**Astronomy**
**&**
**Astrophysics**

# The environment of Low Surface Brightness galaxies

S. D. Rosenbaum and D. J. Bomans

Astronomisches Institut, Ruhr-Universität Bochum (AIRUB), Universitätsstr. 150, 44780 Bochum, Germany
e-mail: [dominik.rosenbaum;bomans]@astro.rub.de

**Abstract.** Using the Early Data Release of the Sloan Digital Sky Survey (SDSS) we investigated the clustering properties of Low Surface Brightness (LSB) galaxies in comparison to normal, High Surface Brightness (HSB) galaxies. We selected LSB galaxies and HSB galaxies with well measured redshifts from the SDSS data base and performed three-dimensional neighbour counting analysis within spheres of radii between 0.8 Mpc and 8.0 Mpc. As a second analysis method we used an $N$th neighbour analysis with $N$ varying from one to ten galaxies. Our results show significant differences between the galaxy densities of LSB galaxies and HSB galaxies on scales from 2 to 5 Mpc. At scales larger than 5 Mpc LSB and HSB galaxies share the same clustering properties. In the pie-slice diagrams the LSB galaxies appear to favour the inner rims of filaments as defined by the HSB galaxies, with a couple of LSB galaxies even being located inside the voids. Our results support the idea of gas-rich LSB galaxies forming and developing in low density regions without many galaxy interactions and just now reaching the filaments of the large scale structure.

**Key words.** galaxies: distances and redshifts – galaxies: evolution – galaxies: statistics

## 1. Introduction

The existence of gas-rich disk-galaxy-like LSB galaxies with central surface brightnesses of $\mu_B > 22.5$ mag/arcsec$^2$ has been established over the last 15 years, whereas the formation and evolution scenarios that led to such a class of galaxies with a sparse stellar population are not well understood so far (e.g., Impey & Bothun 1997). Although LSB galaxies have HI components with low surface densities (e.g., van der Hulst et al. 1993) systematically below the Kennicutt (1998) criterion for star formation, they can be regarded as gas-rich in general (e.g., Pickering et al. 1997).

The key in understanding LSB galaxies lies then in the answer to the question what prevented them from sufficient star formation. One explanation might be found in the differences in the spin parameter of the dark matter halo between LSB and HSB galaxies. Dalcanton et al. (1997) and Boissier et al. (2003) found some evidence that LSB galaxies could be disk galaxies with a larger spin parameter than HSB spirals. This would imply larger scale lengths for LSB disks and originate the observed low HI surface densities.

Another way to reconstruct the evolutionary history and to understand the properties of these galaxies might be found in the nature of the small and large-scale environments in which LSB galaxies are embedded, since the lack of star formation can only occur if the galaxies were formed in low density regions. Only a low density scenario can warrant that neither tidal encounter with companions nor infall of

massive gas clouds could have taken place and have triggered a sufficient star formation which would have gradually brightened the stellar disk. Evidence for the stronger isolation of LSB galaxies in comparison to HSB galaxies was found before by Bothun et al. (1993) and Mo et al. (1994). A lack of nearby ($r \leq 0.5$ Mpc) companions of LSB galaxies was detected by Zaritsky & Lorrimer (1993).

Today, with the availability of several substantial galaxy redshift surveys containing high quality redshifts, the possibility for intensive studies on the environmental galaxy densities of LSB galaxies is given.

## 2. Data characteristics and analysis

The Early Data Release (EDR) of the Sloan Digital Sky Survey (SDSS, Stoughton et al. 2002) covers around 460 deg$^2$ of imaging data and 54 000 spectra mainly from scans in two equatorial stripes, one in the southern and the other in the northern Galactic cap.

We retrieved LSB candidates and a HSB comparison sample from the EDR using the SDSS Query Tool. The following parameters of each object, classified as a galaxy with spectroscopic data avaliable were downloaded: an object identifier, right ascension, declination, an azimuthally averaged radial surface brightness profile in the $g$- and $r$-band and the redshift of the object (for technical details to the SDSS parameters see Chap. 4.10 in Stoughton et al. 2002). The sample was limited to the two equatorial stripes of the EDR, a redshift of $0.02 \leq z \leq 0.1$ and in order to minimize the uncertainty of the redshift a $z$-confidence greater than 90% was demanded. A sample of 16 123 galaxies was obtained.

*Send offprint requests to*: S. D. Rosenbaum,
e-mail: dominik.rosenbaum@astro.rub.de

Equipped with this data set we were able to distinguish between LSB galaxies with a central surface brightness $\mu_B > 22.5$ mag/arcsec$^2$ and HSB galaxies (if $\mu_B \leq 22.5$ mag/arcsec$^2$). The central surface brightness $\mu_B$ was calculated for each galaxy from the central annulus (0.23″) of the radial surface brightness profile in the filters $g$ and $r$ using an equation following Smith et al. (2002). At the faint end the surface brightness distribution was cut off at $\mu_B = 25$ mag/arcsec$^2$. We did not apply any selection criterion based on the apparent size of the galaxies since the intrinsic selection criterion of the SDSS spectroscopic sample limits the angular diameter of the galaxies on which spectroscopy was applied to a value of 5″ or larger. With these selection criteria a sample of 804 LSB galaxies from both equatorial stripes of the EDR with a redshift of $z \leq 0.1$ was obtained. In this data set 15319 Galaxies remained as HSB galaxies.

For further analysis of the LSB environment and density distribution, two different methods were used. First, the environmental density for each sample LSB and HSB galaxy was measured by counting the number of galaxies within a sphere around the scrutinised galaxy. Second, the distance to the $N$th (with $N$ between 1 and 10) nearest neighbour of each galaxy was determined and used as a measure of the local density. The separation between LSB and HSB galaxies was performed after statistical environmental analysis in both methods.

## 2.1. Neighbour counting within spheres

The program for neighbour counting was fed with the catalog file of the sample containing both LSB and HSB galaxies downloaded as described before. First the code converted the redshift, right ascension and declination of all galaxies from our sample into the 3 dimensional spatial distribution of galaxies. For that a Hubble constant of $H_0 = 71$ km s$^{-1}$ (Bennet et al. 2003) was used. The purpose of the algorithm was to deliver the number of neighbours within a sphere of a certain radius for every single galaxy. The radius of the sphere was a fixed parameter during each run. In several runs the radius of the sphere was varied between $r = 0.8$ Mpc and $r = 8.0$ Mpc in steps of 0.6 Mpc. In order to avoid biasing of the sample due to boundary effects, the program limited the sample to galaxies with distances to the boundary of the catalog volume larger than the radius of the sphere. Due to this edge correction, the inspected volume varies depending on the radius $r$. For this analysis both equatorial stripes were used. After this neighbouring analysis the resulting statistical distribution was divided into LSB and HSB subsamples using the central surface brightness criterion $\mu_B > 22.5$ mag/arcsec$^2$ for low surface brightness galaxies as described above.

## 2.2. Nth neighbour analysis

The second analysis using the $N$th nearest neighbour method was limited to the first equatorial stripe which corresponds to the right ascension area of $354° \leq \alpha \leq 53°$. The right ascension, declination and redshift informations from the sample catalog were again translated to a 3-dimensional grid. The
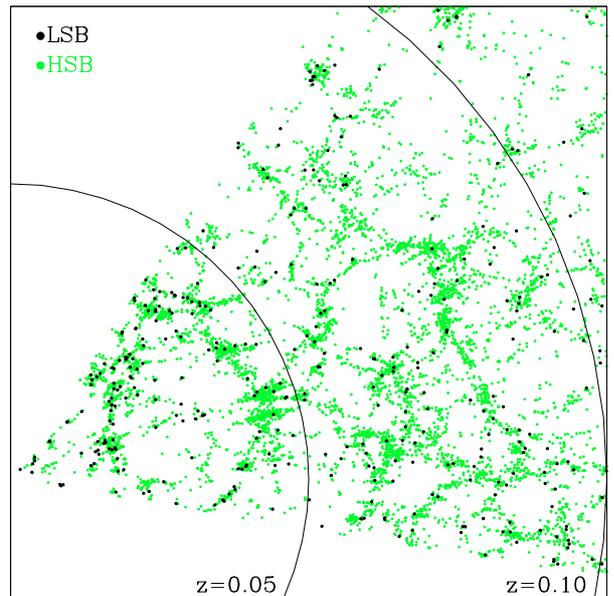


**Fig. 1.** One of the two analysed pie slices. The right ascension range $354° \leq \alpha \leq 53°$ containing ~400 LSB galaxies and ~8000 HSB galaxies is plotted.

distances between the galaxies were calculated and the $N$th lowest distance to the neighbouring galaxies was assigned to each member of the sample as a measure of local galaxy density. Then an edge correction was applied by rejecting all galaxies with distances to the $N$th neighbour larger than to the edge of the sample catalog. At the end, the resulting sample was divided into LSB and HSB subsamples. This kind of analysis was repeated for several values of $N$ varying from 1 to 10.

## 3. Results

In Fig. 1 the distribution of LSB galaxies in comparison to HSB galaxies is shown in a so called pie slice diagram, where the right ascension and the redshift of the galaxies are displayed in a polar plot (the declination range is projected onto the plane). The pie slice diagram shows that LSB galaxies are located in the filaments of the Large Scale Structure (LSS) traced by the distribution of HSB galaxies. Further investigations of the plot lead to the impression that LSB galaxies show the tendency to be located more often at the edges of these filaments than in the center and some LSB galaxies are even found in void regions.

In order to amplify this impression the statistical environmental study as described before was performed. The results of the analysis method using number counting within spheres were plotted in a diagram for each sphere radius showing the neighbouring statistics for LSB and HSB galaxies at several scales. Figure 2 shows as an example the distribution for the number of neighbours within a sphere of the radius $r = 3.2$ Mpc (left panel) around each HSB and LSB galaxy. The mean values of neighbours for LSB and HSB galaxies were calculated for every applied sphere radius and are displayed in the right panel as a function of the corresponding radius. The error bars indicate the statistical error for LSB mean values (error bars for
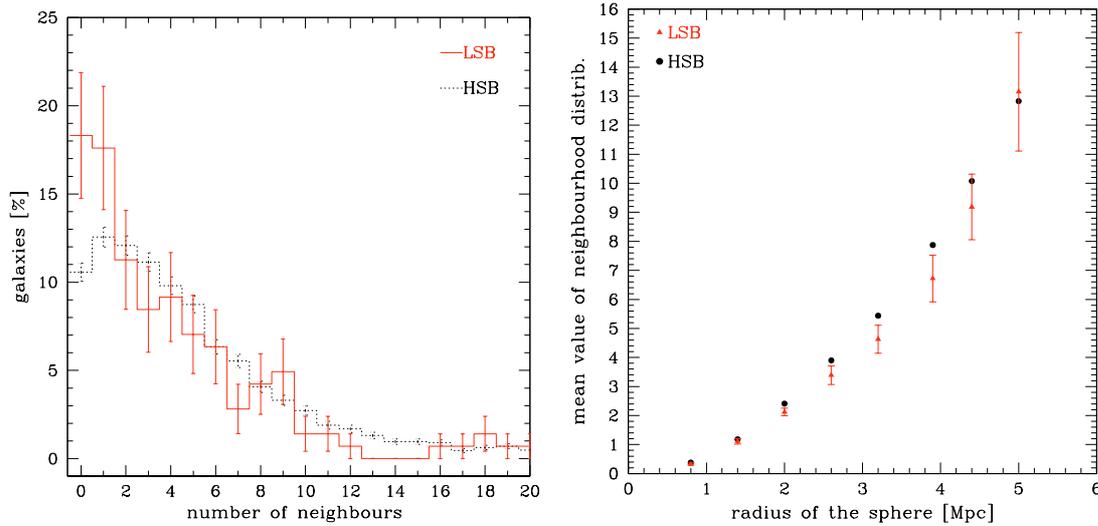
**Fig. 2.** Left panel shows the distribution of the number of neighbours within a sphere with a radius of $r = 3.2$ Mpc for LSB (solid line) and HSB (dashed line) galaxies. Right panel contains the mean values of the neighbourhood distributions for LSB (triangle) and HSB galaxies (dots) at several sphere radii.

the HSB distribution correspond approximately to the size of the dots). In Fig. 3 the results of this analysis for the runs with $N = 1$ and $N = 5$ of the distributions of LSB and HSB galaxies are displayed. In order to increase the low number statistics of the LSB sample a cumulative delineation is chosen.

On lower scales (with $r = 2.0$ Mpc and below, Fig. 2 right panel and Fig. 3) the environmental statistics of the LSB galaxy distribution follows the distribution generated by the HSB galaxies within error margins as well. However, all LSB mean values lie systematically (but partially not significantly) below the corresponding HSB value.

The left panel of Fig. 3 shows that LSB galaxies seem to participate in pairs on the same scales as pure HSB pairs (represented by the HSB curve in the diagram). We want to point out that in our analysis the number of LSB-HSB pairs, which are counted both as HSB and as LSB pairs, is negligibly small compared to the quantity of HSB-HSB pairs. This is due to the fact that the amount of HSB galaxies exceeds the number of LSB galaxies by a factor of 20 (LSB-LSB pairs do not appear in our sample).

Studies of the environment at larger scales ($2.0 \leq r \leq 5.0$ Mpc) led to different results. While at small scales ($r \leq 2.0$ Mpc) the percentage of LSB galaxies with no or one neighbour is nearly the same as for HSB galaxies, this fact does not apply at intermediate scales ($2 \leq r \leq 5$ Mpc, Fig. 2, left panel). This result is reproduced by the dependency of the mean values on the sphere radius (right panel, Fig. 2). On scales between 2 and 4 Mpc the mean values are significantly lower for the LSB galaxies than for the HSB sample. In order to proof the significance of the statistics a Kolmogorov-Smirnov (KS) test was performed. For $2.6 \leq r \leq 4$ Mpc the KS test rejects the null hypothesis that the distributions for LSB and HSB neighbours are the same at a confidence level greater than 92% with a maximum value of 99.3% at a radius of 2.6 Mpc.

These results are also consistent with our $N$th neighbour analysis. The 5th nearest neighbour analysis (Fig. 3, right panel) shows a gap between both cumulative distributions on scales between 3.2 and 5.0 Mpc. This means that significantly fewer LSB galaxies exist with a distance to the 5th neighbour on these scales than HSB galaxies. This phenomenon reappears in the distributions of 3rd and 4th neighbour analysis but shifted slightly to lower scales. For the 4th neighbour analysis this gap is located within the interval of 3.0 to 4.8 Mpc and for 3rd neighbour studies it is found between 2.8 and 4.4 Mpc. The neighbourhood investigations for $N = 4$ and $N = 5$ are important, because they correspond to the typical number of compact group members. For $N \geq 6$ the cumulative distribution of the LSB galaxies follows the HSB distribution.

## 4. Discussion and conclusions

Figure 1 shows that the spatial distribution of LSB galaxies follows in general the LSS defined by HSB galaxies which is in good agreement with the results from investigations on LSB galaxies in the Century Survey (Brown et al. 2001). However, as mentioned before, there are some extremely isolated LSB galaxies located in voids of the LSS. The statistical results show that the isolation of LSB galaxies takes place on intermediate scales beyond the size of compact groups but in the range of the size of large groups and LSS filaments as well. For smaller ($r \leq 2$ Mpc) and larger scales ($r \geq 5$ Mpc) no significant differences in the statistical environments could be found in this study.

Our results contradict the results of Bothun et al. (1993), who found that the neighbouring distribution of LSB galaxies differs only on scales below 2 Mpc from the HSB distribution. Their statistics might be biased towards smaller scales by projection effects due to their two-dimensional treatment of the problem, which might have lead them to see the differences at smaller scales. However we cannot rule out the existence of differences between the LSB and HSB distributions on scales with $r \leq 2$ Mpc since these scales cannot be resolved statistically in our study due to the small numbers of neighbours at these
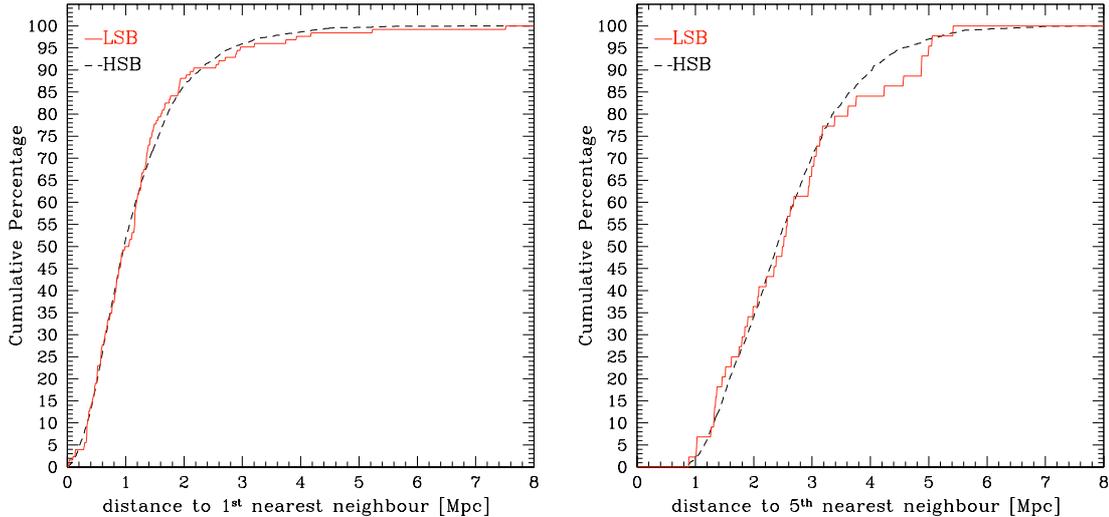
**Fig. 3.** Left panel shows the cumulative distribution of the distances to the first neighbour for LSB (solid line) and HSB (dashed line) galaxies. On the right panel the same distribution for the fifth nearest neighbour analysis is plotted.

scales in our sample. We only see a slight tendency that LSB galaxies may have less neighbours on small scales. Clearly this has to be investigated using the much larger datasets of the SDSS Data Releases 1 and 2 (Abazajian et al. 2003). On scales around 5 Mpc and beyond LSB galaxies trace the identical structure as HSB galaxies consistent with the results from Bothun et al. (1993).

All our results fit well into the following formation scenario, which was proposed by e.g. Bothun et al. (1997): galaxy formation takes place due to an initial Gaussian spectrum of density perturbations with much more low-density fluctuations than high density ones. Many of these low-density perturbations are lost due to the assimilation or disruption during the evolutionary process of galaxy formation but a substantial percentage of the fluctuations survives and is expected to form LSB galaxies. Further on one can assume that the spatial distribution of the initial density contrast consists of small scale fluctuations superimposed on large-scale peaks and valleys. Small-scale peaks lead to galaxy formation, whereas the large-scale maxima induce cluster and wall formation of the LSS.

Based on our results presented here, we propose that the galaxies formed in the large-scale valleys may develop to LSB galaxies due to their isolated environments whereas HSB galaxies formed mainly on the large-scale peaks. The isolation of LSB galaxies on intermediate and small scales must have effected their evolution since tidal encounters acting as triggers for star formation would have been rarer in these LSB galaxies than for HSB galaxies. Our results give strong evidence for this scenario, since the observed isolation of LSB galaxies takes place on scales below 5 Mpc, which is exactly the typical size of LSS filaments (e.g., White et al. 1987; Doroshkevich et al. 1997).

Hence, we conclude that LSB galaxies were formed in the voids of the LSS and that most of them have migrated to the edges of the filaments due to gravitational infall, but some of them still remain in the voids where they have formed in.

## References

Abazajian, K., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2003, AJ, 126, 2081

Bennett, C. L., Halpern, M., Hinshow, et al. 2003, ApJS, 148, 1

Boissier, S., Monnier Ragaigne, D., van Driel, W. Balkowski, C., & Prantzos, N. 2003, Ap&SS, 284, 913

Bothun, G. D., Schombert, J. M., Impey, C. D., Sprayberry, D., & McGaugh, S. S. 1993, AJ, 106, 530

Bothun, G. D., Impey, C. D., & McGaugh, S. S. 1997, PASP, 109, 745

Brown, W. R., Geller, M. J., Fabricant, D. G., & Kurtz, M. J. 2001, AJ, 122, 714

Dalcanton, J. J., Spergel, D. N., & Summers, F. J. 1997, ApJ, 482, 659

Doroshkevich, A. G., Fong, R., Gottlöber, S., Mücket, J. P., & Müller, V. 1997, MNRAS, 284, 633

Impey, C., & Bothun, G. 1997, ARA&A, 35, 267

Kennicutt, R. C. 1998, ARA&A, 36, 189

Mo, H. J., McGaugh, S. S., & Bothun, G. D. 1994, MNRAS, 267, 129

Pickering, T. E., Impey, C. D., van Gorkom, J. H., & Bothun, G. D. 1997, AJ, 114, 1858

Smith, J. A., Tucker, D. L., Kent, S., et al. 2002, AJ, 123, 2121

Stoughton, C., Lupton, R. H., Bernardi, M., et al. 2002, AJ, 123, 485

van der Hulst, J. M., Skillman, E. D., Smith, T. R., et al. 1993, AJ, 106, 548

White, S. D. M., Frenk, C. S., Davis, M., & Efstathiou, G. 1987, ApJ, 313, 505

Zaritsky, D., & Lorrimer, S. J. 1993, in Evolution of Galaxies and their Environment, 82