Environment, morphology and stellar populations of bulgeless low surface brightness galaxies

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ABSTRACT

Based on the Sloan Digital Sky Survey DR 7, we investigate the environment, morphology and stellar population of bulgeless low surface brightness (LSB) galaxies in a volume-limited sample with redshift ranging from 0.024 to 0.04 and \( M_r \leq -18.8 \). The local density parameter \( \Sigma_c \) is used to trace their environments. We find that, for bulgeless galaxies, the surface brightness does not depend on the environment. The stellar populations are compared for bulgeless LSB galaxies in different environments and for bulgeless LSB galaxies with different morphologies. The stellar populations of LSB galaxies in low density regions are similar to those of LSB galaxies in high density regions. Irregular LSB galaxies have more young stars and are more metal-poor than regular LSB galaxies. These results suggest that the evolution of LSB galaxies may be driven by their dynamics including mergers rather than by their large scale environment.

Key words. Galaxies: kinematics and dynamics – Galaxies: evolution – Galaxies: formation – Galaxies: spiral – Galaxies: star formation

1. Introduction

Low surface brightness (LSB) galaxies usually refer to galaxies possessing an exponential disk with a face-on central surface brightness fainter than the ambient night sky. This type of galaxy has been widely discussed since Freeman (1970) found that 28 of 36 disk galaxies have central surface brightness in the range \( \mu_0(B) = 21.65 \pm 0.30 \) mag arcsec\(^{-2} \). Disney (1976) showed that this result is biased by a strong selection effect, which acts against the discovery of LSB galaxies. Thanks to improvements in telescopes and instruments, many works have been done to understand this kind of galaxy. Schombert & Bothun (1988) showed that LSB galaxies span a wide range, from dwarfs and irregulars to disk galaxies. Regardless of their morphology and size, all LSB galaxies have low star formation rates, low metallicities and extended HI gas disks (Impey & Bothun 1997). There is no conventional definition for LSB galaxies yet (Impey & Bothun 1997), although they have been intensively studied. The most common thresholds of \( \mu_0(B) \) for LSB galaxies found in the literature are between 22 and 23 mag arcsec\(^{-2} \) (McGaugh et al. 1995b, de Blok et al. 1995, Rosenbaum & Bomans 2004, Galaz et al. 2011). Since the definition of LSB galaxies only depends on the central surface brightness, more work needs to be done to understand whether LSB galaxies trace the formation/evolution of galaxies in a more representative manner than high surface brightness (HSB) galaxies, or if they just follow the trends of HSB galaxies. This is crucial for understanding the formation and evolution of galaxies.

The nature of the local and large-scale environment in which LSB galaxies are embedded has been analyzed by Bothun et al. (1993) and Mo et al. (1994). They found that LSB galaxies are located in more isolated environments compared to HSB galaxies. The deficiency of nearby companions for LSB galaxies was discovered by Zaritsky & Lorrimer (1993). Recently, based on the large amount of data released by the SDSS, the influence of environment on the evolution of LSB galaxies was further revealed. Using the Early Data Release of the SDSS, Rosenbaum & Bomans (2004) show significant differences in local density between LSB and HSB galaxies on scales from 2 to 5 Mpc. In their following analysis, Rosenbaum et al. (2009) compared LSB galaxies at 0.01<z<0.055 and at 0.055<z<0.1. The results suggested that LSB galaxies formed in a low-density region of the initial universe and have drifted to the outer parts of the filaments and walls of large-scale structures.

In addition to this issue, the origin of the LSB phenomenon is still unknown. Could LSB galaxies result from a similar formation scenario as HSB galaxies? Considerable progress has been done in understanding the formation of HSB disk galaxies. In examining the progenitors of the latter, Hammer et al. (2005) suggested that their disks have been rebuilt after a past collision of gas-rich mergers. This has been supported by the strong evolution of HSB disk morphologies revealed by Delgado-Serrano et al. (2010), showing that half of the disk progenitors were morphologically peculiar 6 Gyr ago. In fact, the combination of morphology and kinematics (Neichel et al. 2008, Hammer et al. 2009) convincingly demonstrated that a significant fraction
of present day disks were formed after being re-processed through a gas-rich major merger, in agreement with expectations from ΛCDM (Puech et al. 2012). This has been discussed by Kormendy et al. (2010) who claimed that most local disks do not have a classical bulge, implying that they could not be related to mergers. However, the question needs further clarifications because pseudo bulges or even bulgeless galaxies can be formed after very gas-rich mergers (e.g., Hammer et al. (2012); Keselman & Nusser (2012)).

As part of our series of works (Zhong et al. 2008 and Liang et al. 2010), that analyzed metallicities in LSB galaxies based on a large sample, we would like to analyze the environment, morphology and stellar populations of bulgeless LSB galaxies. Bulgeless galaxies have lower average surface brightness than galaxies with bulges (Sachdeva 2013). The simulations of Governato et al. (2010) show that strong outflows from star formation can drag dark and luminous matter with them to remove matter with low angular momentum and prevent the formation of a high-density core or bulge. This is supported by Walcher et al. (2005) who found massive star clusters at the cores of bulgeless galaxies. The analysis of central star formation in relation to the environment and dynamics may be helpful for understanding the evolution of bulgeless LSB galaxies. When analyzing stellar populations using SDSS spectra, the selection of bulgeless LSB galaxies has the advantage that most of the light covered by the SDSS fiber will sample the properties of central disks without contaminations from the bulge light. Several studies have found that LSB galaxies are dominated by bulgeless galaxies. McGaugh et al. (1995b) analyzed the images of 22 LSB galaxies and found that most of them show B/D < 0.1. O’Neil et al. (1997) analyzed the morphology of 127 LSB galaxies and found that the majority of them (80%) were well fitted by a single exponential profile. This implies that studying a large sample of bulgeless LSB galaxies may significantly help in general to understand the properties of LSB galaxies.

Our bulgeless LSB galaxies are selected from the nearby universe. The local densities are calculated to see in what kinds of environment bulgeless LSB galaxies are located. Their stellar populations will be analyzed to see which factor, environment or dynamics, drives the evolution of bulgeless LSB galaxies. This paper is organized as follows. In Section 2, we describe the selection of our samples. The relations between surface brightness of bulgeless galaxies and their environment are investigated in section 3. In Section 4, we analyze the stellar populations of bulgeless LSB galaxies and see whether their evolution is driven by their environment or by their morphological behavior. Finally, we discuss our results and summarize our conclusions in Sections 5 & 6 respectively. Throughout the paper, a cosmological model with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$ and $\Omega_{\Lambda} = 0.7$ has been adopted.

2. The sample

2.1. Volume-limited bulgeless sample

The bulgeless LSB galaxies analyzed in this work are obtained from the main-galaxy sample of SDSS Data Release 7 (York et al. 2006; Stoughton et al. 2002; Strauss et al. 2002; Abazajian et al. 2009). The SDSS is the most ambitious astronomical survey ever undertaken in imaging and spectroscopy and targets hundreds of thousands of galaxies. The imaging data, which are obtained in drift scan mode and have covered more than $10^4$ deg$^2$ until now, are 95% complete for point sources at magnitudes of 22.0 22.2 22.2 21.3 and 20.5 in five bands ($ugriz$), respectively. Our samples are selected following the criteria below:

1. We construct a volume-limited sample to investigate the environments and analyze the stellar populations. A volume-limited sample eliminates the luminosity bias in the SDSS database. The redshift range of this sample is $0.024<z<0.04$ and the corresponding absolute magnitude limit is $M_r \leq -18.8$. The lower redshift limit avoids effects from proper motions, which are not negligible in the nearby universe. The upper redshift limit is set to include as many faint galaxies as possible when studying the environment. In Figure 1 we show the limits of our volume-limited sample (sample $S_0$), which is surrounded by the black dashed line.

2. Bulgeless galaxies are selected from this volume-limited sample. Strictly, decomposition is a good method to estimate the fraction of bulge light and disk light in one galaxy. Here we use the parameter $fracDeV_{c}$, which is provided by the SDSS database, to select bulgeless galaxies. However, $fracDeV$ is an qualitative indicator of the existence of a bulge and it cannot be used to represent the fraction of the bulge light quantitatively. Considering the definition of $fracDeV$ only for the case of $fracDeV=0$, it corresponds to a pure disk galaxy without a bulge. So, we choose galaxies with $fracDeV_{c} >0.04$ and have covered more than $10^4$ deg$^2$ until now, are 95% complete for point sources at magnitudes of 22.0 22.2 22.2 21.3 and 20.5 in five bands ($ugriz$), respectively. Our samples are selected following the criteria below:

$fracDeV_{c} = \frac{fracDeV}{1 - fracDeV}F_{exp}$

Table 1. Number of galaxies in the different samples.

| Sample   | Number | Description          |
|----------|--------|----------------------|
| $S_0$    | 31674  | Volume-limited sample|
| $S_1$    | 2606   | Bulgeless volume-limited sample |
| $S_{LSB}$| 1235   | bulgeless LSB galaxies |
| $S_{HSB}$| 1371   | bulgeless HSB galaxies |

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$fracDeV_{c} = \frac{fracDeV}{1 - fracDeV}F_{exp}$
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0.025 0.03 0.035 0.04

0

100

200

300

Fig. 2. The histogram distribution of redshifts for LSB (blue, sample $S_{\text{LSB}}$) and HSB (red, sample $S_{\text{HSB}}$) galaxies and their fraction of the whole sample as a function of redshift. The black solid line denotes the expected number histogram of a complete volume-limited sample.

0 2 4 6 8 10

18

20

22

24

26

Fig. 3. The relation between scale length and surface brightness for sample $S_1$. The dashed line classifies the sample into LSB galaxies and HSB galaxies, and the solid line corresponds to the luminosity cut.

2.2. Low surface brightness sample

The next step, after the selection of a volume-limited sample, is to calculate the surface brightness and classify the whole sample into LSB galaxies and HSB galaxies. For pure disk galaxies, the profile shape is assumed to be exponential:

$$\Sigma(r) = \Sigma_0 \exp\left(-\frac{r}{\alpha}\right)$$

(1)

where $\Sigma_0$ is the central surface brightness of the disk in units of $M_\odot$ pc$^{-2}$ and $\alpha$ is the scale length of the disk. In logarithmic units, the exponential profile is

$$\mu(r) = \mu_0 + 1.086 \left(\frac{r}{\alpha}\right)$$

(2)

where $\mu_0$ is the central surface brightness in mag arcsec$^{-2}$ (McGaugh et al. 1995a). The total flux is

$$F_{\text{tot}} = 2\pi\alpha^2\Sigma_0$$

(3)

if the disk is assumed to be infinitely thin. By including the correction of extinction and cosmological dimming effect (Phillipps et al. 1990), we get the general formula to calculate central surface brightness:

$$\mu_0(m) = m_{\text{disk}} + 2.5\log(2\pi\alpha^2) + \mathcal{E}(b/a) - 10\log(1+z)$$

(4)

where $m_{\text{disk}}$ refers to the apparent magnitude of the disk, $\mathcal{E}(b/a)$ denotes extinction related to the inclination and $z$ is the redshift. Our sample consists of bulgeless galaxies, so the total apparent magnitude of galaxies is denoted as $m_{\text{disk}}$. For galaxies with $b/a>0.5$, extinction related to the inclination cannot be distinguished from intrinsic extinction. Hence we limit our sample to $b/a>0.5$ to avoid any bias.

Therefore, we selected a bulgeless ($\frac{\text{fracDeV}_r}{\text{r}}=0$) and low inclination ($b/a>0.5$) volume-limited (0.024 < $z$ < 0.04, $M_r \leq -18.8$) sample from SDSS DR7 to investigate the environment and stellar populations of LSB galaxies. The number of galaxies selected from the different criteria are list in Table 1.
not an ideal definition, because Freeman's sample was not complete. McGaugh et al. (1995a) (see their Fig. 3) and O'Neil & Bothun (2000) (see their Fig. 2) estimated the distribution of surface brightness in more complete samples. For galaxies with $\mu_0(B)<21.65$ mag arcsec$^{-2}$, their space densities become lower when $\mu_0(B)$ decreases. For galaxies with $\mu_0(B)>21.65$ mag arcsec$^{-2}$, their space densities are almost constant up to $\mu_0(B)=25$ mag arcsec$^{-2}$. In this work, using the same definition as de Blok et al. (1995), Morishita-Esslinger et al. (1999) and Rosenbaum & Bomans (2004), we define LSB galaxies as $\mu_0(B)>22.5$ mag arcsec$^{-2}$ and get 1235 LSB galaxies (sample $S_{l,SB}$, see Table 1). This definition is $3\sigma$ fainter than the median value of the Freeman law (21.65 mag arcsec$^{-2}$). For the rest, i.e. 1371 galaxies with $\mu_0(B)<22.5$ mag arcsec$^{-2}$, we define them as HSB galaxies (sample $S_{h,B}$). But we should note that the HSB galaxies defined that way are not all high surface brightness galaxies, since some LSB galaxies could be part of them if one follows the classical definition of $1\sigma$ below 21.65 mag arcsec$^{-2}$. However, this does not affect our results when we analyze the dependence between surface brightness and environment by dividing these bulgeless galaxies into two parts.

### 2.3. Selection effects

Since we select bulgeless LSB galaxies in a volume-limited sample, the possible selection effects of our sample need to be checked. We use $fracDeV r=0$ to define bulgeless LSB galaxies, so some bulgeless LSB galaxies with $fracDeV r>0$ might still be excluded from our sample. Unfortunately, we have not found a complete sample of LSB galaxies with the same selection criteria as our sample with which we can compare. Disseau et al. (2015, in preparation) selected a representative sample of 150 galaxies from a volume-limited sample with $0.022<z<0.033$ and $M_r \leq -18$. Although this sample was not selected in exactly the same way, we use it to roughly estimate the selection bias. In order to remove the extinction bias, they selected 68 low inclination galaxies with $b/a > 0.5$. Using bulge-disk decomposition, they calculate the surface brightness and finally obtained 11 low inclination LSB galaxies by defining $\mu_0(r)>21.7$ mag arcsec$^{-2}$. The fraction of LSB galaxies in their volume-limited sample is $16.6\pm4.9\%$. In our work, we obtain 1235 bulgeless LSB galaxies in the volume-limited sample of 31674 galaxies (which contains 13731 low inclination galaxies). The fraction of bulgeless LSB galaxies is $9.0\pm0.2\%$. Compared with these two samples, the fraction of LSB galaxies only differs by $\sim1.5\sigma$, indicating that perhaps we may have lost $\sim40\%$ of bulgeless LSB galaxies by using the $fracDeV r=0$ criterion.

Figure 3 shows the histogram distribution of redshifts for LSB and HSB galaxies in sample $S_1$ and their fraction of the whole sample as a function of redshift. In the left panel, one can see that the number in our sample grows as $z^2$. This is in line with volume geometry at extremely low redshift. In the right panel, one can see that the fraction of LSB and HSB galaxies in each bin is almost identical, although only bulgeless galaxies are selected here. These two figures suggest that the selection of bulgeless galaxies does not introduce any significant bias into the distribution of LSB and HSB galaxies. Figure 4 shows the relation between scale length and surface brightness for sample $S_1$. The dashed line classifies the sample into LSB galaxies and HSB galaxies. Most galaxies with surface brightness larger than 24 mag arcsec$^{-2}$ are not included in this sample. This is probably due to the effective isophotal limit of the SDSS. Very diffuse galaxies below the detection limit cannot be identified. In Figure 3 we also show a line corresponding to the luminosity cut for a mean profile.

### 3. The environments of LSB and HSB galaxies

The local density parameter $\Sigma_5$ (Rosenbaum & Bomans 2004, Silverman et al. 2008, Padilla et al. 2010, Galaz et al. 2011) is used to estimate the density of the local environment. To obtain this parameter, we need to calculate the projected distance from an individual sample galaxy to the 5th nearest neighbor galaxy. During this step, the galaxies in volume-limited main-galaxy sample of SDSS DR7 (sample $S_0$), of which the K-corrected absolute magnitude are brighter than $-18.8$ (i.e. $M_r \leq -18.8$), are used as the tracers to count the Nth nearest neighbor. The selection of tracers is consistent with that of LSB and HSB sample galaxies in terms of limiting the absolute magnitude and will help to eliminate the luminosity bias. Here we would like to note that, for the tracers, we do not constrain the $fracDeV r$ and $b/a$. This means that not only the disk galaxies but also the galaxies with a bulge or elliptical galaxies are also included in this tracer-sample. The information about the environment of one certain galaxy should include all types of neighboring galaxies, as all of them will influence the formation and evolution of the target-galaxies.

After the tracers are constructed, we are able to calculate the projected distance to the Nth nearest neighbor galaxies and then compute the local density parameter $\Sigma_5$. We define the Nth nearest neighbor within a velocity shell of $\pm500$ km s$^{-1}$ and count the nearest neighbor from the first one to the fifth one. Then we get the projected distance of the fifth nearest neighbor $d_5$ in the unit of Mpc, and define the local density by:

$$\Sigma_5 = 5/\left(\pi d_5^2\right)$$

in the unit of Mpc$^{-2}$.

Whether the local density parameter $\Sigma_5$ can represent realistic environments of LSB and HSB galaxies needs to be investigated. We cross-correlate our volume-limited sample with the volume-limited galaxy group and clusters catalogues provided by Tempel et al. (2011). They used a modified friends-of-friends method with a variable linking length (LL) to identify the realistic groups/clusters with SDSS data release 10. For each galaxy, all neighbors within the LL radius are regarded as belonging to the same system. Their Vol-lim-18.0 catalogue, of which the r-band absolute magnitude limit is $-18.0$ and the LL radius is 0.38 Mpc, is consistent with the selection of our samples. We use objID to make the cross-correlation between their Vol-lim-18.0 catalogue and our samples, and the parameter $N_{gal}$ is recovered. $N_{gal}$ denotes the richness (number of members) of groups/clusters to which the individual galaxy belongs and is a useful parameter to reflect the realistic environment where LSB galaxies are located. Figure 4 shows the relation between log($N_{gal}$) and log($\Sigma_5$) for LSB galaxies (blue triangles) and HSB galaxies (red squares). The black dots give the median of log($\Sigma_5$) for each log($N_{gal}$) and the error bars show the dispersions. We can see that log($\Sigma_5$) increases when log($N_{gal}$) becomes large. This relation is very clear.
The relation between $\log(N_{\text{gal}})$ and $\log(\Sigma_5)$ for LSB galaxies (left panel, blue triangles) and HSB galaxies (right panel, red squares). The black dots give the median of $\log(\Sigma_5)$ for each $\log(N_{\text{gal}})$ and the error bars show the dispersions.

The histogram distributions of $\log(\Sigma_5)$ for LSB galaxies (blue solid line) and HSB galaxies (red dashed line) are nearly the same, suggesting the surface brightness of bulgeless galaxies does not depend on the environment.

4. The Stellar Populations

In this section, we study the stellar populations of LSB galaxies and see which factors, environment or dynamics, drive their evolution.

4.1. Spectral synthesis analysis

In order to investigate the evolution of LSB galaxies, we would like to analyze their stellar populations by fitting the full optical spectra using spectral synthesis. Spectral synthesis provides an efficient way to retrieve information about stellar populations of galaxies from observed spectra, which is very important for understanding the formation and evolution of galaxies. The information on both age and metallicity distributions of stars contained in galaxy spectra can reflect the star formation and chemical histories of LSB galaxies. Here we analyze the stellar populations of LSB galaxies to see which factor, environment or dynamics, affects their evolution.

We fit the absorption lines and continua of the spectrum of every individual galaxy using the software STARLIGHT (Cid Fernandes et al. 2005, 2007). This software fits an observed spectrum $O_\lambda$ with a model $M_\lambda$ that adds up $N$ Simple Stellar Populations (SSPs) with different ages and metallicities taken from Bruzual & Charlot (2003) (BC03). In our analysis, we take 24 SSPs, including 12 different ages from 40 Myr to 13 Gyr (40, 280, 900 Myr and 1.27, 1.43, 2.5, 4.25, 5, 6.25, 7.5, 10, 13 Gyr) and two metallicities (0.2 and 1.0 $Z_{\odot}$), the stellar evolutionary tracks of Padova 1994 (Alongi et al. 1993; Girardi et al. 1996), the initial mass function (IMF) from Chabrier (2003) and the extinction law of Cardelli et al. (1989) with $R_V = 3.1$. The Galactic extinctions are corrected by the reddening map of Schlegel et al. (1998) and the spectra are shifted to the rest frame. The range of the spectra is from 3700 to 8000Å with a step of 1Å and normalized to the median flux in the 4010 to 4060Å region. During spectral synthesis fitting, we exclude the emission lines and four windows (5870-5905 Å, to avoid the NaD$\lambda\lambda5890, 5896$ doublet, which is from the interstellar medium; 6845-6945 Å and 7550-7725 Å, which are the strong absorption bands from the Earth’s atmosphere and were flagged by BC03 as issues in the STELIB library (Le Borgne et al. 2003); 7165-7210Å, which shows a systematic broad residual in emission as mentioned by Mateus et al. (2006)), see also Chen et al. (2009, 2010).

As discussed in Cid Fernandes et al. (2005), the individual components of stellar populations are fluctuant, but the combined stellar populations are robust enough. We need to
combine the individual stellar population into young population (<1 Gyr), intermediate-age population (1 ∼ 5 Gyr) and old population (≥5 Gyr). When doing the spectral synthesis, we fit every spectrum 30 times with different random seed to get a robust result and estimate the associated uncertainty. For every individual galaxy, we take the median value of these 30 fitting results as a robust result and the standard deviation as the uncertainty. The typical value of the relative uncertainty of mass fraction in our sample is 13%, 21% and 30% for young, intermediate-age and old stellar populations, respectively.

4.2. Stellar population of LSB galaxies in different environments

Figure 6 shows the histogram distributions of young, intermediate-age and old stellar populations for LSB galaxies located in a low density region (log(Σ5)<0.5) and a high density region (log(Σ5)>0.5). Isolated LSB galaxies are defined with log(Σ5)<-0.4.

Fig. 6. The histogram distributions of young, intermediate-age and old stellar populations for LSB galaxies located in a low density region (log(Σ5)<0.5) and a high density region (log(Σ5)>0.5). Isolated LSB galaxies are defined with log(Σ5)<-0.4.

Figure 7 shows the histogram distributions of metal-poor stellar populations for LSB galaxies located in a low density region (log(Σ5)<0.5) and a high density region (log(Σ5)>0.5). Isolated LSB galaxies are defined with log(Σ5)<-0.4.

Fig. 7. The histogram distributions of metal-poor stellar populations for LSB galaxies located in a low density region (log(Σ5)<0.5) and a high density region (log(Σ5)>0.5). Isolated LSB galaxies are defined with log(Σ5)<-0.4.

LSB galaxies exhibit a wide range of morphologies from dwarf irregular to luminous disk (McGaugh et al. 1995b). Like LSB galaxies in different environments, whether the stellar populations of LSB galaxies with different morphologies are similar or not is an important issue to investigate. To make this clear, we would like to compare the stellar population of LSB galaxies which have different morphologies.

4.3. Stellar population of LSB galaxies with different morphologies

Morphological classification of LSB galaxies has been done by visual inspection of galaxy images from the SDSS. The whole LSB sample is classified into two groups: regular LSB galaxies and irregular LSB galaxies. Most LSB galaxies can be classified well, except some very small ones because of the spatial resolution. The classification has been done
Fig. 8. The histogram distributions of young, intermediate-age and old stellar populations for regular LSB galaxies and irregular LSB galaxies. Notice that regular LSB galaxies have almost no young stellar component compared to morphologically peculiar LSB galaxies that spread over significant fractions.

Table 2. Median value of different stellar populations

| Age            | Young | Intermediate | Old  | Metallicity |
|----------------|-------|--------------|------|-------------|
|                |       |              |      | Poor        |
| Isolated LSB   | 3.3%  | 55.5%        | 38.3%| 74.9%       |
| LSB in Low Density | 3.2%  | 55.9%        | 37.5%| 73.9%       |
| LSB in High Density | 2.2%  | 53.6%        | 42.2%| 68.2%       |
| Irregular LSB   | 12.9% | 60.1%        | 11.0%| 88.6%       |
| Regular LSB     | 2.7%  | 55.1%        | 40.5%| 71.0%       |

Fig. 9. The histogram distributions of metal-poor stellar populations for regular LSB galaxies and irregular LSB galaxies.

by XS and FH and some examples of irregular galaxies are shown at the end of the paper (Figure 12 and Figure 13). The major difficulty is to distinguish Irr from SBm (very late type galaxies) and this is certainly the main uncertainty in this visual classification.

Figure 8 shows the histogram distributions of metal-poor stellar populations for regular and irregular LSB galaxies. Regular LSB galaxies have less metal-poor stellar populations than irregular LSB galaxies. These results suggest that irregular LSB galaxies formed more stars than regular LSB galaxies at recent epochs. The increase of metallicity in regular LSB galaxies may go faster than in irregular LSB galaxies.

5. Discussion

5.1. Differences of environment between LSB and HSB galaxies

In the above analysis, we found that the surface brightness of bulgeless galaxies does not depend on the environment. We notice that this appears to be different from previous studies. Bothun et al. (1993) and Mo et al. (1994) found that LSB galaxies are located in more isolated environments than HSB galaxies. The differences are probably due to the different selection criteria. They selected not only bulgeless galaxies but also galaxies with bulges, but we only select bulgeless galaxies. However, only selecting bulgeless LSB and HSB galaxies, which are late type galaxies, should not bring significant bias when comparing their environments. Indeed, massive galaxies are located in higher density regions and have higher B/T than low mass galaxies (Hammer et al. 2005). This suggests that galaxies with high B/T may be located in high density regions. Considering the large fraction of HSB galaxies with bulges, which may make them have higher average density than LSB galaxies, previous works may have bias when comparing their environment by selecting galaxies with bulges.

5.2. Aperture effect in spectral synthesis

As is well known, SDSS is a fiber-based survey. The spectra of objects are taken by fibers with diameters of 3 arcsec. When extended sources are analyzed, such as nearby galaxies, there are aperture effects. Tremonti et al. (2004) and Kewley et al. (2003) have discussed the aperture effects of SDSS spectroscopy in detail. In order to check how much
light is covered by SDSS observation, one simple and accurate way is to compare the fiber magnitude and Petrosian magnitude of our samples. The fiber magnitude is a measurement of the light falling into the fiber and the Petrosian magnitude is a good estimate of the total light. Thus, we adopt the formula below (Hopkins et al. 2003) to estimate how much light is covered by fiber observations:

\[
f_{\text{light}} = 10^{-0.4(m_{\text{fiber}} - m_{\text{petro}})}
\]

The typical value of \( f_{\text{light}} \) is \( \sim 0.08 \), indicating that the light of the spectra comes from the inner regions of galaxies.

Generally there are age and/or metallicity gradients in LSB galaxies (de Jong 1996; Bell et al. 2000). Inner regions have old and metal-rich stellar populations, while young and metal-poor stellar populations dominate outer regions. Therefore, our estimations of the stellar populations represent the properties of the central regions. The whole disk of LSB galaxies could be younger and more metal-poor than central regions. On the other hand, our samples consist of bulgeless galaxies and the spectra sample only the central part of the disks. So, our results represent the properties of central disks well without contaminations from bulge light.

In order to check whether the above results are biased by different aperture effects, we show the histogram distributions of \( f_{\text{light}} \) for different LSB galaxies in Figure 10. We can see that, for LSB galaxies in different environments or with different morphologies, the distributions are nearly the same, suggesting our results are not biased by different aperture effects and are robust enough.

5.3. The origin of star formation in irregular LSB galaxies

Table 2 shows the median values of different stellar populations for irregular LSB galaxies and regular LSB galaxies. Irregular LSB galaxies have more young and metal-poor stellar populations in the center than regular LSB galaxies. Because of the degeneracy between age and metallicity, it is difficult to analyze the star formation histories in detail using these results. But for a young stellar population with poor metallicity, there is no degeneracy. Generally the central region of disk galaxies has old and metal-rich stellar populations, and the outer region has young and metal-poor stellar populations (de Jong 1996; Bell et al. 2000). It is interesting that the irregular LSB galaxies have such a high fraction of young stars (<1Gyr) in their central regions. What kind of mechanisms can make young stars appear in the center of irregular LSB galaxies?

The detection of young stars suggests that the central regions of irregular LSB galaxies may experience recent star formation episodes, which result in the so-called clumps. What drives the formation of clumps has been widely studied. By analyzing the kinematics of clumpy galaxies at \( z \sim 0.6 \) (Puech 2010) suggests that cold flows are expected to feed \( z>1 \) clumpy galaxies, while mergers are probably the dominant driver leading to the formation of clumpy galaxies at \( z<1 \). For our sample with redshifts ranging from 0.024 to 0.04, mergers may be one of the reasons for the appearance of irregularities and central star formations.

Figure 11 shows the histogram distributions of stellar masses for regular and irregular LSB galaxies. The red and blue dot-dashed lines denote the mass-completeness limits of regular and irregular LSB galaxies, respectively.

\[\text{Fig. 10. The histogram distributions of light fraction for different LSB galaxies.}\]

\[\text{Fig. 11. The histogram distributions of stellar mass for regular LSB galaxies and irregular LSB galaxies. The red and blue dot-dashed lines denote the mass-completeness limits of regular and irregular LSB galaxies, respectively.}\]
fits to the photometry. Irregular, star forming galaxies have lower stellar mass than others. This is probably due to the different mass-to-light ratios (M/L) of these two subsamples. Such variations have been really presented when we found the differences in the fraction of young stars. In order to estimate this incompleteness, we determine the mean stellar mass of the galaxies which are located very near the luminosity cut (between -19 and -18.8) and consider that as a mass-completeness limit. In Figure 11 the dot-dashed lines give the mass-completeness limits of irregular and regular LSB galaxies, which are 9.0 and 9.25, respectively. The LSB galaxies with stellar mass higher than these limits are considered to be complete in stellar mass. We focus in the following on irregular LSB galaxies with log$M_\odot$ > 9.5 (to compare to the regular ones) as well as the irregular ones with log$M_\odot$ < 9.0.

For massive LSB galaxies (log$M_\odot$ > 9.5), normally it is difficult for the gas to fall into the center and form stars. One possible mechanism to form young stars in the central region is through a gas-rich merger that could transport gas from the outskirts of the galaxy into the center [Hammer et al. 2001; Rodrigues et al. 2008, 2012]. For more than half of irregular LSB galaxies in Figure 12, we see a merger happening within them when checking their images. For the irregular LSB galaxies with log$M_\odot$ > 9.5 in our sample, we also find seven with bars appearing in the center, a phenomenon that can be enhanced by merging in peculiar galaxies. The presence of a bar is believed to be an efficient way to drive gas towards the central region of a galaxy [Norman et al. 1996], which may trigger strong star formation [Haan et al. 2009]. McConnachie (2012) reviewed nearly 100 nearby dwarf galaxies and found that most of them have stellar mass less than 10^9$M_\odot$. When checking the images of irregular LSB galaxies with log$M_\odot$ < 9.0 in Figure 13 we find that most of them are dwarf irregulars (dIrrs). Several studies have revealed that recent star formation in dIrrs takes place at their center [Wilcots & Miller 1998; Miller et al. 2001; Garcia et al. 2009; Liouon & Cole 2013; Fouquet et al. 2013]. These star formation episodes might be triggered by the collapse of high density gas. Indeed [Momany et al. 2005] found that young stars are located near regions with high HI column density in the Sagittarius dwarf irregular galaxy. There is still the possibility that the low-mass irregular LSB galaxies are tidal dwarf galaxies (TDGs), which can form young stars in their center [Hammer et al. 2013; Fouquet et al. 2015]. For irregular LSB galaxies with 9.0 < log$M_\odot$ < 9.5, the situation is more complicated. Kinematics need to be done in detail to see why they have a large fraction of young stars in their central region.

From this quite crude analysis in absence of support from kinematics, it seems that LSB galaxies share most of their properties with HSB galaxies. Mostly depending on their masses, the star formation history of the most massive ones are affected by past mergers, while the least massive ones are gradually more affected by stellar phenomena (e.g., outflows) and minor mergers.

6. Conclusion

The environments in which bulgeless LSB galaxies and bulgeless HSB galaxies are located are compared and the stellar populations of bulgeless LSB galaxies are investigated in this work. We selected a large sample of 1235 bulgeless low inclination LSB galaxies in a volume-limited sample with redshifts ranging from 0.024 to 0.04 and M_r ≤ −18.8. The local density parameter $\Sigma_V$ is calculated to trace their environment. This parameter gives a hint as to how far the nearest neighbours are away from the galaxy, but it does not provide any insight into what interactive histories the galaxies might have had. For bulgeless galaxies, we find that their surface brightness does not depend on the environment. Compared with previous studies, only selecting bulgeless galaxies avoids significant bias when comparing their environments.

The stellar populations of bulgeless LSB galaxies in low density regions are similar to those of bulgeless LSB galaxies in high density regions, suggesting the environment may play a less important role in the evolution of bulgeless LSB galaxies. On the other hand, bulgeless LSB galaxies with different morphologies have significant differences in the stellar populations. Different dynamic situations make irregular LSB galaxies have more young stars in the center than regular LSB galaxies. These results suggest that the dynamics and mergers for at least the more massive ones may play a dominant role in the evolution of LSB galaxies rather than environment.

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Fig. 12. The images of high mass irregular LSB galaxies (log $M_\odot > 9.5$, top panel) and high mass regular LSB galaxies (log $M_\odot > 9.5$, bottom panel). From top-left to bottom-right in the top panel, the 3rd, 5th, 6th, 8th, 9th, 10th, 12th and 15th show evidences for either multiple components, double nuclei and tidal features evidencing merging.

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Fig. 13. The images of low mass irregular LSB galaxies ($\log M_\odot < 9.0$).
