALFA; Giovanelli et al. 2005). People can dig deeper and wider in the sky, bringing more opportunities to search for LSBGs. For example, 12,282 LSBGs were selected from SDSS Data Release 4 (DR4) to study their stellar populations (Zhong et al. 2008) and metallicities (Liang et al. 2010); Galaz et al. (2011) also selected 9,421 LSBGs from SDSS DR4 to investigate their spatial distribution. The combination of optical images and H I spectra provides one of the best laboratories for studying gas-rich LSBGs. Haynes et al. (2011) provide a cross-reference catalog containing 12,468 galaxies from α.40 (40% sky area of the full ALFALFA) and SDSS Data Release 7 (DR7; Abazajian et al. 2009), and Du et al. (2015, hereafter Du15) developed a pipeline to re-estimate the sky background for 12,423 galaxies belonging to the PhotoPrimary catalog in the α.40 SDSS DR7 sample to avoid sky background overestimation by the SDSS photometric pipeline. Based on the background-resubtracted images, Du15 selected a non-edge-on LSBG sample of 1,129 galaxies using single exponential model fitting. This paper focuses on selecting LSBGs from different models and searching for LSBGs with bulges by applying the disk+bulge model.

The rest of the paper is arranged as follows. In Section 2, we describe our parent sample, model fitting, and the method of central surface brightness ($_0$) calculation. Section 3 shows our LSBG samples and their statistical properties. In Section 4, we discuss gLSBG selection. Finally, we summarize this paper in Section 5.

2.1. Parent Sample

Many researchers, including those in the SDSS team, noticed that the sky background in the SDSS imaging pipeline is overestimated (Adelman-McCarthy et al. 2006, 2008; Lauer et al. 2007; Liu et al. 2008; Hyde & Bernardi 2009; He et al. 2013), leading to galaxy brightness being underestimated. Because the central surface brightness of LSBGs is fainter than the sky background, the outer parts of LSBGs are even fainter. The inaccurate background will influence the photometry, model fitting, and LSBG selection.

Du15 carefully estimated the sky background of SDSS images in both g and r bands for 12,423 galaxies in the α.40 SDSS DR7 sample (Haynes et al. 2011). After their background subtraction, the count distributions for the whole image and the local vicinity, defined as the region between two square boxes sized 250 × 250 pixels and 500 × 500 pixels from the galaxy center, are both well fitted by a Gaussian profile with mean values very close to 0 ADU (see Figure 3 in Du15). We take the 12,423 galaxies as our parent sample in selecting LSBGs, taking advantage of their better analysis on sky subtraction.

We performed photometry for all galaxies in our parent sample using SExtractor software (Bertin & Arnouts 1996). A flexible elliptical aperture, the Kron aperture defined by Kron (1980), was used to obtain magnitude (MAG_{AUTO}). The apertures of g and r bands are the same, defined by the r-band image. The parameters from SExtractor, including magnitude, effective radius, axis ratio, and position angle, are used as the initial guess for model fitting.

2.2. Model Fitting

Galfit is a two-dimensional fitting algorithm to extract structural components of galaxies (Peng et al. 2002, 2010). It provides some of the most commonly used radial profiles in astronomical literature, e.g., exponential, Sérsic, de Vaucouleurs, Gaussian, Moffat, and PSF profiles. The exponential and de Vaucouleurs profiles are special cases of the Sérsic function when n = 1 and n = 4, respectively. Users can adopt a single profile or a combination of profiles, and set initial values for input parameters of each profile. During fitting, the reduced ^{2} is minimized, and the minimization engine is based on the Levenberg-Marquardt downhill gradient algorithm.

We carried out two kinds of single-component fitting and two kinds of two-component (disk+bulge) fitting: single exponential profile, single Sérsic profile, combination of exponential and de Vaucouleurs profile (hereafter exp+deV), and combination of exponential and Sérsic profile (hereafter exp+ser). Since most galaxies in our parent sample can be fully shown in 501 × 501 pixels, all fittings are performed in this region with the target located at the center to improve Galfit fitting efficiency. During fitting, a PSF image and mask image were used to obtain better results. The PSF images were derived from the SDSS website (http://das.sdss.org/imaging) to describe the local PSF profile surrounding the target, and the mask images were produced based on the segmentation image from SExtractor. We masked out other objects; only the background and target regions are fitted.

We also set limitations on the variable range of parameters to avoid unphysical fittings. For all models and subcomponents, the variable range of the galaxy center is $±$5 pixels in both horizontal and vertical directions. Based on the assumption that half of the diagonal size of our images (354 pixels) is exactly three times the R of the galaxy, we set the variable range of the effective radius (R) as $1 \leq R \leq 118$ pixels, i.e., $1 \leq R \leq 118$ for Sérsic and de Vaucouleurs profiles and $1 \leq 1.678 \times R \leq 118$ for the exponential profile, where R is the scale length. Here we use R for the exponential profile because the exponential profile provided by Galfit (Equation (1)) uses R , and there is a relation between R and R for the exponential profile, $R = 1.678 \times R$ (Peng et al. 2010, Equation (7)). For the Sérsic model, the variable range of the n index is 0.5 8.0, which is the same range as Simard et al. (2011). When $n < 0.5$, the luminosity density of the Sérsic profile has a depression in its center, which is often unphysical (see Trujillo et al. 2001, Figure 6 [Figure 6: see original paper]). For the exp+ser model, the variable range of the n index of the Sérsic component is 1.0 8.0; here we force the bulge component (Sérsic) to be more concentrated than the disk component (exponential) by applying a larger n value for the Sérsic profile than that for the exponential profile.

Note that all galaxies have been fitted with the exponential and Sérsic profiles, then 5,233 galaxies (42.12% of the parent sample) were selected to run the disk+bulge model fitting by eliminating 7,190 galaxies whose Sérsic n index satisfies $0.5 \leq n \leq 1.5$ for both g and r bands. This is because, for disk-dominated galaxies, forced application of a disk+bulge model would lead Galfit to fail to converge.

After fitting, we took the following steps to filter the fitting results:

1. Eliminate numerically unreasonable fittings. When numerical convergence issues occur during fitting, the entire solution is not reliable, and we remove the galaxy from further analysis. The galaxy is also removed if the output parameters reach the boundaries we set. In this step, for Sérsic and exp+ser models, most removed galaxies are because their fitted n index is at boundary values.
2. Eliminate fitting results whose structure parameters, such as axis ratio (b/a) and position angle (PA), are not consistent between the g and r bands. For b/a and PA, we calculate the difference for all galaxies and execute a 3σ clipping.
3. For disk+bulge fitting, galaxies are removed if their fitted effective radius of the disk component is smaller than that of the bulge component.

After these steps, we constructed four “well-fitted” samples containing 11,697, 10,582, 1,981, and 1,066 galaxies for exponential, Sérsic, exp+deV, and exp+ser model fitting, respectively. The galaxies in the “well-fitted” samples have good fitting results in both g and r bands and are used in the following analysis. The numbers of galaxies after each step are listed in Table 1 .

2.3. The Central Surface Brightness

In the following, we illustrate step-by-step the procedures for how we calculate $_0$ for the exponential profile and the Sérsic profile.

The expression of the exponential profile is:

$$I(r) = I_0 \exp\left(-\frac{r}{R_s}\right)$$

The flux integrated out to r = ∞ is:

$$F_{\text{total}} = \int_0^\infty I(r) \cdot 2\pi r \, dr = 2\pi I_0 R_s^2$$

where q is the axis ratio. So the central surface brightness can be expressed as:

$$\mu_0 = m + 2.5 \log_{10}(2\pi R_s^2 q)$$

Then, applying cosmological dimming correction and converting the unit of $_0$ to mag arcsec^{-2}, the central surface brightness is:

$$\mu_0 = m + 2.5 \log_{10}(2\pi R_s^2 q) + 10 \log_{10}(1 + z)$$

where m is the model magnitude, R is the disk scale length, and z is from the α.40 catalog.

For the Sérsic model, the function is:

$$I(r) = I_0 \exp\left[-\kappa\left(\frac{r}{R_e}\right)^{1/n}\right]$$

The flux integrated out to r = ∞ is:

$$F_{\text{total}} = \int_0^\infty I(r)\cdot 2\pi r\,dr = 2\pi I_0 R_e^2 n\kappa^{-2n}\Gamma(2n)$$

So the surface brightness at galaxy center ($_0$) is:

$$\mu_0 = m + 2.5\log_{10}\left(2\pi R_e^2 qn\kappa^{-2n}\Gamma(2n)\right)$$

where R is the effective radius, n is the Sérsic index,   is related to n index by   = 1.9992n − 0.3271 (Capaccioli 1989), and Γ function is Γ(2n) = (2n − 1)!.

Then, applying cosmological dimming correction and converting the unit of $_0$ to mag arcsec^{-2}, the central surface brightness is:

$$\mu_0 = m + 2.5\log_{10}\left(2\pi R_e^2 qn\kappa^{-2n}\Gamma(2n)\right) + 10\log_{10}(1+z)$$

Finally, the B-band central surface brightness can be transferred by an empirical equation (Smith et al. 2002):

$$\mu_{0,B} = \mu_{0,g} + 0.28 + 0.45(g-r)$$

Figure 1 [Figure 1: see original paper] shows how the difference in $_0$ between exponential and Sérsic fitting varies with Sérsic n index for galaxies that have 0.5 ≤ n ≤ 1.5 in both g and r bands. The red solid lines are the linear fitting of the points, which can be described as follows:

g band: MATH_1
r band: MATH_2

which are also written at the top of each panel. The expression can be simplified to:

$$\mu_{0,\text{Sérsic}} - \mu_{0,\text{exp}} = -2.5(n-1)$$

The relationship between $_0$ difference and n index distributes along a biconical shape, which is best when n = 1 and becomes worse with increase or decrease of n index. When n > 1, the $_0$ obtained from the Sérsic model is brighter than that from the exponential model, and when n < 1, $_0$ obtained from the Sérsic model is dimmer than that from the exponential model. The two models yield a $_0$ difference of up to approximately 0.7 mag arcsec^{-2}.

3. LSBG Samples

3.1. LSBG Selection

There has been no consensus on the threshold values of $_{0}$ to define LSBGs; different cuts are applied in the literature: 22.0 mag arcsec^{-2} (McGaugh et al. 1995a), 22.5 mag arcsec^{-2} (McGaugh 1996; Rosenbaum et al. 2009; Du15), 23.0 mag arcsec^{-2} (Impey & Bothun 1997); 20.8 mag arcsec^{-2} (Courteau 1996; Brown et al. 2001); 21.0 mag arcsec^{-2} (Pahwa & Saha 2018). In this paper, we adopt a threshold of $_{0}$,disk(B) $>$ 22.5 mag arcsec^{-2} and apply b/a $>$ 0.3 to avoid internal extinction effects (He et al. 2020).

With this selection criterion and subsequent visual inspection, we selected four LSBG samples from the "well-fitted sample" of each model: LSBG_{exp}, LSBG_sérsic, LSBG_{exp}+deV, and LSBG_{exp}+ser, containing 1,105 galaxies (9.45% of the "exponential" well-fitted sample), 1,038 galaxies (9.81% of the "Sérsic" well-fitted sample), 207 galaxies (10.45% of the "exp+deV" well-fitted sample), and 132 galaxies (12.38% of the "exp+ser" well-fitted sample). During visual inspection, fittings were deleted if the model was obviously influenced by neighbors or morphology. Considering our original intention to find LSBGs with bulge, we set a limitation on the n index of the bulge component of the "exp+ser" model n_b $>$ 1.5 to exclude some "disk+disk" fitting results, and there are 75 LSBGs satisfying this criterion in both g and r bands. The galaxy numbers of initial LSBG samples and final LSBG samples are listed in Table 1 . The table containing all parameters of our LSBGs (DOI: 10.57760/sciencedb.13130) is available in its entirety in machine-readable form in the Science Data Bank database; column descriptions are listed in Table 2 .

For LSBGs selected from two-component fitting, the two-component fitting is usually better than one-component fitting. Figure 2 [Figure 2: see original paper] shows an example of Galfit fitting results (AGCNr 248917) for our four models—exponential, Sérsic, exp+deV, and exp+ser—from top to bottom. This galaxy is selected as an LSBG by "exp+deV" and "exp+ser" models. The first image in the upper left panel shows the observed image, the second column shows the model images, the third column shows the residual images (observed image minus model image), and the fourth column shows the radial distribution of surface brightness obtained from a series of elliptical annuli on the observed image and models, with a step of 2 pixels. The pure disk image is also displayed in the bottom two rows of the first column using the observed image minus the bulge component. From the residual images of exponential and Sérsic fitting, it is obvious that there is a small bright spot in the galaxy center, and this small bright spot can be fitted well by exp+deV and exp+ser models.

3.2. Statistical Properties of LSBG Samples

Figure 3 [Figure 3: see original paper] shows the statistical properties of our four LSBG samples: panels (a) and (b) show the distribution of B-band central surface brightness ($_0$,disk(B)) and g-band effective radius (R ,disk(g)) of the disk component; panels (c)–(g) show the distribution of g − r color, g-band absolute magnitude (M_g), H I gas mass (M_{HI}), H I line width (W_{50}), and stellar mass (M) for the whole galaxy. The H I gas mass and W_{50} are from the α.40 catalog (Haynes et al. 2011). The stellar mass was calculated using the prescription in Du et al. (2020), where we compute mass-to-light ratio using the g − r color: log(M /L_g) = a_g + b_g(g − r) and log(M /L_r) = a_r + b_r(g − r), where a_g = −0.857, b_g = 1.558, a_r = −0.7, and b_r = 1.252. The absolute magnitude was calculated using the distance from the α.40 catalog by adopting H_0 = 70 km s^{-1} Mpc^{-1} (Haynes et al. 2011), and the absolute magnitude of the Sun is M_g, = 5.11 and M_r, = 4.65 (Willmer 2018). We list the median values of these parameters for our four LSBG samples in Table 3 . Table 4 lists the number statistics of overlapping galaxies that are selected as LSBGs in any two LSBG samples.

3.2.1. Comparison of LSBG_{exp} and LSBG_sérsic It is obvious that all parameters of LSBG_{exp} (gray filled histograms) and LSBG_sérsic (black steps) have very similar distributions, and the median values of these parameters are close. Figure 4 [Figure 4: see original paper] shows the distribution of n index for galaxies in LSBG_sérsic: 97.40% (1011/1038) of galaxies have 0.5 < n < 1.5 for g band and 91.62% (951/1038) for r band, indicating that our LSBGs selected by Sérsic fitting are in principle the same type of galaxies as those selected by exponential fitting. These two samples have 756 galaxies (68.42% of LSBG_{exp} and 72.83% of LSBG_sérsic) in common; the rest of the discrepancy is due to the difference in obtaining $_0$ between the two models as mentioned in Section 2.3. That is, the remaining galaxies have $_0$ brighter than 22.5 mag $arcsec^{-2}$ in one fitting result and dimmer than 22.5 mag $arcsec^{-2}$ in the other fitting result.

3.2.2. Comparison of LSBG_{exp}+deV and LSBG_{exp}+ser The distributions of all parameters of galaxies in LSBG_{exp}+deV (red steps) and LSBG_{exp}+ser (blue steps) are also similar, but these parameters of LSBG_{exp}+deV are slightly larger than those of LSBG_{exp}+ser. The median values of R ,disk, g-band stellar mass, H I mass, and W_{50} of LSBG_{2comps} are 3.8–4.1 kpc, 0.63–0.76 dex, 0.44–0.52 dex, and 30–50 km s^{-1} larger than those of LSBG_{1comp}, respectively, and the median value of g-band absolute magnitude of LSBG_{2comps} is about 1.5–1.7 mag brighter than that of LSBG_{1comp}. Compared to LSBG_{1comp}, the distributions of LSBG_{exp}+deV and LSBG_{exp}+ser have another peak at the red and massive (or bright) end; we point out these peaks in panels (c), (d), and (e) in Figure 3 [Figure 3: see original paper] with red arrows. Giant low surface brightness galaxies (gLSBGs) contribute significantly to this peak. However, the median value of g − r color distribution of LSBG_{2comps} is only 0.03–0.05 mag redder than that of LSBG_{1comp}, because the bulges are not prominent in the majority of our LSBG_{2comps}.

Fisher & Drory (2008) found that the Sérsic index of bulge can be used to distinguish between classical and pseudo bulges: classical bulges have n_b $\geq$ 2 and pseudo bulges have n_b $\leq$ 2 in V band with almost no overlap. Considering that g band has more similar wavelength coverage to V band than r band, we divide the bulges in the LSBG_{exp}+ser sample into classical and pseudo bulges according to their n index of bulge component (n_b) in g band. Of these 75 galaxies, 50 galaxies are classified as having classical bulges. Among the 50 LSBGs that host classical bulges, 24 are selected as LSBGs by "exp+deV" fitting. In the remaining 26 galaxies in LSBG_{exp}+ser, 25 are not in the "exp+deV" well-fitted sample, and only one galaxy (AGCNr 102234) is in the sample but not selected as an LSBG because it does not satisfy the b/a > 0.3 criterion. The reason why one model can obtain a fitting result but the other cannot is beyond the scope of this paper. Considering only galaxies for which both models can obtain good fitting results, almost all LSBGs with classical bulges selected by the "exp+ser" model can be selected by the "exp+deV" model.

3.2.3. Comparison of LSBGs Selected by One-component and Two-component Fitting For convenience, we call the galaxies in LSBG_{exp} and LSBG_sérsic "LSBG_{1comp}" (1,387 galaxies total), and the galaxies in LSBG_{exp}+deV and LSBG_{exp}+ser "LSBG_{2comps}" (247 galaxies total). There are 88 duplicate galaxies in LSBG_{1comp} and LSBG_{2comps}, suggesting that 15.98% (247/1546) of our LSBGs host a bulge. It should be noted that this fraction might be smaller than it actually is, since we perform two-component fitting only for galaxies with n > 1.5 in single Sérsic fitting; as a result, some galaxies with small bulges are missed.

Among the 88 overlapped galaxies of LSBG_{1comp} and LSBG_{2comps}, 96.59% (85/88) have B/T < 0.25, as shown by the blue histogram in Figure 7 Figure 7: see original paper, suggesting that the 88 overlapped LSBGs have small bulges and can be fitted well by a single-component model. The remaining 1,299 galaxies in LSBG_{1comp} can be considered as single disks without bulges. Even if they do contain a bulge, the B/T would be smaller than that of the overlaps.

The median values of R ,disk, g-band stellar mass, H I mass, and W_{50} of LSBG_{2comps} are 3.8–4.1 kpc, 0.63–0.76 dex, 0.44–0.52 dex, and 30–50 km s^{-1} larger than those of LSBG_{1comp}, respectively, and the median value of g-band absolute magnitude of LSBG_{2comps} is about 1.5–1.7 mag brighter than that of LSBG_{1comp}. Compared to LSBG_{1comp}, the distributions of LSBG_{exp}+deV and LSBG_{exp}+ser have another peak at the red and massive (or bright) end; we point out these peaks in panels (c), (d), and (e) in Figure 3 [Figure 3: see original paper] with red arrows. Giant low surface brightness galaxies (gLSBGs) contribute significantly to this peak. However, the median value of $g-r$ color distribution of LSBG_{2comps} is only 0.03–0.05 mag redder than that of LSBG_{1comp}, because the bulges are not prominent in the majority of our LSBG_{2comps}. The distribution of bulge-to-total ratio (B/T) shown in Figure 5 [Figure 5: see original paper] indicates that 82.61% (171/207) of galaxies in LSBG_{exp}+deV and 77.33% (58/75) in LSBG_{exp}+ser have B/T < 0.3.

Figure 6 [Figure 6: see original paper] shows the stellar mass distribution of our parent sample and galaxies fitted by two-component models. The histogram is normalized by its peak value. We can see that the galaxies selected for two-component fitting are indeed the more massive galaxies in the parent sample, and the fraction of selected galaxies in each mass bin increases with stellar mass. This suggests that the result we obtained—that the g-band stellar mass of LSBG_{2comps} is 0.63–0.76 dex larger than that of LSBG_{1comp}—is partly due to selection effect. However, we think part of the result reflects true differences between LSBG_{2comps} and LSBG_{1comp}: the disk component in “disk+bulge” LSBGs is larger than that in single-disk LSBGs (Figure 3(b)), and larger size often corresponds to larger mass. Moreover, the presence of a bulge also contributes to the stellar mass observed in LSBG_{2comps}.

3.2.4. Loss Fraction of LSBGs with Bulges Among our LSBG_{2comps}, about 35.63% (88/247) were also identified as LSBGs by single-component fitting (blue circles in Figure 7 [Figure 7: see original paper], denoted as “also LSBG_{1comp}”), 61.13% (151/247) were not identified as LSBGs by single-component fitting (red circles in Figure 7 [Figure 7: see original paper], denoted as “not LSBG_{1comp}”), and 3.24% (8/247) do not have good single-component fitting results because they were deleted in the second step of fitting results filtering (see Section 2.2). That is, more than 60% of LSBG_{2comps} would not be selected if we adopt a single disk model only. The $_0$,disk from two-component fitting is dimmer than that from single-component fitting, and the $_0$ difference is related to the B/T of the galaxy. 72.47% (179/247) of our LSBG_{2comps} have B/T ≤ 0.2, and in this range single-component fitting will overestimate $_0$ by approximately 0.8 mag arcsec^{-2}.

4. Giant Low Surface Brightness Galaxies

Giant low surface brightness galaxies (gLSBGs) are a subset of LSBGs. Compared with the Milky Way, they could have comparable or larger mass but several times the size of the Milky Way. One of the most well-known gLSBGs, Malin 1, was discovered by Bothun et al. (1987). Subsequent studies show Malin 1 has H I mass M_{HI} 10^{11} M (Bothun et al. 1987), disk central surface brightness $_0$,disk = 24.7 mag arcsec^{-2} (for h = 0.7; Moore & Parker 2006), and its optical diameter can reach 160 kpc (Galaz et al. 2015). UGC 1382 is also a very large gLSBG whose effective radius is 38 kpc (Hagen et al. 2016). However, gLSBGs with size comparable to Malin 1 and UGC 1382 are rare; most gLSBGs have scale lengths from a few kpc to dozens of kpc (McGaugh & Bothun 1994; Sprayberry et al. 1995; Honey et al. 2018; Saburova et al. 2023).

In Table 5 , we list different criteria used to select gLSBGs in previous works. In general, there are roughly three kinds of selection criteria. The first criterion proposed by Sprayberry et al. (1995) is the “diffuseness index”:

$$\mu_{0,B} + 5\log_{10}(hR_s) > 24.7$$

where the scale length is in units of h^{-1} kpc. The second is the mass criterion: Honey et al. (2018, hereafter H18) selected 41 gLSBGs from their spiral LSBGs with criteria M_{HI} $> 10^9$ M and M $> 10^{10}$ M ; O’Neil et al. (2023) adopted M_{HI} $\geq 10^{10}$ M to identify massive LSBGs. The third is the size criterion: Impey & Bothun (1997) claimed that gLSBGs have scale lengths in excess of 10 kpc; Saburova et al. (2023, hereafter S23) detected 42 gLSBGs with R_{iso},28B > 50 kpc or four times scale length 4R_s > 50 kpc.

This work uses these three kinds of criteria to select gLSBGs from our LSBG_{2comps}. Figure 8 [Figure 8: see original paper] shows that the $_0$ difference between B and g bands is 0.35 mag arcsec^{-2} in our sample, so we adopt $\log_{10}$(hR_s) > 1.356 and select a sample named “gLSBG_{diffuse}” containing seven gLSBGs from LSBG_{exp}+deV and eight gLSBGs from LSBG_{exp}+ser with two galaxies replicated. Following the mass criterion in H18, we select a sample named “gLSBG_{mass}” containing 27 gLSBGs from LSBG_{exp}+deV and seven gLSBGs from LSBG_{exp}+ser with three galaxies replicated. We also select a sample named “gLSBG_{size}” under the criterion R_s,g ≥ 10 kpc, containing three galaxies from LSBG_{exp}+deV and two gLSBGs from LSBG_{exp}+ser with no galaxies replicated. There are 39 non-repetitive gLSBGs in total, with detailed information listed in Table 6 , and SDSS color images shown in Figure 9 [Figure 9: see original paper].

Figure 10 [Figure 10: see original paper] shows the color–magnitude diagram of gLSBGs superimposed on kernel density estimation (KDE) of LSBG_{exp}+deV (light yellow) and LSBG_{exp}+ser (light blue). The gray triangles and gray crosses represent gLSBGs from H18 and S23, respectively. The gray dotted lines represent stellar masses of 10^9 M , $10^{9 \bullet 5}$ M , 10^{10} M , and $10^{10 \bullet 5}$ M . Different marker shapes represent gLSBGs selected from different criteria. Among our 39 non-repetitive gLSBGs, 31 lie on the right side of the 10^{10} M stellar mass line. 90.32% (28/31) of these 31 gLSBGs have Sérsic n index of the bulge component n_b > 2, indicating most of our gLSBGs host a classical bulge. These 31 gLSBGs are located in the same region as gLSBGs in H18 and S23, and they appear similar to the gLSBGs most people recognize—red in color and giant in luminosity, mass, and size.

There are eight galaxies on the left side of the 10^{10} M stellar mass line, and all these gLSBGs are selected by the “diffuseness index” criterion. They appear different from the gLSBGs most people know, more like normal LSBGs with bulge. This is because the dim $_0$,disk contributes significantly to the “diffuseness index”. The median value of $_0$,disk of these eight gLSBGs is 1.356 mag arcsec^{-2} dimmer than that of the 31 gLSBGs with stellar mass $> 10^{10}$ M . This is the drawback of the “diffuseness index” criterion. We eliminate these eight galaxies from our gLSBG sample. Our result suggests that for gas-rich LSBGs, M >

10^{10} M is a good criterion to distinguish between gLSBGs and normal LSBGs with bulge.

5. Summary

In this work, we carried out fitting of four models—exponential, Sérsic, exp+deV, and exp+ser—to check systematic effects in selecting LSBGs. Our parent sample is all galaxies in the α.40 SDSS DR7 sample, and the images we used are SDSS images after background re-estimation (Du15). We performed photometry and two-dimensional fitting for these images.

According to the criteria that B-band central surface brightness of the disk component $_{0}$,disk(B) $>$ 22.5 mag arcsec^{-2} and axis ratio of the disk component b/a $>$ 0.3, we selected 1,105, 1,038, 207, and 75 non-edge-on LSBGs from each model. Because our parent sample is rich in H I gas, most of our LSBGs are blue. The LSBGs selected by Sérsic fitting are in principle the same type of galaxies as those from exponential fitting. LSBG_{exp} and LSBG_sérsic have 756 galaxies (68.42% of LSBG_{exp} and 72.83% of LSBG_sérsic) in common; the rest of the discrepancy is due to the difference between exponential and Sérsic models in obtaining $_{0}$. When $0.5 \leq$ n ≤ 1.5, the relation of $_{0}$ obtained from Sérsic and exponential models can be written as $_{0}$,sérsic = $_{0}$,exp + 2.5(1 − n).

There are 1,546 non-repetitive LSBGs, and at least 15.89% of them host a bulge. The galaxies in LSBG_{2comps} have larger disks, luminosities, and masses than galaxies in LSBG_{1comp}. However, the bulges are not prominent in the majority of our LSBG_{2comps}. More than 60% of galaxies in LSBG_{2comps} would not be selected if we adopt a single disk model only. We also identified 31 non-repetitive gLSBGs, with 90.32% of them hosting a classical bulge. They are located in the same region in the color–magnitude diagram as normal gLSBGs in the literature.

Based on our gas-rich LSBGs, we find M $>$ 10^{10} M is a good criterion to distinguish between gLSBGs and normal LSBGs with bulge after comparing three kinds of criteria.

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Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences.

ORCID iDs

https://orcid.org/0000-0002-6659-1152 Bing-qing Zhang
https://orcid.org/0000-0002-4333-3994 Hong Wu
https://orcid.org/0000-0003-4546-8216 Wei Du
https://orcid.org/0000-0002-4328-538X Pin-song Zhao
https://orcid.org/0000-0001-6139-7660 Min He
https://orcid.org/0000-0003-0408-5497 Feng-jie Lei

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