

An automated search for nearby low-surface-brightness galaxies – II. The discussion

Z. Morshidi-Esslinger, J. I. Davies and R. M. Smith

University of Wales, Cardiff, Department of Physics and Astronomy, PO Box 913, Cardiff CF2 3YB

Accepted 1998 November 13. Received 1998 November 13; in original form 1998 March 16

ABSTRACT

An automated search for low-surface-brightness (LSB) galaxies over 2187 deg² of sky produced 2435 galaxies. The technique, calibration, background contamination, models of the galaxy populations, survey and catalogue were discussed in Paper I. In this paper we present an analysis of our results. The number density of Fornax LSB galaxies drops exponentially with radius from the cluster centre with a scalelength of 1.25° while the bright galaxies have a scalelength of 0.48°. Spectroscopic observations in the Fornax region reveal that two LSB galaxies are at approximately the same redshift as the Fornax cluster, yet they are six bright galaxy scalelengths from the cluster centre. A correlation analysis of the sample indicates that our galaxies are much more strongly clustered ($A_\omega = 0.82$) than the general faint population (at the same magnitude limit) but less so than the bright nearby RC3 galaxies ($A_\omega = 2.23$) sampled within the same volume. This implies that LSB galaxies are associated with bright galaxies, but distributed over a larger scale. We have compared our observations with a fading model of the faint galaxy number counts. This model predicts ≈ 60 galaxies per field while we detect on average 13. Either the fading models are incorrect or there is strong differential fading between clusters and field. The luminosity function of the Fornax cluster has a slope of $\alpha = -1.58 \pm 0.6$. The total luminosity of the Fornax cluster is dominated by bright galaxies with a LSB-to-bright luminosity ratio of 0.02 while the field has a ratio of 0.03.

Key words: catalogues – surveys – galaxies: clusters: general – galaxies: evolution – galaxies: luminosity function, mass function.

1 INTRODUCTION

It is gradually being realized that observational selection effects may severely influence our view of the galaxy population of the Universe (Impey & Bothun 1997). We now know that dwarf and other low-surface-brightness galaxies (hereafter referred to as LSB galaxies) are the dominant population, at least numerically, in clusters (Binggeli, Sandage & Tammann 1985; Davies et al. 1988; Ferguson & Sandage 1988). Previous to our study (Morshidi-Esslinger, Davies & Smith 1999, hereafter Paper I) the spatial distribution and numbers of LSB galaxies in the general field was very uncertain (exceptions are Binggeli, Tarenghi & Sandage 1990; Dalcanton et al. 1997). This was primarily because deep large-area sky surveys did not exist. To maximize the chances of success, previous studies have concentrated on searches for LSB galaxies in nearby clusters. In Paper I we described our automated search for LSB galaxies over a total area of 2187 deg² in the southern sky using APM scan data of UKST photographic plates. We showed in that paper that our search technique was optimized to detect dE galaxies (though we will refer to the detected galaxies

collectively as LSB galaxies) with the following characteristics:

- (i) μ_0 fainter than 22.5 B mag arcsec⁻²;
- (ii) α larger than 3.0 arcsec;
- (iii) B_T brighter than 20th magnitude.

We also described the plate calibration, the detection methods and our estimates of background contamination from ‘normal’ galaxies. In this paper we describe and discuss the spatial distribution of the LSB galaxies compared with brighter galaxies, the possible relationship between local LSB galaxies and the faint blue galaxies (FBG) seen at higher redshifts and the contribution of these LSB galaxies to the local luminosity density.

2 THE CORRELATION FUNCTION OF LSB GALAXIES

We begin our analysis by carrying out a correlation study of our sample and compare it with that of a bright sample of galaxies (RC3) at equivalent depth. The results can then be used to test current theories of galaxy formation and evolution.

2.1 Previous studies of the correlation function

Biased galaxy formation (Dekel & Silk 1986) suggests that *normal* high-surface-brightness galaxies are formed from the highest peaks of the primordial density fluctuation whilst smaller peaks result in dwarf galaxies. The theory predicts that bright galaxies tend to be in higher density regions like clusters and superclusters while dwarf galaxies, which also exist in lower density regions, can provide a tool to trace the real mass distribution. The theory also predicts that the dwarf galaxies cluster less strongly, by a factor of 4 to 9, than the normal bright galaxies.

The conventional way of quantifying galaxy clustering is by means of the two-point spatial correlation function $\xi(r)$ [where $\xi(r) = (r/r_0)^{-\gamma}$]. However, this requires knowledge of the three-dimensional distribution of galaxies. Loveday et al. (1995) have found, from their correlation analysis of the Stromlo–APM redshift sample of 1787 galaxies brighter than $B_J = 17.15$, that early-type galaxies are clustered 3.5 to 5.5 times more strongly than late-type galaxies. The slope of $\xi(r)$ was found to be $\gamma = 1.85 \pm 0.13$ for the former class of galaxies and $\gamma = 1.64 \pm 0.05$ for the latter. They have also found that low-luminosity galaxies are clustered twice as weakly as L^* and brighter galaxies. Mo, McGaugh & Bothun (1994) found $\gamma = 1.7$ from their sample of 339 LSB galaxies. The comparison between the amplitude of the cross-correlation between their LSB galaxies and bright galaxies (CfA and IRAS) indicates that $(A_{\text{LSB-CfA}})/(A_{\text{CfA-CfA}}) \approx 0.4$ and $(A_{\text{LSB-IRAS}})/(A_{\text{IRAS-IRAS}}) \approx 0.6$. This suggests that while LSB galaxies are embedded in the same large-scale structure as bright galaxies, they are less strongly clustered, as indicated by the amplitudes (see below).

As the redshifts of the entire sample of our galaxies are prohibitively difficult to obtain, we have to resort to performing the analysis in two dimensions. This method, called the two-point angular correlation function, will nevertheless enable us to gain some insights into the clustering of our sample of LSB galaxies compared with nearby bright galaxies and fainter more distant ones.

The correlation function is defined by writing the probability of finding a companion to a given galaxy at some angular distance θ as follows:

$$\delta P(\theta) = N^2 [1 + \omega(\theta)] \delta\Omega_1 \delta\Omega_2, \quad (1)$$

where $\delta\Omega_1$ is the area element within which the first galaxy is found, $\delta\Omega_2$ is that of the companion galaxy and N is the mean surface density of galaxies. The quantity $\omega(\theta)$ is the two-point angular correlation function at separation θ . Assuming $\xi(r)$ follows a simple power law $\xi(r) = Br^{-\gamma}$, the two-point angular correlation function can be parametrized as (Koo & Szalay 1984; Groth & Peebles 1986; Maddox 1988)

$$\omega(\theta) = A_\omega \theta^{1-\gamma} \quad (2)$$

or

$$\omega(\theta) = A_\omega \theta^{-\delta}. \quad (3)$$

This correlation function describes the clustering properties of a galaxy sample, where its amplitude, A_ω , indicates the strength of the clustering.

Several groups have found that the slope of the correlation function seems to be approximately 0.8. Hewett (1982) analysed different types of estimators used by several groups to derive the angular correlation $\omega(\theta)$. Using data extracted from the Zwicky, Lick and Jagellonian photographic catalogues of bright galaxies (Peebles & Hauser 1974, Groth & Peebles 1977 and Peebles 1975,

respectively), he found a power-law index, δ , of 0.8 at small scales (and larger at greater scales). From an angular correlation analysis of their sample of 11 000 faint galaxies observed over a 0.4-deg^2 region, Koo & Szalay (1984) determined a slope of 0.8 for galaxies brighter than 20.0 (and 0.5 for fainter ones). Phillipps, Fong & Shanks (1981) used about 18 000 galaxies complete to $B_J = 21.5$ detected from COSMOS images of UK Schmidt plates. They found a slope of 0.7 for a magnitude limit of 19.5 (and 0.5 for a magnitude limit of 21.5). Using the Lick catalogue of galaxies brighter than $B = 20.0$, Groth & Peebles (1986) found the slope of their correlation function to be 0.741. Maddox et al. (1990) used APM data (two million galaxies brighter than $B_J = 20.5$) to study the angular correlation of galaxies and found the slope to be 0.668. From a sample of 860 dwarf and LSB galaxies Thuan et al. (1991) found dwarf LSB galaxies to have the same clustering properties as bright galaxies with clustering amplitude ratio $(A_{\text{Bright}})/(A_{\text{LSB}}) \sim 1.2$. In the following section we will describe how we have determined the correlation function of our LSB galaxy sample and how it compares with that of a sample of bright galaxies detected within the same volume.

2.2 The technique

In this section we will determine the autocorrelation function of our sample, i.e. a measure of the excess of galaxy–galaxy pairs over random pairs. We will also determine the cross-correlation function, which is a measure of correlation between two different classes of galaxies, in this case our LSB galaxies against bright RC3 galaxies.

The autocorrelation function $\omega(\theta)$ is determined by considering the distribution of our sample of galaxies relative to a reference Monte Carlo distribution of random points. The technique is described in detail by Hewett (1982) and Couch, Jurcevic & Boyle (1993). The values of $\omega(\theta)$ are computed using the following equation (Schwartzzenberg 1996):

$$\omega(\theta) = \frac{N_{\text{gg}}}{N_{\text{gr}}} - \frac{N_{\text{rg}}}{N_{\text{rr}}},$$

where N_{gg} , N_{gr} , N_{rg} , N_{rr} are respectively the number of galaxy–galaxy pairs, galaxy–random pairs, random–galaxy pairs and random–random pairs, respectively. This equation (a slightly modified version of that given in Couch et al. 1993) takes into account edge effects. The term $N_{\text{rg}}/N_{\text{rr}}$ accounts for small-amplitude large-scale gradients across the field, giving a more stable estimate of the two-point angular correlation function (Couch et al. 1993). The values of galaxy–random, random–galaxy and random–random pairs are averaged over sets of 100 values. The bin size in angular separation is decreased in order to keep a constant annulus area. The initial bin size was 1° .

In the cross-correlation analysis between LSB galaxies and bright ones, we used the following equation (Schwartzzenberg 1996; Mo et al. 1994):

$$\omega(\theta) = \frac{N_{\text{lb}}}{N_{\text{lr}}} - 1,$$

where N_{lb} and N_{lr} are the number of LSB–bright pairs and LSB–random pairs, respectively.

2.3 The data

The raw data for the correlation analysis are extracted from our catalogue of 2345 LSB galaxies (fig. 5 of Paper I). We have used a rectangular area of $22^\circ \times 45^\circ$ for the correlation analysis. The area

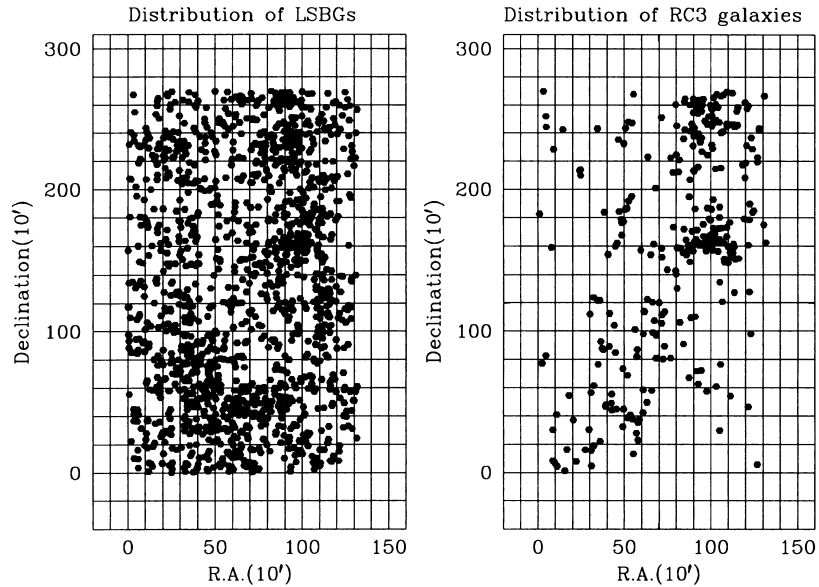


Figure 1. Our subsample of LSB galaxies and the corresponding RC3 galaxies in the rectangle of $22^\circ \times 45^\circ$. The origin of the coordinates at (0,0) corresponds to the south-east corner of the sky area.

contains 1604 LSB galaxies (see Fig. 1). As far as bright galaxies are concerned, we used 321 objects taken from RC3 (de Vaucouleurs 1991). These galaxies are distributed within the same $22^\circ \times 45^\circ$ region of sky as the LSB galaxies. The bright objects were selected within a distance corresponding to a radial velocity of 5000 km s^{-1} or 100 Mpc for $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ so that they extend to the same depth as the LSB galaxies in our sample. In Paper I we demonstrated using a numerical model that the dwarf galaxies in our sample have a maximum radial velocity of $\approx 5000 \text{ km s}^{-1}$. The effects of LSB galaxies, at higher velocities, on our correlation analysis will be dealt with later. Fig. 1 shows the distribution of our LSB and bright galaxy samples.

2.4 The results and analysis

The autocorrelation function of our sample of 1604 LSB galaxies is shown in Fig. 2. The errors plotted on all points are calculated following the method of Couch et al. (1993), which is based on a \sqrt{N} uncertainty in N_{gg} and N_{gr} . The result of a least-squares fit to this function is shown in Table 1. The analysis indicates that the slope of the LSB correlation function is 0.69 ± 0.14 . This slope is in agreement, within the errors, with the ones found by many groups who analysed galaxies with magnitude limits down to 22.5 (Koo & Szalay 1984; Stevenson et al. 1985; Pritchet & Infante 1986; Couch et al. 1993). Our results show that the excess of LSB galaxy pairs over random ones (as indicated by the power-law index) approximately follow that of normal bright galaxies.

The amplitude of the LSB correlation function of our sample is measured to be 0.32, somewhat higher than that found by others who have carried out a similar analysis to a similar magnitude limit using higher surface brightness galaxies. This shows that our LSB galaxies correlate more strongly in the sky than the general faint populations observed by others. This is expected if we have selected galaxies relatively nearby, in contrast with what one would typically expect for a sample down to this magnitude limit. The correlation function of bright RC3 galaxies are shown in Fig. 3 is found to have a slope of 0.60 ± 0.13 and an amplitude of 1.95.

A plot of the cross-correlation function between LSB and bright

galaxies is presented in Fig. 4. The error on each point is calculated as before. The result of the least-squares fit is again given in Table 1. The slope is found to be 0.98 ± 0.14 and the amplitude 0.50. This former value indicates that there is indeed a good correlation between the LSB and bright samples and that at least some of the LSB galaxies share the same distance as the bright RC3 objects.

The amplitude of the autocorrelation of the LSB galaxies is lower than that of the bright objects, which suggests that either some fraction of the LSB galaxies is in the background (≈ 19 per field, see Paper I) or they have a more extended distribution than their bright counterparts. We can make an estimate of the influence that the background galaxies might have on our correlation analysis by trying to extricate it from that of our combined sample of local LSB galaxies and possible background galaxies. Recall that $\delta P(\theta) = N^2 [1 + \omega(\theta)] \delta\Omega_1 \delta\Omega_2$ is the probability of finding a

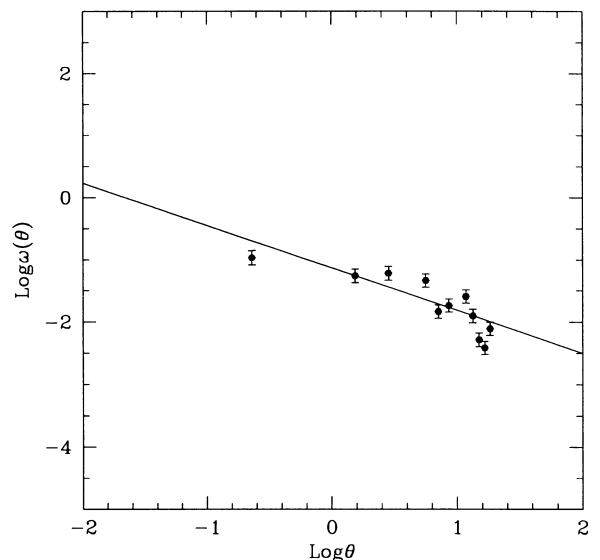


Figure 2. The autocorrelation function of LSB galaxies (θ is measured in degrees).

Table 1. The results of the autocorrelation and the cross-correlation analyses of LSB and bright samples.

Samples	Gradient	Intercept	Amplitude A_ω
LSB–LSB	-0.69 ± 0.14	-1.15 ± 0.14	0.32
bright–bright	-0.60 ± 0.13	0.67 ± 0.11	1.95
LSB–bright	-0.98 ± 0.14	-0.69 ± 0.12	0.50

companion to a galaxy in our combined sample of background and local galaxies. In this case N is the surface density of the combined sample. Note that the combined sample contains the local population (of galaxies with $V_r \leq 5000 \text{ km s}^{-1}$) and the background population (of galaxies with $V_r > 5000 \text{ km s}^{-1}$). The probability δP can be written as

$$\delta P_c = \delta P_{aa} + \delta P_{bb} + \delta P_{ab} + \delta P_{ba},$$

where δP_c is the probability of finding a companion to a galaxy in the combined sample. δP_{aa} and δP_{bb} are respectively the probabilities for the local and background samples. δP_{ab} and δP_{ba} are the cross-probabilities between the two samples. δP_c can then be written as (Phillipps 1979)

$$N_c^2 [1 + \omega_c(\theta)] = N_{aa}^2 [1 + \omega_{aa}(\theta)] + N_{bb}^2 [1 + \omega_{bb}(\theta)] \\ + N_a N_b [1 + \omega_{ab}(\theta)] + N_b N_a [1 + \omega_{ba}(\theta)].$$

As the local and background populations are uncorrelated (i.e. they are not at the same distance), $\omega_{ab}(\theta) = \omega_{ba}(\theta) = 0$. Therefore,

$$N_c^2 \omega_c(\theta) = N_{aa}^2 \omega_{aa}(\theta) + N_{bb}^2 \omega_{bb}(\theta),$$

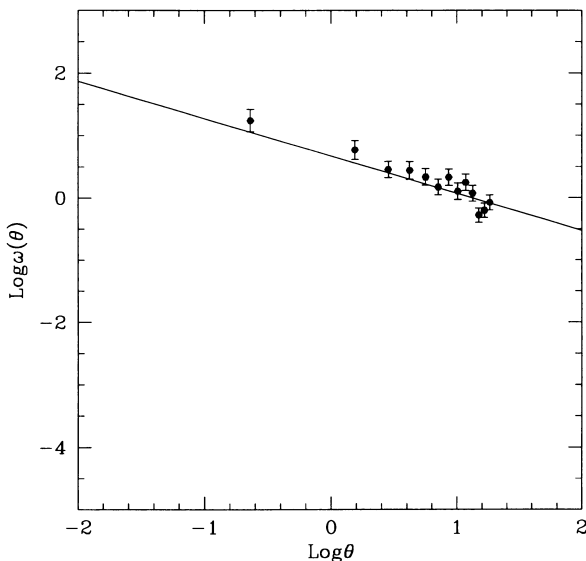
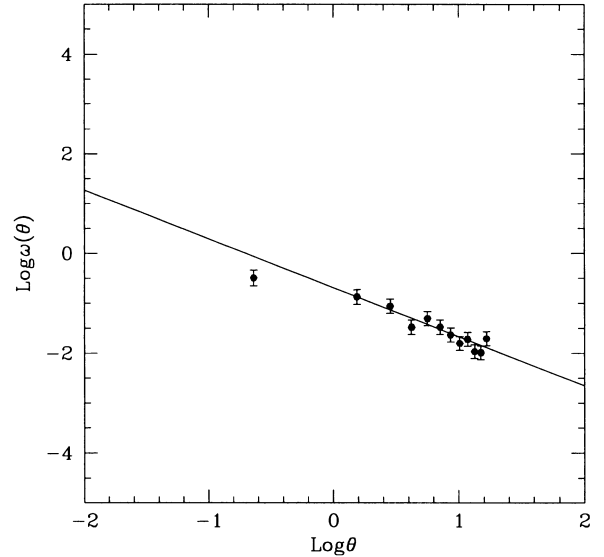
because

$$N_c^2 = (N_{aa} + N_{bb})^2.$$

The local autocorrelation $\omega_{aa}(\theta)$ can be rearranged as

$$\omega_{aa}(\theta) = \left(\frac{N_c}{N_{aa}}\right)^2 \omega_c - \left(\frac{N_{bb}}{N_{aa}}\right)^2 \omega_{bb}.$$

The surface density of the combined sample N_c is calculated to be $1.62 \text{ galaxy deg}^{-2}$, that of the background population (our estimates indicate that there are about 19 background galaxies per

**Figure 3.** The autocorrelation function of bright RC3 galaxies (θ is measured in degrees).**Figure 4.** The cross-correlation function of LSB galaxies against bright RC3 galaxies.

$5.83^\circ \times 5.83^\circ$ field, see Paper I) N_{bb} as $0.56 \text{ galaxy deg}^{-2}$ and that of the local sample N_{aa} as $1.06 \text{ galaxy deg}^{-2}$. We take the background correlation function from Maddox et al. (1990) where $\omega_{bb}(\theta) = 0.0284\theta^{-0.668}$ [we use the results of Maddox et al. (1990) because they have sampled to approximately the same magnitude limit]. The autocorrelation function of local LSB galaxies is then calculated as follows:

$$\omega_{aa}(\theta) = 0.749\theta^{-0.690} - 0.008\theta^{-0.668}.$$

As the second term is much smaller than the first term for reasonable values of θ , we have

$$\omega_{aa}(\theta) \approx 0.75\theta^{-0.69}.$$

In this case, the amplitude of the autocorrelation of the local LSB galaxies is 0.75. Fixing the slope of the correlation function of the nearby LSB galaxies at -0.8 (Hewett 1982), the amplitude becomes 0.82. Fitting the correlation function of the nearby RC3 galaxies with the same slope of -0.8 , the corresponding amplitude becomes 2.23. Comparing the two amplitudes, one can say that the nearby bright RC3 galaxies cluster \approx three times more strongly than their LSB counterparts (see Table 2).

3 THE DISTRIBUTION OF LSB GALAXIES

How are the LSB galaxies distributed in comparison with their bright counterparts? We analyse here first the radial density as a function of radius from the centre of the Fornax cluster, secondly the number per radial velocity bin and finally the correlation function of our LSB galaxies compared with that of the bright galaxies discussed in the previous section.

Table 2. For a comparison of clustering strengths of the LSB and bright galaxies, we fix their respective slopes at -0.8 .

Samples	Gradient	Intercept	Amplitude A_ω
LSB–LSB	-0.8	-0.2	0.82
bright–bright	-0.8	0.8	2.23

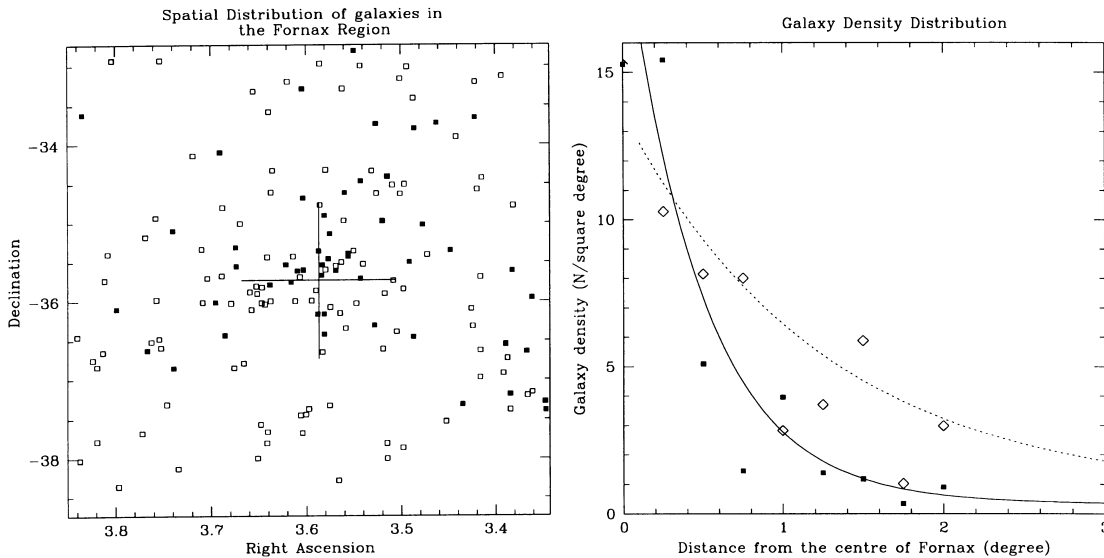


Figure 5. The left panel (filled symbols bright galaxies, open symbols LSB galaxies) illustrates the spatial distribution of the LSB galaxies in the Fornax region relative to the brighter population. The centre of the Fornax cluster is marked by a cross. The right panel shows how the number density of the LSB galaxies relates to distance from the centre of the cluster compared with bright galaxies. The curved lines are exponential fits of the density distributions of the bright galaxies (the solid line) and of the LSB population (the dashed line).

3.1 Number density distribution

We described our initial analysis of the Fornax cluster in Paper I. The number density of LSB galaxies falls with distance from the centre of the cluster more slowly than that of the bright galaxies. The exponential fits to the number density versus radius plots indicate a scalelength of 1.25° for the LSB galaxies while that of the bright galaxies has a scalelength of 0.48° (see Fig. 5). In Paper I we showed that there is a background galaxy count of ≈ 0.5 LSB galaxy deg^{-2} and that there is a strong contrast between the cluster and this background.

3.2 Redshift data

In Paper I we also presented redshift data for a sample of 20 LSB galaxies that obey our selection criteria. The redshift data reveal that there are two galaxies on either side of the Fornax field that are at about the same distance as the Fornax cluster. If these two galaxies are part of the Fornax LSB galaxy population then they appear to have a far more extended distribution than that of the bright population that is confined to the Fornax field. From the centre of the cluster, these galaxies are at distances of about 3.2° and 2.0° (i.e. 1.5 Mpc and 1.0 Mpc). In comparison with the number density distribution of bright galaxies, these two galaxies are at as much as six times the scalelength of the bright galaxy distribution.

In terms of radial velocities, the LSB galaxies have a flat number distribution compared with that of bright galaxies (see Fig. 7 of Paper I). This result is consistent with the radial velocity distribution of Held & Mould (1994). It suggests that LSB galaxies have a more extended radial velocity distribution compared with bright galaxies, analogous to their two-dimensional angular distribution.

3.3 The correlation results

The details of our correlation studies were described in the previous section. Having attempted to separate the contribution of the nearby population from that of the background population, we found that

the nearby LSB galaxies cluster \approx three times less strongly compared with the nearby bright RC3 galaxies.

4 IMPLICATIONS FOR GALAXY FORMATION AND EVOLUTION SCENARIOS

The biased galaxy formation theory (Dekel & Silk 1986) predicts that dwarf galaxies cluster four to nine times less strongly than bright ones. The amplitude of the autocorrelation of our sample of local LSB galaxies is about three times lower than that of bright ones. The LSB galaxies are therefore less strongly clustered than the bright galaxies, but not by quite as much as Dekel & Silk (1986) would predict. The strong cross-correlation indicates that the LSB population follows the distribution of their bright counterpart quite well. The excess number of LSB galaxies in the cluster over that in the field (see below) suggests another possible galaxy formation scenario – i.e. rather than being formed from primordial density fluctuations, the LSB galaxies could have been formed from the debris of galaxy interactions in high-density environments like clusters (as proposed by Hickson 1982 and Hunsberger, Charlton & Zaritsky 1996). It is difficult to distinguish between these two alternatives.

Merging model explanations of the FBG problem (Rocca-Volmerange & Guiderdoni 1990; Broadhurst, Ellis & Glazebrook 1992; Carlberg & Charlot 1992) require that the excess population of faint galaxies at $z \sim 0.2-0.5$ cluster very strongly for galaxy interactions to occur. Evidences from correlation studies of galaxies as faint as $B_J = 24$ indicate that, although they have a high number density per unit area, these faint galaxies are very weakly clustered (Koo & Szalay 1984; Pritchet & Infante 1992; Couch et al. 1993). Assuming that these faint galaxies are indeed a population at $z \sim 0.2-0.5$, their weak clustering argues against merging as a possible solution to the FBG problem. In Paper I we showed that we detected far too few galaxies for a typical fading model to be correct unless there is strong differential fading between the clusters and the field. The rapid fading and normal fading models (Cowie, Songaila & Hu 1991; Babul & Rees 1992; Driver 1994), which

do not require strong clustering, provide a better alternative to the merging models and the galaxy harassment model. The rapid fading model of Babul & Rees (1992) proposed that the faint galaxies underwent their initial starbursts at $z \sim 1$. They predict that, having faded very rapidly, the surviving dwarf galaxies at the present epoch should be clustered relatively strongly because of differential fading between cluster and field. The observed distribution of local dE galaxies would concentrate within the large-scale structure defined by the bright nearby galaxies. This model does provide a satisfactory explanation of our observations and those of the clustering of the FBG population.

5 CONTRIBUTION OF LSB GALAXIES TO FBG POPULATION

In this section we describe the contribution that these local LSB galaxies could make to the excess faint blue galaxies (FBG) seen at higher ($z \approx 0.5$) redshifts (see Ellis 1997). Essentially we wish to test the hypothesis (Driver 1994) that the FBG have now faded in surface brightness so that they exist locally, but are very difficult to detect because of their LSB. We described a numerical model in Paper I using Driver's luminosity function and various surface brightness distributions. Below we use this model to predict the numbers of LSB galaxies we should expect to find within each field if Driver's fading model is the correct explanation of the FBG problem.

5.1 The results and implications

We showed in Paper I that if we are to explain the FBG problem using a fading model (without differential fading between field and cluster) we would expect to detect ≈ 60 LSB galaxies per field. This is much higher than the 13 galaxies actually detected. There are not enough nearby LSB galaxies to support the excess population at intermediate redshift without involving rapid evolution in the field compared with the clusters.

The results indicate a real dilemma as to how the faint blue galaxies at intermediate redshift evolve. The weak clustering of the faint galaxies (despite their high surface density) found by Koo & Szalay (1984), Pritchett & Infante (1992) and Couch et al. (1993) suggests that merging is not likely to be the mechanism for galaxy evolution. The normal fading model suggested by Driver (1994) also faces considerable difficulties because we have not detected sufficient local LSB galaxies to account for the faint galaxies at intermediate redshifts. Several possibilities which can explain the discrepancy are listed, as follows.

(i) Driver's model is correct but the intrinsic surface brightness distribution we used is incorrect, i.e. the surface brightness–magnitude relation (observed in the cluster samples) does not apply in the field. Neither does the flat intrinsic surface brightness distribution, although the best information we have seems to suggest that the distribution is flat (e.g. Davies et al. 1988; McGaugh, Bothun & Shombert 1995).

(ii) Our data lack lumpy galaxies (e.g. irregulars). The APM classifies lumpy galaxies, i.e. objects which appear to have multiple nuclei or two galaxies (or more) very close together by line-of-sight coincidence, as merged objects and not as galaxies. Therefore, our survey also tends to miss 'lumpy' (irregular) galaxies. If these lumpy galaxies are more prolific in the field than in the clusters (morphology–density relation) then the fading model could still be viable (the evidence for more irregular galaxies in the field is presented in Section 6.3).

(iii) The nearby field LSB galaxies have faded much more than cluster ones. The rapid fading model of Babul & Rees (1992), as described earlier, does again offer a satisfactory explanation of the observations. dE galaxies in the field fade more quickly because they cannot retain their gas for subsequent star formation. The model predicts that 60 to 80 percent of the faint galaxies in the general field, having been subjected to a more severe gas loss than their cluster counterparts, would by now have faded from sight. A comparison between the observed local number densities of 76, 39, 65 and 13 galaxies per field, respectively, in the Fornax cluster, NGC 1400 and the Dorado groups and the general field shows that there are 67 to 83 per cent more local LSB galaxies in the cluster and groups than in the general field.

6 THE MORPHOLOGY OF THE LSB GALAXIES IN OUR SAMPLE

A subsample of galaxies in the Fornax–Sculptor survey (see Paper I) was used in order to study the morphology of cluster and field galaxies. We based our classification on the method employed by Ferguson & Binggeli (1994), where galaxies with round and smooth features are taken as dE while the ones with lumpy and irregular features are taken as dI or background spirals. These LSB galaxies were examined by eye using the Digitized Sky Survey images, where the pixel resolution is rather poor and so LSB irregular and distant spirals are difficult to distinguish. The quality is, perhaps, sufficient for a crude estimate of cluster and field galaxy morphological types. A more accurate study requires high-resolution images similar to the ones used by Ferguson (1989) in his study of the Fornax galaxies.

The Fornax field alone seems to have about 80 per cent dE galaxies and 20 per cent dIs or background spiral. In contrast, the general field seems to be populated by a much greater fraction of dIs and/or background spirals. The field appears to have approximately 43 per cent dE and 57 per cent dI or background spirals. Our estimate of approximately 19 background galaxies per field (see Paper I) is consistent with this being equivalent to about 60 per cent of the field population.

Although we find more irregular looking galaxies in the field, this is entirely consistent with our estimate of background contamination by spirals, but there do appear to be dE galaxies well away from the clusters (≈ 13 per field).

7 THE CONTRIBUTION OF LSB GALAXIES TO THE LOCAL DENSITY

In this section we will first discuss the number density of LSB galaxies in the cluster, groups and the general field. Secondly, we will consider the slopes of the luminosity functions of LSB galaxies in these fields. Finally, we will assess the total luminosity of LSB galaxies compared with bright galaxies.

7.1 The local number density of LSB galaxies

Our data show a distinctly different surface density between cluster, groups and general field. We observe an overdensity in the cluster and groups of 67 to 83 per cent compared with the general field. The field has a surface density of $0.88 \text{ galaxy deg}^{-2}$, while the Fornax Cluster, NGC 1400 and Dorado groups respectively have surface densities of $2.24 \text{ galaxy deg}^{-2}$, $1.15 \text{ galaxy deg}^{-2}$ and $1.91 \text{ galaxy deg}^{-2}$ (the respective surface densities of these systems were measured per field containing the cluster and groups). All these

values are lower than that obtained by Dalcanton et al. (1997) in their CCD survey for field LSB galaxies with $23 < \mu_0 < 25$ V mag arcsec⁻² (or $24 < \mu_0 < 26$ B mag arcsec⁻² assuming $B - V = 1$) and $\alpha > 2.5$ arcsec. They have obtained a value of $4.1^{+2.6}_{-2.1}$ galaxy deg⁻². Their value is probably higher than we obtained in our survey because their CCD detector allows them to probe deeper than our photographic study can. Their criteria also allow them to detect smaller galaxies. The difference in the scalelength limit is only 0.5 arcsec, but the difference in the detected number is large because of the steep rise in detections as the scalesize is reduced. For a flat surface brightness distribution we should expect Dalcanton et al. (1997) to detect $(3.0/2.5)^3 \times (2.0/1.5)$ more galaxies in the field than we can, i.e. 2.5 galaxy deg⁻². This value is consistent with their lower limit of 2.0 galaxy deg⁻² [the $(3.0/2.5)^3$ term accounts for the difference in scalesize selection, while the factor $(2.0/1.5)$ accounts for the different range of surface brightness sampled].

7.2 The luminosity contribution of LSB galaxies

In the last section we found that the LSB galaxies dominate the Fornax Cluster numerically. In this section we shall discuss how significant their luminosity contribution is compared with that of bright galaxies. As for the general field, we will use the average number of nearby field LSB (background galaxies subtracted) and bright galaxies per field and their average luminosities.

Assuming that the bright RC3 galaxies and the faint LSB galaxies are contained within the same volume, the apparent magnitudes can be used to estimate the luminosity ratio of the LSB galaxies compared to the bright ones.

The RC3 catalogue lists 73 bright galaxies in the Fornax cluster, while the general field has an average of four bright galaxies per field within 5000 km s⁻¹ (see Section 2 and Paper I). In comparison, our catalogue indicates that there are 76 LSB galaxies in the Fornax cluster, the majority of which have an apparent magnitude of $B = 18.0$, and there are an average of 13 nearby LSB galaxies in the field with an average apparent magnitude of $B = 19.0$.

The LSB-to-bright field galaxy luminosity ratio is then 0.03, while in the Fornax Cluster the luminosity ratio is 0.02. Assuming the same (M/L) ratio for LSB galaxies as for bright galaxies, the result shows that the LSB galaxies contain only a small fraction of the total mass and luminosity in the local Universe. However, much higher (M/L) ratios have been found for some LSB galaxies, which could lead to a higher mass contribution. Several attempts to determine the (M/L) ratios of dwarf spheroidals in the Local Group indicate that they could have (M/L) as high as 245 ± 155 (M_{\odot}/L_{\odot}) (Irwin & Hatzidimitriou 1995).

8 SUMMARY

(i) Our sample LSB galaxies are more spatially extended compared with brighter galaxies. This has been determined in four separate ways. First, the number density of Fornax LSB galaxies falls exponentially with distance from the cluster centre with a scalelength of 1.25° while their bright counterparts are distributed with a scalelength of 0.48° . Secondly, two Fornax LSB galaxies, measured by virtue of spectroscopic observations, are found to be 6.7 times farther away than the scalelength of the number density distribution of the bright galaxies, the clustering strength of the LSB galaxies ($A_{\omega} = 0.82$) is three times lower than that of the bright galaxies ($A_{\omega} = 2.23$) and finally from a limited redshift survey we find a flatter distribution of radial velocities than for brighter galaxies. Our clustering result is not wholly consistent with the

prediction of the biased galaxy formation model in that the LSB galaxies should be four to nine times less strongly clustered than the bright galaxies. The rather strong cross-correlation between the LSB and the bright galaxies suggests that they define the same large-scale structure.

(ii) A comparison of our data with a model indicates that a simple fading model is not a satisfactory explanation of the FBG seen at higher redshifts. Differential fading between clusters and the field is required.

(iii) The study of LSB galaxy morphology on a subsample of our survey indicates that, while the Fornax field is dominated by 79 dwarf ellipticals and 16 background irregulars and spirals, the general field is populated by ≈ 13 dwarf ellipticals and ≈ 19 background irregulars or spirals per UKST field (5.8×5.8 deg²). These numbers are in good agreement with our other estimates of the background contamination and the nearby population. The excess of dwarf ellipticals in clusters, by a factor of 6, over that of the field is again consistent with the suggestion by Babul & Rees (1992) that the evolution of dwarf ellipticals depends very much on environment.

(iv) The surface densities of LSB galaxies in the Fornax cluster, NGC 1400 group, Dorado group and the general field are respectively 2.24, 1.15, 1.91 and 0.38 galaxy deg⁻².

The LSB galaxies do not appear to contribute significantly to the luminosity of the Fornax cluster. The LSB-to-bright luminosity ratio is calculated to be 0.02. In the field the luminosity fraction of LSB galaxies compared with bright galaxies is 0.03.

ACKNOWLEDGMENTS

ZME thanks MARA for financing her PhD and the University of Wales, Cardiff for providing occasional funding. Thanks also go to Mike Irwin, Steve Maddox, Jon Loveday and Michael Drinkwater for providing us with APM, calibration and redshift data. We also thank Steve Phillipps for useful discussions.

REFERENCES

- Babul A., Rees M. J., 1992, MNRAS, 255, 345
 Binggeli B., Sandage A., Tammann G. A., 1985, AJ, 90, 1681
 Binggeli B., Tarengi M., Sandage A., 1990, A&A, 228, 42
 Carlberg R. G., Charlot S., 1992, ApJ, 397, 5
 Couch W. J., Jurcevic J. S., Boyle B. J., 1993, MNRAS, 260, 241
 Cowie L. L., Songaila A., Hu E. M., 1991, Nat, 354, 460
 Dalcanton J. J., Spergel D. N., Gunn J. E., Schmidt M., Schneider D. P., 1997, AJ, 114, 635
 Davies J. I., Phillipps S., Cawson M. G. M., Disney M. J., Kibblewhite E. J., 1988, MNRAS, 232, 239
 Dekel A., Silk J., 1986, ApJ, 303, 39
 de Vaucouleurs G. H., 1991, Third Reference Catalogue of Bright Galaxies. Springer-Verlag, New York
 Driver S. P., 1994, PhD thesis, Univ. Wales College of Cardiff
 Ellis R., 1997, ARA&A, 35, 389
 Ferguson H. C., 1989, AJ, 98, 367
 Ferguson H. C., Binggeli B., 1994, ARA&A, 6, 67
 Ferguson H. C., Sandage A., 1988, AJ, 96, 1520
 Groth E. J., Peebles P. J. E., 1977, ApJ, 217, 385
 Groth E. J., Peebles P. J. E., 1986, ApJ, 310, 499
 Held E. V., Mould J. R., 1994, AJ, 107, 1307
 Hewett P. C., 1982, MNRAS, 201, 867
 Hunsberger S. D., Charlton J. C., Zaritsky D., 1996, ApJ, 462, 50
 Impey C., Bothun G., 1997, ARA&A, 35, 267
 Koo D. C., Szalay A. S., 1984, ApJ, 282, 390

- McGaugh S. S., Bothun G. D., Schombert J. M., 1995, *AJ*, 110, 573
Maddox S. J., 1988, PhD thesis, Univ. Cambridge
Maddox S. J., Efstathiou G., Sutherland W. J., Loveday J., 1990, *MNRAS*, 242, 43p
Mo H. J., McGaugh S. S., Bothun G. D., 1994, *MNRAS*, 267, 129
Morshidi-Esslinger Z., Davies J. I., Smith R. M., 1999, *MNRAS*, 304, 297
(Paper I, this issue)
Peebles P. J. E., 1975, *ApJ*, 196, 647
Peebles P. J. E., Hauser M. G., 1974, *ApJS*, 28, 19
Phillipps S., 1979, PhD thesis, Univ. Durham
Phillipps S., Fong R., Shanks T., 1981, *MNRAS*, 194, 49
Pritchett C. J., Infante L., 1986, *AJ*, 91, 1
Pritchett C. J., Infante L., 1992, *ApJ*, 399, L35
Rocca-Volmerange B., Guiderdoni B., 1990, *MNRAS*, 247, 166
Schwartzberg J. M., 1996, PhD thesis, Univ. Bristol
Stevenson R., Shanks T., Fong R., MacGillivray H., 1985, *MNRAS*, 213, 953
Thaun T. X., Alimi J. M., Gott J. R., Schneider S. E., 1991, *ApJ*, 370, 25