Surface Photometry of LSB Galaxies

Based on a paper by W.J.G. de Blok, J.M. van der Hulst & G.D. Bothun

Low surface brightness (LSB) galaxies are galaxies dominated by an exponential disk whose central surface brightness is much fainter than the Freeman-value of $\mu_0^B = 21.65 \pm 0.30$ B-mag arcsec$^{-2}$. In this paper we present broadband photometry of a sample of 21 late-type LSB galaxies. The median central surface brightness of the sample is $\mu_0^B = 23.2$ B-mag arcsec$^{-2}$ and the median scale length is 4.3 kpc, showing that LSB galaxies are normal-sized galaxies. We find colors that are comparable to or bluer than those of the more widely studied ‘normal’ high surface brightness galaxies. LSB galaxies are therefore not faded disks that have stopped forming stars. The colors cannot be ascribed entirely to metallicity effects, but we can explain them by assuming a sporadic star formation rate scenario. LSB galaxies appear to be unevolved and quiescent objects, which give us an insight into the evolution of galaxies in an unperturbed environment.

The brightness of the night sky results in a strong bias against objects with central surface brightnesses much fainter than the Freeman value of $\mu_0^B = 21.65 \pm 0.30$ mag arcsec$^{-2}$ (Freeman 1970). These objects are therefore under-represented in many galaxy catalogs. Recent deep surveys (e.g. Schombert & Bothun 1988; Schombert et al. 1992 [hereafter SBSM]) have shown the presence of many field galaxies with peak surface brightnesses much fainter than the surface brightness of the night sky.

These Low Surface Brightness (LSB) galaxies are dominated by an exponential disk with a face-on central surface brightness $\mu_0^B \gtrsim 23$ mag arcsec$^{-2}$. They resemble normal late-type spirals, usually with a few ill-defined spiral arms. There are usually a few H II regions present, but these do not trace the spiral arms very well and are usually found towards the edges of the galaxy. The LSB galaxies we study here are neither Malin-1-like giant galaxies, nor intrinsically small galaxies such as the dwarf ellipticals and dwarf irregulars from our Local Group. Rather, the range in sizes and masses of the galaxies studies here is comparable with that of high surface brightness (HSB) galaxies that define the Hubble sequence.

H I masses of LSB galaxies are a few times $10^9 M_\odot$ (van der Hulst et al. 1993; McGaugh 1992; SBSM; de Blok, McGaugh & van der Hulst 1996). H I surface densities are usually close to or even below the critical surface density for star formation as formulated by Kennicutt (1989). The oxygen abundances in the few H II regions these galaxies possess are quite low: ~0.1 to ~0.5 solar metallicity (McGaugh 1994; de Blok & van der Hulst 1997a). LSB galaxies are unusually blue compared to normal late-type galaxies (McGaugh 1992; van der Hulst et al. 1993; Knezek 1993). So far no CO emission has been detected (Schombert et al. 1990; de Blok & van der Hulst 1997b). Thuan, Gott & Schneider (1987) and Bothun et al. (1993) find that, although LSB galaxies follow the spatial distribution of HSB galaxies, they tend to be more isolated from their nearest neighbors than HSB galaxies. The lack of major star formation suggest that LSB galaxies are relatively unperturbed, and have not suffered from mergers or interactions. These galaxies thus offer a unique opportunity to extend the range of environments in which we can study the properties of galaxies and star formation.

In this paper we present structural parameters and colors of our sample of LSB galaxies as derived from optical multicolor broad-band data. Section 2.1 will discuss the sample and the reduction techniques. In Section 2.2 we will show and
2.1 Sample and Reduction

The sample

We refer to Sect. 8.1 for an extensive description of the sample selection. In short, we selected 21 galaxies from SBSM and the UGC (Nilson 1973) with $\mu_0^B > 23$ mag arcsec$^{-2}$ and inclinations less than 60 degrees for which single-dish HI observations were available. The selected galaxies are all morphologically similar to late-type HSB galaxies. Fig. 2.1 shows R-band images of our sample of LSB galaxies. These images are presented using a linear intensity scale adjusted to bring out the faint outer parts, so that the brighter inner parts are saturated. Table 2.1 lists the sample. The distances were derived from the heliocentric redshifts (SBSM) after corrections for Galactic rotation and Virgocentric flow. We adopt a Hubble constant $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$. All magnitudes and colors have been corrected for Galactic extinction assuming a standard stellar extinction curve, following Allen (1973) and Burstein & Heiles (1982). Extinctions in the $B$-band were determined using the NED database.

Observations

$UBVR\!I$ images of the galaxies in the sample were taken during 4 nights in the period from 1991 January 8 until January 14, with the 2.5-m Isaac Newton Telescope at La Palma. The nights were excellent, with good ($\sim$1 arcsec) seeing and mostly photometric conditions. A GEC CCD was used, with a pixel size of 0.54 arcsec.

Images were bias-subtracted, flatfielded and co-added with the MIDAS package using standard methods. Flatfield images had been taken several times each night. Deviations between flats made on different nights using the same filter were $\leq 1$ per cent.

The images were flux-calibrated using standard stars (Landolt 1983). Since many standard star exposures had been taken through each filter we could compare these to determine the errors in the photometry over the 4 nights. We found these to be 0.04 mag ($1\sigma$) for the $I$-filter, based on 19 exposures. The deviation for the $B$-filter was the largest: 0.05 mag, based on 12 exposures. The deviation for the $V$-filter was 0.02 mag, based on 11 exposures. The $R$-filter standard stars showed a deviation of 0.02 mag, based on 17 exposures, and the $I$-filter stars also showed a deviation of 0.02 mag, based on 5 exposures.

If the sky background had a significant gradient across the image an attempt was made to fit and remove this gradient, without changing the mean value of the sky background. To do this the brightest stars were first removed from the image, after which the image was Gaussian-smoothed, decreasing its resolution by a factor of two. This removed small-scale noise fluctuations and showed more clearly which parts of the image were affected by the glare of the remaining fainter stars. A two-dimensional first-order polynomial was then fitted to those parts of the smoothed sky background that were judged to be free of any emission from stars or the galaxy itself. This gradient was then subtracted from the original image, essentially flattening the image background, without affecting the mean value of the sky or the values for the galaxy. We then measured the mean value of the sky background and the standard deviation in small boxes that were placed on parts of the image that were free of stellar or galaxy emission.

The mean difference between the median sky levels in these boxes was used as an estimate for the error introduced by fitting and subtracting the sky. Typically these errors were less than 0.5 per cent of the subtracted sky level.

Ellipse fitting and inclinations

We used the GIPSY image processing package to make ellipse fits to the isophotes of the galaxies, and to integrate along these ellipses. The centers of the ellipses were usually determined by taking the maximum of the light distribution as the center. In one or two cases the light distribution was too irregular and the central position was taken as a free parameter in the ellipse fit. For each set of $UBVR\!I$ images of an object only one set of ellipse orientation parameters was determined (usually from a slightly smoothed $R$-image), and applied to the other images to get radial azimuthally integrated surface brightness profiles for each band. We fitted ellipses with constant axial ratios, centers and position angles where the axial ratios and position angles were determined by the outer isophotes. These outer isophotes give the best idea of the overall shape of the galaxy. Prior to
2.1 Sample and Reduction

FIGURE 2.1(A)— R-images of the sample of LSB-galaxies. Image sizes are 2.3 × 2.3 arcmin². North is at the right, east is at the top. top-left: F561-1; top-right: F563-1; middle-left: F563-V1; middle-right: F564-V3; bottom-left: F565-V2; bottom-right: F567-2
FIGURE 2.1(b)—top-left: F568-1; top-right: F568-3; middle-left: F568-V1; middle-right: F571-5; bottom-left: F571-V1; bottom-right: F574-2
2.1 Sample and Reduction

Figure 2.1(c)—top-left: F577-V1; top-right: UGC 128; middle-left: UGC 628; middle-right: UGC 1230; bottom-left: UGC 5005; bottom-right: UGC 5209
FIGURE 2.1(D)— *top-left:* UGC 5750; *top-right:* UGC 5999; *bottom:* UGC 6614, image size is $3.4 \times 3.4$ arcmin$^2$.
the fitting, stars and cosmic ray defects were first blanked. As an extra check a few images were also fitted using a free parameter fitting routine, with no constraints on the axial ratio or orientation, which resulted in virtually identical radial surface brightness profiles.

Inclinations were derived from these ellipse fits, using \( \cos i = (b/a) \), and corrected for the intrinsic thickness of the disk by using the following formula from Holmberg (1958):
\[
\cos^2 i = \frac{(b/a)^2 - q_0^2}{1 - q_0^2}
\]

where \( q_0 \), the edge-on axial ratio of the disk, is taken to be 0.15 (cf. Huizinga 1994; Giovanelli et al. 1994). Due to the low inclinations the exact value of \( q_0 \) is not important.

### 2.2 Disk Parameters

#### Surface brightnesses and scale lengths

The surface brightness profiles of LSB galaxies can be very well approximated by an exponential disk component of the form
\[
\Sigma(r) = \Sigma_0 \exp\left(-\frac{r}{h}\right),
\]

where \( \Sigma_0 \) is the surface brightness of the disk in linear units (\( \text{M}_\odot \text{pc}^{-2} \)), and \( h \) is the exponential scale length of the disk (de Vaucouleurs 1959).

This equation can be converted to logarithmic units:
\[
\mu(r) = \mu_0 + 1.086 \left(\frac{r}{h}\right),
\]

where \( \mu_0 \) is the central surface brightness of the disk in logarithmic units (mag arcsec\(^{-2} \)). Figure 2.2 shows the azimuthally integrated radial surface brightness profiles of the galaxies in our sample for the \( B \)- and \( R \)-bands. It is clear from Figs. 2.1 and 2.2 that most of the galaxies in our sample do not have significant bulges. The central surface brightness \( \mu_0 \) of the disk and the exponential major axis scale length \( h \) were found by fitting a straight line to the exponential part of the profile, where the inner few points were excluded from the fit.

Table 2.2 shows the fit parameters, along with other parameters derived from them. We have corrected the central disk surface brightness to face-on values, without corrections for internal extinction. The mean error in the central surface brightness is about 0.1 mag arcsec\(^{-2} \) and the mean error in the scale length is ~ 20 per cent. These errors are derived from the error in the fit and the error bars in the outer points, which are in turn

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(1) Name of the galaxy. “U” means from the UGC; “F” means SBSM. (2) Right Ascension (1950.0) from either UGC or SBSM. (3) Declination (1950.0) from UGC or SBSM. (4) Inclination as derived from our data. (5) Distance in Mpc (\( h_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \)). (6) Total magnitude \( B_{025} \) within 25 B-mag arcsec\(^{-2} \) ellipse. (7) Radius in arcsec of 25 B-mag arcsec\(^{-2} \) ellipse. (8) Total magnitude \( B_{027} \) within 27 B-mag arcsec\(^{-2} \) ellipse. (9) Radius in arcsec of 27 B-mag arcsec\(^{-2} \) ellipse. (10) Total magnitude \( R_{025} \) within 25 B-mag arcsec\(^{-2} \) ellipse. (11) Total magnitude \( R_{027} \) within 27 B-mag arcsec\(^{-2} \) ellipse (12) Applied extinction correction in B. NOTES—(R) \( R \)-band data \((a) \) the distance to UGC 628 of 65 Mpc as given in van der Hulst et al. (1993) is incorrect.
mainly determined by the error due to sky subtraction.

Figure 2.3 shows the distributions of central disk surface brightnesses and scale lengths. The median values for our sample are $\mu_0^B = 23.6$ mag arcsec$^{-2}$ and $h = 4.3$ kpc. Combination of our data with those of McGaugh & Bothun (1994, their Fig. 3) yields median values of respectively 23.4 mag arcsec$^{-2}$ and 4.3 kpc. The median of the surface brightness is thus shifted more than 6$\sigma$ from the Freeman (1970) value $\mu_0^B = 21.65 \pm 0.30$ mag arcsec$^{-2}$. The peaked distribution in the central surface brightness histogram (Figs 2.3c and d) is caused by two effects. The upper cut-off in the histogram is due to a selection criterion of the sample: objects with central blue surface brightnesses brighter than 23 mag arcsec$^{-2}$ were excluded$^1$. The lower cut-off is caused by the detection limit of the plates and the diameter limits imposed on the SBSM sample. The range in surface brightness in the histogram is large and reaches from $\sim$ 24.5 mag arcsec$^{-2}$ to close to the Freeman value: a factor of 10 in luminosity surface density. The range of scale lengths found is virtually indistinguishable from that found for complete samples of HSB spiral galaxies (van der Kruit 1987; Grosbøl 1985; de Jong 1995).

Figure 2.4 illustrates the decline in central surface brightness towards later Hubble types. We have used the sample of UGC galaxies of de Jong (1995) as a HSB comparison sample, and used the Hubble types of the LSB galaxies as given in SBSM. The LSB galaxies clearly form a continuation of the trend outlined by the Hubble sequence galaxies.

**Total magnitudes**

The total integrated magnitude of the disk, integrated out to infinity, as given in Column (6) of Table 2.2 is calculated using

$$m_T = \mu_0 - 2.5 \log(2\pi h^2).$$  

(2.1)

The conventional $m_{25}$ magnitude, which gives the amount of light within the 25 mag arcsec$^{-2}$ isophote, is not a good measure for the total luminosity of LSB galaxies. In HSB galaxies most of the light is concentrated within this isophote ($\sim$ 80 per cent), but this is not the case for LSB galaxies. F565-V2, for example, has a central $B$-surface brightness of $\sim$ 24.5 mag arcsec$^{-2}$ and a scale length of 3 kpc. Assuming a purely exponential light distribution, this means that only 8 per cent of the light of this galaxy is emitted within the 25 mag arcsec$^{-2}$ isophote. The total magnitude out to infinity $m_T$, as defined by equation (2.1), is a better estimate for the total luminosity of a LSB galaxy. It is, however, difficult to get very accurate values for $m_T$, as they do depend on an extrapolation of the light profile, thus introducing extra uncertainties.

In our sample we can trace the galaxies out to a surface brightness of $\sim$ 28 $B$-mag arcsec$^{-2}$ ($\sim$ 3.5 scale lengths). Assuming that our galaxies are perfect exponential disks, this implies that we have detected more than 90 per cent of the total light. The data are thus good enough to determine the total magnitude directly. We have done this by using curves of growth to simulate aperture photometry. The magnitude $m_{ap}$ we derive is given in column (7) of Table 2.2. It is a better estimate for the total magnitude than $m_T$ as it takes any central surplus non-disk light into account, and no extra light is introduced at very large radii. Also for $m_{ap}$ the errors in the magnitudes are still mainly determined by the errors in the sky subtraction. It is instructive to compare $m_{25}$ with $m_{ap}$, the amount of light within the maximum aperture radius. This is done in Fig. 2.5. It is clear that $m_{25}$ underestimates the amount of light present. Therefore, one should be careful in using $m_{25}$ to calculate, for example, mass-to-light ratios, since use of $m_{25}$ will artificially raise this ratio, and more so in LSB galaxies. For example, a LSB galaxy with $\mu_0^B = 24.5$ mag arcsec$^{-2}$ has 10 times less light within the 25 $B$-mag arcsec$^{-2}$ isophote than a HSB galaxy with a central surface brightness equal to the Freeman value. Its mass-to-light ratio will therefore artificially be 10 times higher when $m_{25}$ is used, even though these galaxies may have the same mass and total luminosity.

### 2.3 Colors: The Data

The color profiles were determined by subtracting the surface brightness profiles from each other. Four colors were chosen: $U - B$, $B - V$, $B - R$ and $V - I$. The lower panels in Fig. 2.2 show the radial color profiles of the galaxies. The errors in the color profiles were estimated by adding in quadrature the errors in the surface brightness profiles.

To show that the gradients that are seen in most galaxies are real and not a product of the az-

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1When measured with a CCD some central surface brightnesses were found to be a few tenths of a magnitude brighter, hence the galaxies which have $\mu_0^B < 23$ mag arcsec$^{-2}$
2.3 Colors: The Data

FIGURE 2.2(A)— Radial surface brightness and color profiles. Top panels contain $B$ (lower profile) and $R$ (upper profile) surface brightness profiles; bottom panels contain radial color profiles (where measured). In all cases $V - I$ has been offset by +0.5 mag. Left row contains galaxies F561-1 (top); F563-1 (center); F563-V1 (bottom). Right row contains F564-V3 (top); F565-V2 (center); F567-2 (bottom).

Immutual integration we show a representative set of color maps of the LSB galaxies F561-1 and UGC 128 in Fig. 2.6. Two-color mapping of galaxies using CCD data has been fully described by Bothun (1986). The goal of this procedure is to show the spatial structure of the galaxy as a function of color, over wide color ranges. For the sample here, we have chosen the passbands $B$ and $R$ because this represents the optimal combination of signal to noise ratio and color baseline. Average $B$- and $R$-surface brightnesses were measured in boxes of size $7 \times 7$ pixels. Boxes where the combined error in $B - R$ exceeded 0.07 mag were rejected. Typically several hundred boxes passed the error threshold criteria, and in fact the median error per galaxy is 0.04 mag per box. The errors are entirely dominated by the noise of the $R$-band sky. The spatial positions of all boxes that pass this error...
threshold (i.e., with errors in $B - R$ smaller than 0.07 mag) were then plotted as a function of $B - R$ color. A color bin width of 0.2 mag was chosen for the different panels to help ensure that we are recording the spatial position of significant color differences. Fig. 2.6 thus indicates which parts of the galaxies fall in each of four $B - R$ bins and so demonstrates the very systematic change of color with radius.

Table 2.3 gives the gradients in the color profiles per $B$-scale length as derived from Fig. 2.2 and the distances in Table 2.1. The gradients were determined by making a least-squares fit to the linear part of the profile as shown in Fig. 2.2. Usually the inner few points had to be excluded as seeing effects or nuclear colors dominated here. It is clear that many of the galaxies show a color gradient, which is usually strongest in $U - B$. The outer parts of the disk are bluer than the inner parts. The large gradient in $U - B$ of F563-1 is
2.3 Colors: The Data

FIGURE 2.2(C)—Top panels contain B (lower profile) and R (upper profile) surface brightness profiles; bottom panels contain radial color profiles (where measured). In all cases V – I has been offset by +0.5 mag. For some UGC galaxies no color profiles are available, and only the R-band profile is given. Left row contains galaxies F577-V1 (top); U128 (center); U628 (bottom). Right row contains from top to bottom: U1230, U5209, U5005, U5770, U5999, and U6614.

probably caused by the large bright region near the center of the galaxy which is prominent in U (see Figs. 2.1 and 2.2).

To determine total colors, all images were smoothed first, decreasing their original resolution by a factor of two to reduce the noise. For each galaxy the smoothed images were divided by each other, excluding pixels less than 2σ from the sky levels, resulting in images showing the distribution of color. Three different types of color were determined.

- **nuclear color**: color within a central ellipse with major axis of 5 arcsec.
- **luminosity-weighted color**: average color of the entire galaxy within the isophote that is 2σ above sky level. This isophote had approximately the same value for all galaxies, and
turns out to be the \( \sim 25.5 \) \( B \)-mag arcsec\(^{-2}\) isophote.

Area-weighted color: average color of the entire galaxy, within the 25.5 \( B \)-mag arcsec\(^{-2}\) isophote, calculated by first computing the color of each pixel in the galaxy, and then taking the mean of all color pixel values. As pixel values less than 2\( \sigma \) above sky were blanked, the value of this parameter does not diverge.

In the case of a disk with a constant surface brightness the luminosity- and area-weighted colors are equal. However, when determining the luminosity-weighted color for a real galaxy most weight is given to the colors of the luminous and bright parts of a galaxy. This is in contrast with the area-weighted color where all parts of the galaxy have equal weights, and only the area matters. The difference between area- and luminosity-weighted colors is almost completely determined by the relative strength of the redder inner parts with respect to the bluer outer parts. This is important even in galaxies that show no
In Fig. 2.7 we show the area-weighted $B - V$ colors and structural parameters of the disks with respect to each other. In these figures values found by McGaugh & Bothun (1994) for their LSB galaxies and by de Jong (1995) for his HSB galaxies are also plotted. The bluest galaxies are found at the lowest surface brightnesses, with the LSB galaxies lying at the most extreme ends of both the surface brightness and color range. The colors do not depend strongly on the size (scale length) of the galaxy as Fig. 2.7 shows, with the exception that large galaxies tend to be slightly redder.

In Fig. 2.7 we have also plotted the $B - R$ colors of the LSB galaxies and the HSB galaxies from the sample of de Jong (1995) versus the central surface brightness $\mu_0^c$. The LSB galaxies are again significantly bluer in $B - R$ than late-type HSB galaxies. Combined with Fig. 2.4 this suggests that characteristics such as color and surface brightness do not correspond uniquely to Hubble type.
filled circles represent our sample of LSB galaxies. The individual galaxies from the sample of de Jong (1995). We compare them with evolutionary models from the HSB galaxy. The LSB galaxy must differ from that of a late-type and Hubble type does not have a one-to-one correspondence with the star formation history, as evidently the star formation history of a late-type LSB galaxy must differ from that of a late-type HSB galaxy.

2.4 Colors: Discussion

We will discuss the colors of LSB galaxies, and compare them with evolutionary models from the literature, with the goal of tracing a possible star formation history for these objects. Where possible we will supplement our data with those of McGaugh & Bothun (1994), who have used the same selection criteria for their sample as we have. A comparison of the photometry of the few galaxies that our sample and McGaugh’s sample have in common shows that any systematic differences between the measurements are much smaller than.

Table 2.3: Color gradients per B-scale length $h_B$ in LSB galaxies.

<table>
<thead>
<tr>
<th>Name</th>
<th>$\Delta(U-B)$</th>
<th>error</th>
<th>$\Delta(B-V)$</th>
<th>error</th>
<th>$\Delta(B-R)$</th>
<th>error</th>
<th>$\Delta(V-I)$</th>
<th>error</th>
</tr>
</thead>
<tbody>
<tr>
<td>F561-1</td>
<td>$-0.30$</td>
<td>0.14</td>
<td>$-0.11$</td>
<td>0.08</td>
<td>$-0.19$</td>
<td>0.08</td>
<td>$-0.14$</td>
<td>0.16</td>
</tr>
<tr>
<td>F563-1</td>
<td>$-1.15$</td>
<td>0.22</td>
<td>$-0.06$</td>
<td>0.13</td>
<td>$-0.16$</td>
<td>0.13</td>
<td>$-0.07$</td>
<td>0.13</td>
</tr>
<tr>
<td>F563-V1</td>
<td>$-0.09$</td>
<td>0.11</td>
<td>$+0.04$</td>
<td>0.07</td>
<td>$-0.05$</td>
<td>0.07</td>
<td>$-0.10$</td>
<td>0.06</td>
</tr>
<tr>
<td>F564-V3</td>
<td>$-0.12$</td>
<td>0.16</td>
<td>$-0.09$</td>
<td>0.08</td>
<td>$-0.12$</td>
<td>0.08</td>
<td>$-0.04$</td>
<td>0.06</td>
</tr>
<tr>
<td>F567-2</td>
<td>$-0.21$</td>
<td>0.17</td>
<td>$-0.09$</td>
<td>0.13</td>
<td>$-0.17$</td>
<td>0.13</td>
<td>$-0.47$</td>
<td>0.22</td>
</tr>
<tr>
<td>F568-1</td>
<td>$-0.12$</td>
<td>0.16</td>
<td>$-0.09$</td>
<td>0.06</td>
<td>$-0.15$</td>
<td>0.06</td>
<td>$-0.12$</td>
<td>0.15</td>
</tr>
<tr>
<td>F568-V1</td>
<td>$-0.07$</td>
<td>0.10</td>
<td>$-0.07$</td>
<td>0.05</td>
<td>$-0.12$</td>
<td>0.05</td>
<td>$-0.10$</td>
<td>0.10</td>
</tr>
<tr>
<td>F571-V1</td>
<td>$-0.09$</td>
<td>0.11</td>
<td>$-0.18$</td>
<td>0.07</td>
<td>$-0.20$</td>
<td>0.07</td>
<td>$-0.10$</td>
<td>0.05</td>
</tr>
<tr>
<td>F571-V1</td>
<td>$-0.09$</td>
<td>0.11</td>
<td>$-0.05$</td>
<td>0.05</td>
<td>$-0.10$</td>
<td>0.05</td>
<td>$-0.10$</td>
<td>0.05</td>
</tr>
<tr>
<td>F574-V2</td>
<td>$-0.17$</td>
<td>0.13</td>
<td>$-0.09$</td>
<td>0.09</td>
<td>$-0.26$</td>
<td>0.09</td>
<td>$-0.10$</td>
<td>0.09</td>
</tr>
<tr>
<td>U0128</td>
<td>$-0.21$</td>
<td>0.35</td>
<td>$-0.21$</td>
<td>0.21</td>
<td>$-0.35$</td>
<td>0.21</td>
<td>$-0.21$</td>
<td>0.35</td>
</tr>
<tr>
<td>U0628</td>
<td>$-0.16$</td>
<td>0.16</td>
<td>$-0.12$</td>
<td>0.12</td>
<td>$-0.16$</td>
<td>0.08</td>
<td>$-0.16$</td>
<td>0.2</td>
</tr>
<tr>
<td>U1230</td>
<td>$-0.20$</td>
<td>0.20</td>
<td>$-0.12$</td>
<td>0.16</td>
<td>$-0.24$</td>
<td>0.12</td>
<td>$-0.12$</td>
<td>0.24</td>
</tr>
</tbody>
</table>

(1) Name of the galaxy. (2(4)(6)(8) Gradient per B-scale length in respectively $U - B$, $B - V$, $B - R$, and $V - I$. (3(5)(7)(9) Uncertainties in the gradients. Notes— (a) Points with $r < 4$ arcsec are excluded. (b) Points with $r < 5$ arcsec are excluded.

Figure 2.4: Distribution of the central surface brightness in $B$, as a function of Hubble type. The open squares represent the individual galaxies from the sample of de Jong (1995). The filled circles represent our sample of LSB galaxies.

Figure 2.5: Magnitude within 25 $B$-mag arcsec$^{-2}$ isophote, $m_{25}(B)$, plotted against aperture magnitude in $B$, $m_{ap}(B)$. The black circles represent our sample. The open squares represent the sample of McGaugh & Bothun (1994). Galaxies common to both samples are connected.
the typical errors in the colors. Comparisons with independent observations of UGC 628 (Knezek 1993; de Jong & van der Kruit 1994) give differences in the measured $B - R$ color profiles of < 0.1 mag. In order to make comparisons with colors of other types of objects we will assume that the median area-weighted colors of our and McGaugh’s samples combined are representative for the sample as a whole. The median area-weighted colors of the combined sample are $U - B = -0.13$, $B - V = 0.51$, $B - R = 0.78$, and $V - I = 0.76$. These colors are also given in Table 2.5. The large difference in $V - I$ between our and McGaugh’s samples is immediately apparent. For the galaxy F563-V1, which is common to both samples, there is a large difference in the colors as determined by McGaugh and us. According to McGaugh (priv. comm.) this may be due to a defect in his V-image of this galaxy. This galaxy is therefore excluded from the present sample.

**Comparison with HSB galaxies**

Morphology shows that very late-type HSB galaxies (Sd and later) are the most likely candidates for comparison. These too have small to absent bulges, and loose, less strongly developed spiral arms. There are of course also differences, such as the number of H II regions present and the amount of star formation.

We have used the RC3 (de Vaucouleurs et al. 1991), the ESO-LV (Lauberts & Valentijn 1989), and results from Huchra (1977), Byun (1992) and Han (1992) to determine the colors of typical HSB Sdm–Sm (comparison) galaxies. These colors are $U - B = -0.14$, $B - V = 0.51$, $B - R = 0.92$, and $V - I = 0.9$ (cf. Figs 2.8 and 2.9). The scatter in $B - R$ and $V - I$ is quite large (Han 1992; ESO-LV). The value of $V - I$ is rather uncertain due to the fact that Han’s corrections for extinction are larger than we expect them to be for these late-type galaxies.

Comparison with Table 2.5 shows that the values of $U - B$ and $B - V$ of the LSB galaxies are roughly equal to those of late-type HSB galaxies. Blue colors are generally associated with star formation, which is definitely taking place in late-type HSB galaxies. It is surprising that LSB galaxies that have no or only small traces of star formation, and which generally look much more quiescent, should have comparable colors. The presence of small amounts of star formation is confirmed by Hα imaging.

Figure 2.8 shows a $UBV$ diagram based on the ∼ 500 late-type galaxies (Sc and later) for which both $U - B$ and $B - V$ were available in the RC3.

**TABLE 2.4— Colors of LSB galaxies.**

<table>
<thead>
<tr>
<th>Name</th>
<th>$U - B$</th>
<th>$B - V$</th>
<th>$B - R$</th>
<th>$V - I$</th>
<th>$r_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>F561-1</td>
<td>0.04</td>
<td>-0.04</td>
<td>-0.20</td>
<td>0.62</td>
<td>0.55</td>
</tr>
<tr>
<td>F563-1</td>
<td>0.23</td>
<td>0.07</td>
<td>-0.05</td>
<td>0.67</td>
<td>0.64</td>
</tr>
<tr>
<td>F563-V3</td>
<td>0.05</td>
<td>-0.01</td>
<td>-0.05</td>
<td>0.55</td>
<td>0.59</td>
</tr>
<tr>
<td>F564-V3</td>
<td>0.57</td>
<td>0.57</td>
<td>0.56</td>
<td>0.88</td>
<td>0.87</td>
</tr>
<tr>
<td>F565-V2</td>
<td>0.52</td>
<td>0.51</td>
<td>0.49</td>
<td>0.83</td>
<td>0.82</td>
</tr>
<tr>
<td>F567-2</td>
<td>0.05</td>
<td>-0.05</td>
<td>-0.14</td>
<td>0.69</td>
<td>0.61</td>
</tr>
<tr>
<td>F568-V1</td>
<td>0.21</td>
<td>-0.09</td>
<td>-0.20</td>
<td>0.71</td>
<td>0.58</td>
</tr>
<tr>
<td>F571-5</td>
<td>-0.06</td>
<td>-0.12</td>
<td>-0.13</td>
<td>0.56</td>
<td>0.54</td>
</tr>
<tr>
<td>F571-V1</td>
<td>0.58</td>
<td>0.55</td>
<td>0.51</td>
<td>0.93</td>
<td>0.89</td>
</tr>
<tr>
<td>F574-2</td>
<td>0.63</td>
<td>0.59</td>
<td>0.51</td>
<td>0.96</td>
<td>0.86</td>
</tr>
<tr>
<td>F577-V1</td>
<td>0.12</td>
<td>-0.19</td>
<td>-0.40</td>
<td>0.54</td>
<td>0.50</td>
</tr>
<tr>
<td>UGC 0128</td>
<td>0.36</td>
<td>0.16</td>
<td>0.02</td>
<td>0.73</td>
<td>0.60</td>
</tr>
<tr>
<td>UGC 0628</td>
<td>0.19</td>
<td>0.04</td>
<td>-0.07</td>
<td>0.75</td>
<td>0.61</td>
</tr>
<tr>
<td>UGC 1230</td>
<td>0.01</td>
<td>-0.19</td>
<td>-0.30</td>
<td>0.63</td>
<td>0.54</td>
</tr>
</tbody>
</table>

**Comparison of colors.**

<table>
<thead>
<tr>
<th>Col</th>
<th>Our</th>
<th>McG</th>
<th>Comb</th>
<th>HSB</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U - B$</td>
<td>-0.14</td>
<td>-0.12</td>
<td>-0.13</td>
<td>-0.14</td>
</tr>
<tr>
<td>$B - V$</td>
<td>+0.52</td>
<td>+0.44</td>
<td>+0.51</td>
<td>0.51</td>
</tr>
<tr>
<td>$B - R$</td>
<td>+0.78</td>
<td>-0.78</td>
<td>0.78</td>
<td>0.92</td>
</tr>
<tr>
<td>$V - I$</td>
<td>+0.69</td>
<td>+0.95</td>
<td>+0.76</td>
<td>0.80</td>
</tr>
</tbody>
</table>

We have binned these galaxies by Hubble type, and plotted the mean colors and 1σ deviations in each bin. It is clear that there is a trend of color with Hubble type, in the sense that galaxies become bluer toward later Hubble type. It is also clear that the spread in color for a given type is so large that we cannot use the color of a galaxy as a good measure for its Hubble type. The stars in Fig. 2.8 represent the LSB galaxies from both our and McGaugh’s samples. These galaxies have colors that scatter around the typical colors for Sdm and Sm galaxies.

Figure 2.9 shows a BRI diagram. The mean colors and 1σ deviations of the ~200 late-type galaxies (Sc and later) for which both colors were available in Byun (1992) and the ESO-LV are shown, binned by Hubble type. The stars represent the LSB galaxies. Once again there is a clear trend of color with Hubble type, and once again color does not correspond unambiguously with Hubble type. It is clear that in these colors the LSB galaxies are consistently bluer than Sdm–Sm HSB galaxies.
2.4 Colors: Discussion

Dust and extinction effects

A possible hypothesis to explain the blue colors of LSB galaxies is that LSB galaxies are merely dustless HSB galaxies. Using a simple overlying screen model for the extinction and reddening one then needs $\sim 0.5$ mag less extinction in the $V$-band for the LSB galaxies than for the HSB galaxies, assuming that the mix of stellar populations in LSB and Sc galaxies is equal. This implies that LSB galaxies should have a higher surface brightness than HSB galaxies, which is obviously not true. The assumption of identical stellar populations is, however, likely to be wrong, in view of the different star formation histories. The assumption of an overlying screen is also too crude. In reality, reddened stars will become fainter and more obscured, and thus will contribute less light to the total color. The least obscured parts of a galaxy will determine its colors (Disney, Davies & Phillips 1989; Witt, Thronson & Capuano 1992).

In both LSB and Sc galaxies we may therefore expect global colors to be largely determined by stars that are not or only lightly obscured by dust. We are therefore unable to derive the relative amounts of dust these using just broad-band optical colors.

For a correct analysis of extinction and reddening, one also has to take scattering into account. As suggested by the models described in Elmegreen (1980) and Rix & Rieke (1993), scattering is particularly important when studying face-on galaxies at optical wavelengths. Photons have a greater chance of being scattered out of the disk perpendicularly (in the face-on direction) than in the edge-on direction (in the plane of the disk). In the latter case they have a larger chance of being absorbed. The scattered photons that reach us will effectively make the observed colors bluer, bringing them closer to their intrinsic values. Dust will play a role in determining colors, but it is clear that age and metallicity effects must also play a role.

Metallicity effects: comparison with globular clusters

McGaugh (1994) and de Blok & van der Hulst (1997a) show that LSB galaxies have low metallicities, which can give rise to bluer colors. To get an idea of the magnitude of this effect we will compare the colors of other metal-poor objects with those of the LSB galaxies. We will not compare the sample with, for example, blue compact galaxies: although these objects have low metallicities, their high star formation rates make them unsuit-

![Figure 2.8— $UBV$ diagram. The filled circles represent the mean colors for each Hubble type. The error bars denote $1\sigma$ deviations from the mean colors. The stars represent the colors of the LSB galaxies.](image)

able for a comparison. Better comparison objects are metal-poor globular clusters.

For these metal-poor ([Fe/H] $\sim -2.0$) globular clusters values of $U - B = 0.1$, $B - V = 0.65$, $B - R = 1.1$ and $V - I = 0.95$ are found (Reed 1985; Reed, Hesser & Shawl 1988; Hesser & Shawl 1985). Very metal-poor globular clusters in the Magellanic Clouds (Elson & Fall 1985) show $U - B = 0.2$ and $B - V = 0.5$. Globular clusters are thus redder than LSB galaxies. In order to explain the blue colors of LSB galaxies with metallicity effects, LSB galaxies thus need to be more metal-poor than metal-poor globular clusters. This is not consistent with the observations. Age must certainly play a major role.

The ambiguity between age and metallicity also affects the interpretation of the measured color gradients. The general trend towards bluer colors with increasing radius could be a reflection of lower metallicity in the outer parts or it could represent a difference in mean age between the inner and outer regions. Observations (see de Blok & van der Hulst 1997a) suggest that LSB galaxies do not have a strong metallicity gradient. This would imply that, as LSB galaxies have long collapse times, star formation may proceed first in the inner, denser regions while the outer regions are still collapsing.
CHAPTER 2  SURFACE PHOTOMETRY OF LSB GALAXIES

**Figure 2.9 — BRI diagram.** The filled circles represent the mean colors for each Hubble type. The error bars denote 1σ deviations from the mean colors. The stars represent the colors of the LSB galaxies.

**Age effects**

The $U - B$ and $B - V$ colors, which are comparable to those of HSB galaxies, and the presence of a small number of star forming regions imply that part of the stellar content of LSB galaxies must consist of young stars. However, the lack of a large number of prominent star forming regions suggests that star formation should be taking place diffusely across the disk. We constructed a simple model to show the effects of star formation on the total colors. This model consists of a red population with the properties of metal-poor globular cluster stars. To this red population an increasing number of B-stars were added, and the effect on the total colors was calculated. This rather naive model suggests that approximately 5 to 10 per cent of the area of the disk should in some way be affected by star formation, in order to have a noticeable ($\sim 0.1$ mag) effect on the total colors. Judging from color maps (see e.g. Fig. 2.6), 5 to 10 per cent is not an unreasonable value.

**2.5 Star Formation Histories**

In this section we will not try to decipher the star formation history and evolution of LSB galaxies in detail. Rather, to set the scene for Chapter 3, we will describe a few possible star formations scenarios that may apply to LSB galaxies, and discuss their possible merits and shortcomings.

The range of properties of galaxies (gas density, metallicity, star formation rate) is so wide that many of the published galaxy evolution models only cover a small section of parameter space. Despite these short-comings we will use models by Searle, Sargent & Bagnuolo (1973), Larson & Tinsley (1978), Guiderdoni & Rocca-Volmerange (1987) and Mazzei, Xu & De Zotti (1992) and compare their results with the observations. Most of the published models were computed assuming solar metallicity. As the metallicity in LSB galaxies, as measured in HII regions, is about a fifth of the solar metallicity, it is likely that the metallicity of the stellar population is also below solar. This will affect the model colors. However, as we will see, the assumptions about the form of the star formation history have a much larger effect, and the assumptions about metallicity are not critical.

**Disk-fading scenario**  This scenario explains LSB galaxies as faded remnants of normal disk galaxies that for some reason have ceased to form stars a few Gyr ago. We can use the data as presented in Fig. 2.7 and the models of Searle et al. to disprove this scenario. In the absence of star formation a galaxy will become redder and fainter with time (regardless of metallicity), as the short-lived blue stars die. From Searle et al. we can derive a reddening of 0.22 mag in $B - V$ for each magnitude fading in $B$. If this scenario were correct Fig. 2.7 should have shown at least a clear reddening with decreasing surface brightness. **LSB galaxies are not the faded remnants of normal HSB galaxies.**

**Initial starburst with cut-off**  An initial starburst with subsequent cut-off in star formation is equivalent to the disk-fading scenario, and is therefore not likely to explain the observed colors. Indeed, for a model that has an initial starburst with cut-off after $10^7$ years, Larson & Tinsley (1978) find colors that are too red to fit our measured colors.

**Exponentially declining star formation rate**  The exponentially declining star formation rate (SFR) has frequently been used as the 'standard' star formation history for spiral galaxies. This scenario can result in the low present SFR that we measure in LSB galaxies.

The colors at the blue end of the spectrum, $U - B$ and $B - V$, are very similar to those of HSB galaxies, as noted in previous sections. This is understandable, as these colors are sensitive to recent star formation, which is, albeit in different quantities, present in both HSB and LSB galaxies. The exponential nature of this star formation history implies that the amount of stars formed in the
past was much greater. Consequently any galaxy that has undergone an exponential star formation history must have a large population of old stars. The bulk of these stars will have their peak optical emission at the red end of the spectrum, i.e., we will mainly detect them in the $R$- and $I$-bands. The $B - R$ and $V - I$ colors of LSB galaxies are significantly bluer than those of HSB galaxies, which suggests a relative lack of this old population.

$V - I$ furthermore is an indicator of the position and degree of development of the giant branch in the HR-diagram (Bothun et al. 1984) and is therefore metallicity dependent, as the position of the giant branch in the HR-diagram changes with metallicity. The values found for $V - I$ suggest low metallicity and no early enrichment of the interstellar medium, once again suggesting a lack of major star formation in the past. Observations in the near-infrared should be able to confirm this as an old population will manifest itself most clearly there. Observations in the $K'$ and $H$ bands by de Jong (1995) show that LSB galaxies at these wavelengths are significantly bluer than HSB galaxies.

**Constant star formation rate** A constant (high amplitude) SFR can reproduce the measured $U - B$ and $B - V$ colors (Larson & Tinsley 1978) because of the recent star formation. But a constant SFR also implies that by now a large old population should be present and visible in the $B - R$ and $V - I$ colors. A further clue can be found in the models of Mazzei et al. (1992). These models take some chemical evolution into account, and the poorly known evolution of stars in their giant phases. The $U - B$ and $B - V$ colors can only be modeled using models with an age of 10 Gyr, while the $B - R$ and $V - I$ can only be modeled with an age between 2 and 5 Gyr. Although the absolute values of the colors will probably not be right due to the different metallicities, the trend in age suggests we need an underdeveloped old population to explain the colors.

**Sporadic star formation rate** The lack of clear signs of an old population, combined with the fact that we still find evidence for young stars in LSB galaxies, suggests the following scenario for the star formation history of LSB galaxies. As the current metallicity is low, it is not likely that there has been much star formation in the past. The blue $U - B$ and $B - V$ suggest that some young high-mass stars are present. We can reach this stage by including small surges in the SFR, either superimposed on a very low constant SFR, or not. Where this temporary increase occurs is largely determined by the critical density for star formation in H I. Salzer et al. (1991) show that the larger contrast between the old and the young populations, the less young stars are needed to produce blue colors. Because of the low surface brightness of the underlying (old) population, we only need a small fraction of the total number of stars to be young stars to make the colors significantly bluer. This is discussed more extensively in Gerritsen & de Blok (1997).

**Summary** The star formation scenarios suggest that the colors can be explained by assuming a less developed old population, and a small young, blue population. The LSB galaxies had a low (sporadic) SFR in the past, so fewer stars were formed. Recent star formation made $U - B$ and $B - V$ bluer with respect to $B - R$ and $V - I$. The low metallicities in these galaxies will furthermore make the colors still bluer. Because of the low present and past star formation rates an old population has not yet had time to develop. But a LSB disk can contain only a limited amount of young stars without becoming a HSB disk.

We can speculate that the LSB galaxies in our sample are ones that are at the moment going through a phase of slightly enhanced star formation. For an extensive discussion of this see Gerritsen & de Blok (1997). One of the problems created by assuming that this extra star formation causes the LSB galaxies to be as blue as they are is that there must then necessarily also be red LSB galaxies that are quiescent and not undergoing a burst. A possible reason why these galaxies are not in our sample is that the LSB galaxy catalogs by SBSM were composed after visual inspection of the blue POSS-2 plates. Red LSB galaxies may therefore have been missed which would serve to increase the overall space density of LSB galaxies. Indeed, recent observations by O’Neill, Bothun & Cornell (1997) indicate the existence of a population of red LSB galaxies with colors of $B - V \sim 0.8$. In the absence of redshift data it is as yet uncertain whether these red LSB galaxies have properties similar to those of the blue LSB galaxies.

### 2.6 Conclusion and Summary

LSB galaxies have scale lengths comparable to those of late-type HSB galaxies. They have bluer disks than HSB galaxies. The blue colors cannot be entirely explained by metallicity effects as judged from comparison with metal-poor globular clusters. Comparison with evolution models shows that part of the blue colors can be ascribed
to age effects for very low star formation rate scenarios. These scenarios can be described by a low star formation rate, with slight periodic surges. This leads to a luminosity-dominant young population, with an underdeveloped old population. The star formation is local and sporadic, as the colors do not support starbursts or vigorous star formation hypotheses. We may be seeing only galaxies that are in a more active phase, while quiescent, inactive and much redder LSB galaxies may until recently have escaped detection.

Acknowledgments

We thank Jon Davies, Roelof de Jong, Stacy McGaugh, Reynier Peletier and Rob Swaters for their help with the original version of this paper.

The Isaac Newton Telescope is operated by the Royal Greenwich Observatory at the Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias with financial support from the PPARC (UK) and NWO (NL).

The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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