LOW SURFACE BRIGHTNESS GALAXIES IN THE CORE OF THE COMA CLUSTER

M. P. Ulmer, G. M. Bernstein, D. R. Martin, R. C. Nichol, J. L. Pendleton, and J. A. Tyson

Received ___________; accepted ______________

1Dept. of Physics and Astronomy, Northwestern University, Evanston, IL 60208-2900; Electronic mail: m-ulmer2@nwu.edu
2Dept. of Astronomy, 829 Dennison Bldg., University of Michigan, Ann Arbor, MI 48109; Electronic mail: garyb@astro.lsa.umich.edu
3Princeton Univ., Princeton, NJ 08544; Electronic mail: drmartin@phoenix.princeton.edu
4Dept. of Astronomy and Astrophysics, University of Chicago, 5640 South Ellis Ave., Chicago, IL 60637; Electronic mail: nichol@oddjob.uchicago.edu
5Current address: Research Systems, Inc., 2995 Wilderness Place, Boulder, CO 80301; Electronic mail: jpendleton@rsinc.com
6AT&T Bell Laboratories, Room 1D432, Murray Hill, NJ 07974; Electronic mail: tyson@physics.att.com
7Visiting Astronomer, Kitt Peak National Observatory
ABSTRACT

We present the results of a search for low surface brightness galaxies (hereafter LSBs) in the Coma cluster. Bernstein et al. report on deep CCD observations in R of a $\sim 7.'5 \times 7.'5$ region in the core of the Coma cluster, and we extend this work by finding and measuring 36 LSBs within this field. We report both R and B$_j$ results. The average magnitude based on the best fit exponential to the images is 22.5 (R) and the typical exponential scale is 1.'3. The range of exponential scales is 0.4 to 1.2 kpc (distance modulus 34.89), and the range of central surface brightnesses is 24 to 27.4 R mag per square arcsecond. Many of these objects are similar in terms of scale length and central surface brightness to those found by others in nearby clusters such as Fornax (Bothun, Impey & Malin), as well as in the low luminosity end of the dwarfs cataloged in the review of Ferguson & Binggeli. We find no evidence for a dependence of color on central surface brightness or on distance from the D galaxies or the X-ray center of Coma. We also find that these LSBs make a small contribution to the overall mass of the cluster. We discuss these results in terms of possible scenarios of LSB formation and evolution.
1. INTRODUCTION

Due to its high galactic latitude, its richness, and relatively low redshift, the Coma cluster of galaxies is an excellent place to study the effects of cluster environment on the formation and evolution of low luminosity galaxies. Extensive studies of the Coma cluster have shown that it has a high mass-to-light ratio (about 300) and a dense ($10^{-3}$ particles/cm$^3$), hot ($10^8$ K), intra-cluster medium (cf. Sarazin 1986). These characteristics of the Coma cluster make its core region an extremely interesting environment to study, and increased knowledge of the faint end of the luminosity function will extend our understanding of the formation and evolution of galaxies in rich clusters. Here we report an analysis of low surface brightness galaxies (LSBs, hereafter) which, for our sample, are effectively a subclass of dwarf ellipticals (dEs, hereafter). Our analysis was based on deep CCD imaging of the Coma cluster core (Bernstein et al. 1995). This study is of the richest cluster environment yet reported, and the purpose of this paper is to find fainter objects in denser cluster environments than previous reports: Fornax (Bothun, Impey & Malin 1991; Bothun, Caldwell & Schombert 1989; Phillipps et al. 1987 and references therein), Virgo (Impey, Bothun & Malin 1988; Binggeli & Cameron 1991), and A3574 (Turner et al. 1993). The LSBs we have found have central surface brightnesses as faint as 27.4 per square arcsecond (R), and exponential scales as large as 1.2 kpc. The projected density of these objects per square Mpc is about 8 times the previously reported maximum value (Turner et al.). A general definition of LSBs is that the central surface brightness of the galaxy be fainter than 23 mag per square arcsecond in B (cf. Bothun et al. 1991), but there are a wide range of values (1" to 20") for the exponential scale factors and net size and brightness (Bothun et al. 1991; Turner et al. 1993; Bothun et al. 1989; Binggeli & Cameron). The origin of these extreme objects is still unknown, but as more data like ours are accumulated, we will achieve better ideas of the formation processes of LSBs and dEs.

After describing the data analysis and results, we compare our results with some of
the many hypotheses that have been proposed to explain the existence of dEs or LSBs. We also demonstrate that, although the objects were a potential source of the missing mass in Coma, they probably play a negligible role in the dynamics of the Coma cluster due to their small numbers.

In this paper, we assume a distance of 95 Mpc to Coma \( (H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}, \nu_r = 7125 \text{ km s}^{-1}, \text{distance modulus} = 34.89) \) and, therefore, the scale is 0.46 kpc/arcsecond.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Observations

For full details regarding the observations and data reduction the reader is referred to Bernstein et al. (1995). Briefly, the Coma field was observed on 2–4 February 1991 from the KPNO 4-meter telescope, using a backside-illuminated \( 1024 \times 1024 \) Tektronix CCD at prime focus. One pixel spans \( 0.473 \text{ of the sky, giving an 8'} \text{ field of view. We made a series of exposures in a typical “shift and stare” mode (Tyson 1986). The shifting reduced the high-S/N area of the final image to a 7.5 square. Both R and B_j filters were used, but the weather conditions were much poorer for the B_j exposures so those observations were not as deep as those made with the R filter. The FWHM of the point spread function in the final R-band image is 1.3 (see Figure 1 of Bernstein et al.). The field is centered at approximately \( 12^h 57^m 30^s, +28^\circ 09' 30'' \) (equinox 1950), near the X-ray centroid of the cluster (Ulmer, Wirth & Kowalski 1992). The giant elliptical (D) galaxies NGC 4874 and NGC 4889 lie 40'' and 280'' off the NW and NE corners, respectively, of our frame.

The data reduction specific to this paper was a three-step process. In Step 1 (§2.2), we used the FOCAS automated detection software (Valdes 1989) to find all significant objects in the R image. Step 2 (§2.3) was to cull the low surface brightness objects from
the all-object FOCAS catalog. This was done by fitting gaussian profiles to all objects (in R band again), and selecting those with fitted size and surface brightness beyond chosen thresholds. Step 3 (§2.4) was to derive true central surface brightnesses and scale lengths for the selected low surface brightness objects in both R and B_j images using exponential profile fits, and to derive colors from common-aperture photometry. For Step 1 only it was necessary to remove the large diffuse-light gradients from the R image. Otherwise the object-finding algorithms would have been overwhelmed and many objects would have been missed. The diffuse-light removal process and the FOCAS object-finding algorithms caused us to underestimate the flux from extended low surface brightness objects, and limited our completeness for very extended objects. In Steps 2 and 3, however, we used the original un-subtracted images for photometry; thus the diffuse-light subtraction may have affected our completeness, but did not bias the magnitudes and scales lengths which we later computed for the detected objects.

2.2. Step 1: Removal of Diffuse Light and Identification of All Objects

The deep exposures we produced revealed diffuse emission that appears to be primarily the result of an extended envelope from the D galaxies NGC 4874 and NGC 4889. The removal of the large-scale features from the R image began with a fit of elliptical isophotes to the 23 brightest galaxies (and one bright star). The fitted ellipses were then subtracted from the image, allowing the FOCAS software (Valdes 1989) to successfully search for dwarf galaxies where it previously was “blinded” by flux gradients due to the emission from these giant galaxies. Regions where the elliptical isophotes were a poor fit were masked and ignored in further processing. Once these larger objects were subtracted, we fit the large-scale gradients in the image by running a 15″-square median filter across the image. These steps of galaxy fitting and diffuse-light subtraction had to be iterated for best results, particularly in the NW corner of the image, which contained steep diffuse-light gradients
from NGC 4874, another bright S0 galaxy, and a bright star.

FOCAS was then used to identify all objects within the frame, and calculate the core magnitude \((m_c)\), total magnitude \((m_t)\), and position of all detected objects. We searched for LSBs using the FOCAS catalog as described below. We visually inspected the images as well, but we were not able to uncover any objects missed by FOCAS.

The FOCAS detections are assuredly not spurious since we were able to detect, in the companion B\(_j\) image, all but one in the final set of LSBs initially found in the R image.

2.3. Step 2: Identification of Candidate Low Surface Brightness Objects

Step 2 of the analysis was to take the objects found by FOCAS and select those which were LSBs—i.e. those which were clearly resolved and which had low central surface brightnesses. Ideally this would have been done by fitting exponential radial profiles to all objects, since LSBs and dEs normally have such profiles (Bothun et al. 1989; Bothun et al. 1987). We found, however, that selecting on exponential-fit parameters produced a large number of spurious candidates because our image is somewhat crowded, and neighbor objects often confused the exponential fits. We chose instead to select low surface brightness objects on the basis of gaussian fits, which also give an indication of the size and surface brightness of each object, but are less sensitive to neighbors because the gaussian drops more rapidly. Furthermore, many of the objects are small, thus similar to the point spread function, which is nearly gaussian. The gaussian fits are better at distinguishing unresolved from slightly resolved objects.

From the FOCAS R catalog we selected objects with \(21.0 < m_t < 24.5\). The FOCAS catalog is 50\% complete for unresolved objects at \(r = 25.5\). We selected objects with \(m_t - m_c < -0.5\) in order to limit stellar contamination. For each of the resultant 1400
objects we produced a radial integration of the surface brightness on the \textit{original} R image (before diffuse-light removal) and fit a gaussian profile. To choose LSB candidates, we needed a measure of the size and of the surface brightness of each object. For the size, we simply used the gaussian \( \sigma \). The surface brightness is taken to be the mean surface brightness inside an aperture whose radius is the point at which the object’s radial profile is 1.5 standard deviations above the local sky background. The size of the annulus used to measure the sky level and the standard deviation was variable since the crowding was more severe in some parts of the image.

Figure 1a shows the distribution of all objects in the size versus surface-brightness plane. We demanded that LSB candidates have \( \sigma > 1.35'' \) (above the horizontal line in Figure 1a), the level at which we judged extended sources to be reliably discerned from the \( \sigma = 0.56'' \) (1.30'' FWHM) point spread function. LSB candidates were also required to have average surface brightness (as defined above) fainter than 27.5 R mag per square arcsecond (to the right of the dashed vertical line). This threshold was chosen to be about 0.2 mag brighter than that of all extremely low surface brightness objects found by an \textit{a priori} visual inspection. All candidate objects in this upper right quadrant were then inspected visually; 18 were found to be true LSBs (diamonds in Figure 1a) while the remainder were superpositions of 2 or more objects. These 18 objects are denoted with an L suffix (“lower”) in the Tables and Figures.

To correct for background contamination, we applied an identical selection procedure to all objects in the 4 high-latitude control fields of Bernstein et al (1995). We found an average of only 2 LSBs per control field, so we have henceforth assumed that nearly all of our detected LSBs are in fact Coma cluster members.

We then extended our selection criteria to correspond roughly to the canonical definition of an LSB as one having central surface brightness fainter than 23.5 B mag per square arcsecond. For our gaussian R image fits, this corresponds to 26.6 mag per
square arcsecond (the solid vertical line in Figure 1a). Visual inspection of the additional candidates to the right of the new surface brightness threshold yielded, coincidentally, another 18 unblended objects.

To give an idea of how the gaussian selection criteria correspond to the more usual exponential parameters, Figure 1b shows the scale length $\alpha$ and central surface brightness $(\mu_0)_R$ of all 1400 objects, with the final 36 LSBs as diamonds. All our LSBs meet the following two criteria: central surface brightness fainter than 24 R mag per square arcsecond, and scale length $\alpha > 0.9''$, which corresponds to about 0.4 kpc for the Coma distance modulus of 34.89. These are indicated by the solid lines in Figure 1b; note that this is just a description of the sample, not the definition of the sample, since we selected on the gaussian fit parameters. Due to the problems with diffuse light in Step 1, it is difficult to define a region over which we can guarantee completeness of the sample.

2.4. Step 3: Exponential Fits, Colors, and Total Magnitudes

The culling of Step 2 left us with a sample of 36 LSBs for analysis. For each of these objects, we integrated radial profiles on both the R and B$_j$ images—as in Step 2 we were using the original images, without diffuse-light removal. The centroids of the LSBs were fixed at the values given by the centroid-finding algorithm in the IRAF package DAOPHOT. These agreed with the FOCAS centroids to within $\sim 0.5''$, well below the 1.3'' seeing FWHM, so sufficiently accurate for fitting radial profiles.

Next we fit exponential surface brightness laws to the radial profiles. Fits were performed to the linear fluxes (not magnitudes), and the sky level was allowed to vary. The object locations and the results of exponential fits to the radial profiles are given in Table 1 for both R and B$_j$ data. Figure 2 plots the R-band radial profile along with best exponential and gaussian fits to each of the 36 LSBs. We have retained the labels we
initially gave the objects, with the “L” suffix denoting the lower surface brightness half. The values of central surface brightness ($\mu_0$) are, of course, extrapolations to $r = 0$ because the seeing smooths the central sections. Our LSBs are, however, at least twice the size of the seeing disk (see Figure 1), so the extrapolation is not too severe. Examination of the Figure 2 profiles suggests that central surface brightness is reliable at the level of a few tenths of a magnitude.

In order to measure colors, we determined magnitudes inside a common aperture for both the R and $B_j$ images of each LSB. In Table 2 we list the aperture magnitudes and the resultant color for each object. Also given is the radius used for the aperture, and the outer radius of the sky determination annulus. The inner radius of the sky annulus was the outer edge of the object aperture. Aperture sizes vary from object to object because of variable object sizes and crowding.

We have calculated total magnitudes (listed in Table 1) by integrating the exponential profiles to infinity. Comparison of these total magnitudes and the aperture magnitudes of Table 2 indicates that the uncertainties in the magnitudes are typically less than 0.2 mag.

2.5. **Exponential Fits, Central Surface Brightness, and Total Magnitudes**

In order to measure colors, we determined magnitudes using the same fixed aperture for both R and $B_j$ for a given object. The aperture radius (“AR”) in Table 2 is not the size of the galaxy but the inner radius on the local background annulus, and the outer radius (“SR” in Table 2) is the outer local background annulus. The aperture radius is not the size of the LSBs, but is the radius over which we performed the LSB integration prior to background subtraction. Since the field was crowded, we had to use different apertures for each object, however. The colors derived in this manner, and the associated apertures for source and background, are given in Table 2 along with the individually derived
magnitudes. We also calculated a total magnitude by integrating the best fit exponential to infinity, and we used the best fits to extrapolate inward to produce a central surface brightness (magnitudes/square arcsecond). We have included the resulting uncertainties in the estimates of the central surface magnitudes given in Table 1. Then, for self-consistent (when considering exponential scale factors or central surface brightnesses) estimates of the total magnitude, the reader should use the magnitudes derived from the exponential fits. The results based on fixed apertures are to be used for colors.

2.6. Interpretation of Objects as LSBs

From our analysis we conclude that in the final selection, the 36 objects are LSBs, and that, based on comparison fields (cf. Bernstein et al. 1995), we estimate that 90% of our objects are located within the Coma cluster. We re-examine the conclusion that these objects are indeed LSBs in this subsection. We begin by noting that all the images were visually inspected and most of the objects were well fitted with an exponential, and those few that were better fitted by a gaussian had a gaussian $\sigma$ much larger than the seeing gaussian. All of the objects came from the initial FOCAS list of objects, and these images were all visually inspected in order to reject blends.

As an alternative to the interpretation that the objects we found are LSBs, we now demonstrate that the following interpretations are unlikely: (1) the objects are globular clusters; (2) they are the blend of two point-like sources; (3) they are a blend of two low surface brightness objects; and (4) they are a blend of one low surface brightness object and one point-like object. We reject case “1” because the gaussian $\sigma$ of a point source is $\sim 0.6''$ versus the observed value of $\geq 1.4''$ in our sample (see Figure 1a), and at the distance of Coma, globular clusters will appear as point sources (cf. Bernstein et al. 1995). For case “2” the blending requires a separation of about $1.3''$, and at such separations these
objects would be easily detected as blends. For case “3” and case “4”, we require that such coincidences are to be within about 1.′′3, but as the total surface density of the objects is so small, the probability of such chance occurrences is less than 1%. We conclude, therefore, that the large majority of objects in our final selection are LSBs in the Coma cluster.

3. DISCUSSION

3.1. Introduction

As noted in the previous subsection, we have produced a list of objects of which the large majority are LSBs in the Coma cluster. For the sake of simplicity, we will assume that all of these objects are LSBs in the Coma cluster and will proceed with the discussion on this basis. This sample is one of extraordinarily faint, low surface brightness objects in a very rich environment, and we begin by presenting 4 examples of these very faint objects in Figure 3.

As a framework for our discussion, we consider just some (out of the myriad of suggestions) of the hypotheses of the origin for (dwarf) LSBs: (1) they are the result of fragmentation of larger galaxies caused by galaxy-galaxy interactions in the cluster; (2) their number density is correlated with the spiral fraction of the cluster (Turner et al. 1993); (3) they are related to the diffuse extended envelopes of the D galaxies in this cluster which would make them different from LSBs in clusters without D of cD galaxies; (4) they are objects which have been confined by a hot intra-cluster medium and have faded from their initial state; and (5) they are the result of large mass loss early in their lifetime. By relating to previous work, we show that none of these scenarios is especially favored and that the origin of these objects remains a mystery. For general discussions of the origin and evolution of LSBs and dEs, see Ferguson & Binggeli (1994), Cole (1991), Bothun et al. (1989), and references therein.
Our definition \([\alpha \gtrsim 0.4 \text{ kpc}, \mu_0 > 24.0 \text{ (in R)}], \text{mean} \alpha \sim 0.6 \text{ kpc}, \text{mean} \mu_0 \sim 26.0 \text{ (R)}]\) overlaps most closely with the Turner et al. (1993) definition of large LSBs \((\alpha \sim 0.6 \text{ to } 1.5 \text{ kpc}, \mu_0 \sim 26.5 \text{ in V})\), which most closely overlaps with those of McGaugh & Bothun (1994; mean values of \(\alpha \sim 1.5 \text{ kpc}, \mu_0 \sim 23.5 \text{ in B}\)) and Bothun et al. (1991; \(\alpha \sim 0.7 \text{ kpc}, \mu_0 \sim 24.5 \text{ in B}\)). Turner et al. use the large LSB definition as their main point of comparison with previous work. For the sake of argument we will use our definition below, but remind the reader that the standard set by Bothun and co-workers over the past 10 years is for B(0) to be fainter than 23 magnitudes per square arcsecond. Also, for a discussion of the various types of dE shapes and selection effects in clusters, see Bothun et al. (1989).

### 3.2. Comparison with Fornax and Virgo

To provide more details, as well as to help elucidate the sensitivity of our survey, we compare our results with previously cataloged objects. This comparison also demonstrates the plausibility of our assumption that these LSBs are dwarf galaxies in the Coma cluster. In Figure 4, we show how faint our LSBs are with respect to the Fornax sample of Bothun et al. (1991). When we correct for cluster distance, we find that the brighter end overlaps the Bothun et al. survey objects. It is also informative to use Figure 4 to understand the sensitivity of the surveys as denoted by the curved lines. To the right of the left-most curved line is the region in which we would expect to detect galaxies, given the angular diameter (smaller objects cannot be distinguished from stars) and isophotal surface brightness limits (the faintest level out to which an image is actually detected) noted next to these curves. These curves are derived by assuming an exponential form for the galaxies of varying scale values as denoted by the diagonal dashed lines. As expected, most of our objects fall to the right of the left-most curved line, based on the seeing (1."3, FWHM) and the fluctuations in the background in B_j \((\sim 29^{th} \text{ magnitude per pixel})\).
Next, in Figure 5 we show our results in relation to those of Ferguson & Binggeli (1994). Our sample is where we would expect to find it relative to the general population of dEs, i.e., in the low surface brightness, low total brightness portion of the plane, as shown in Figure 5. The data in Figure 5 were compiled from Kormendy (1985), Bothun et al. (1987), van der Kruit (1987), Binggeli & Cameron (1991, 1993), and Caldwell et al. (1992). From Figures 4 and 5, we infer that the properties of Coma LSBs overlap those of LSBs or dEs in Fornax or Virgo in terms of their central surface brightnesses and total magnitudes.

As an aside, we remark that, in Figure 5, it appears as though we have not been able to detect larger objects (larger values of $\alpha$) for a fixed central surface brightness that would have populated the brighter side of the luminosity distribution. However, in Figure 4, it appears that we did sample the brighter end of the distribution of LSBs (for a fixed central surface brightness) quite well. As noted previously, however, we do not exclude the possibility that we have missed some larger objects (larger values of $\alpha$), either by slipping below the FOCAS detection in Step 1, or because the likelihood of these objects appearing as blends is larger than for those with smaller values of $\alpha$, e.g., for a scale factor of 3″, we could, on average, integrate only about three to four scale lengths before reaching the next object in the frame. But there is an inconsistency between the interpretations of Figures 4 and 5 (one figure implies we may have missed several faint extended objects for a fixed central surface brightness, the other does not). At least part of the discrepancy between conclusions about our ability to find large-scale size LSBs, based on Figures 4 and 5, could be due to discrepancies in distance estimates to the galaxies in the various samples. It is also possible that selection effects, or the manner in which the total brightnesses (how far from the center a galaxy image was integrated or what model was used) of the galaxies were calculated, could play a role in producing discrepancies between different surveys.

Returning to the main point of this discussion, so far we have shown that the LSBs in Coma have a size and brightness distribution which overlaps that of the LSBs in other clusters [i.e., Fornax and Virgo; most of the Ferguson & Binggeli (1994) dEs are from the
Binggeli & Cameron (1991) survey of the Virgo cluster.

3.3. LSB Counts Versus Richness

When comparing the derived number density of LSBs with previous work, the reader should be aware that the final results are very sensitive to definition, e.g., by simply changing the range of acceptable scale factors for LSBs from the range of 3.″5–9.″0 to all those ≥ 3.″0, Turner et al. (1993) change the total number of LSBs in their sample by about a factor of 4 (see also Figure 1 in this paper). Furthermore, the range of central surface brightnesses of a survey need also be considered, and we have not corrected for any such effects. For example, we only use those LSBs actually detected in our analysis rather than those that extend over some theoretically accessible magnitude range (e.g., Table 6, column 3 of Turner et al.). Therefore, although we find no evidence for trends in number density in comparing our Coma data with the A3574 data of Turner et al., one should keep in mind that the dependence of LSB density on other cluster properties cannot be ruled out at this time, and that our conclusions (below) are based only on a simplistic comparison (good to only a factor of two) of the large LSB number counts of Turner et al. with our LSB counts. Furthermore, as we remark below, there is apparently a dearth of brighter objects with large extents (values of α in the 10 to 30 range). As noted by Turner et al., the difficulty in identifying brighter, more extended, objects is crowding, such that it is not easy to distinguish these objects from blends. Thus, in comparing LSB number counts in sparse versus crowded regions, it is also necessary to be aware that large objects can be lost in the crowded fields, which can suppress the total number counts in crowded fields.

With the above caveats in mind, we now consider the number counts of Coma versus A3574, as these clusters are widely different in richness. Coma is richness 2 and A3574 is richness 0 (Abell, Corwin & Olowin 1989). We can make this comparison in two ways: first
as a ratio of LSBs to “ordinary galaxies” (those brighter than $M_B = -17$); and second, as a net surface density of LSBs. Therefore, effects due to galaxy-galaxy interaction might be observable. We find that for Coma and A3574 this ratio is about the same: 1.5/1 for Coma\(^1\) and 3.5/1 for A3574 (Turner et al. 1993). Looking at this another way, if the fraction of LSBs were constant between the two rich clusters then we would predict the number density for our sample to be about 16 times that of Turner et al., whereas we find a factor of 8 increase ($\sim 800$/Mpc\(^2\) versus $\sim 100$/Mpc\(^2\) for A3574). Although this suggests the existence of a real effect, the accuracy of this comparison is only a factor of 2. Also, if we assume that the interaction rate depends mainly on the square of the density of galaxies (in more massive/denser systems the velocities also tend to be higher), we would expect a much stronger effect than the apparent factor of 2 effect seen here. Therefore, although we cannot exclude the possibility, we conclude that galaxy-galaxy interaction and fragmentation is not likely to be the major cause of LSBs.

\section{3.4. LSB Counts Versus Spiral Fraction}

Related to the above hypothesis is the conjecture by Turner et al. (1993) that a spiral fraction of 62\% might be related to the cause of the high density of LSBs in A3574, as both the spiral fraction and LSB density are higher in A3574 than in Fornax (40\%, Godwin & Peach 1982). But Coma has a spiral fraction of about 14\% (Dressler 1980), yet its surface density of LSBs is 8 times higher than that for A3574, and the ratio of LSBs to ordinary galaxies is about the same as for Fornax (1.5). Thus, spiral fraction and LSB density do not seem to be correlated. Turner et al. note, however, that the situation is complicated and

\(^1\)Here we have assumed an average $B_J$−$R$ of 0.7 to convert the $R$ luminosity function for the core Coma (cf. Bernstein et al. 1995) to the $B_J$ band, and we have converted our LSB surface density to LSB surface density per magnitude.
that part of the difficulty may be related to the small angular scale of our objects which prevents us from distinguishing between dEs and dwarf Irregulars.

3.5. Relationship of LSBs to Extended Envelopes of D Galaxies

Next we consider the possibility that the LSBs in Coma are the result of the fragmentation of extended envelopes around D or cD galaxies. We cannot use a comparison between Coma and A3574 as a discriminator, however, as both clusters contain dominant galaxies. Coma is classified as Bautz-Morgan II, and A3574 as Bautz Morgan I (cf. Abell et al. 1989). But, the similarity of the LSBs in these clusters to those in Fornax fails to support the suggestion that the diffuse envelope fragmentation is important for LSB formation. For this model of extended envelope fragmentation to work, the data also require an ad hoc assumption that the process of the extended envelope fragmentation into LSBs must scale with the ordinary galaxy density. There is no direct evidence to rule out such an extended envelope fragmentation hypothesis, however, until more rich clusters are examined.

Another test of a possible LSB relationship to an extended envelope is to compare the color of the diffuse envelope with the LSBs' color. From our own CCD frames, we estimate a value of $1.2 \pm 0.3 \text{ B}_J - \text{R}$ for the color of the diffuse emission. The mean value of the color of the LSBs in our sample is about 1.1, with a variance of measured values from −0.7 to about 2. We also searched for evidence of a color dependence of the LSBs on the distance from the center of the D galaxies, but we found no statistically significant effect, as can be seen in Figure 6a. We also found that there is no obvious (statistically significant) dependence of the density of LSBs on the distance from NGC 4874. Similarly, we found no statistically significant effect relative to the distance from NGC 4889, the other D galaxy in the cluster. We conclude that there is no evidence that the presence of extended envelopes of D or cD
galaxies is related to LSBs, but we cannot exclude such a possibility.

We searched for such effects relative to the X-ray center as well. Again we found no statistically significant effects. But as our frame only extends about 1/2 of a core radius from the cluster center, we would not expect to see any strong effects in these data.

3.6. LSB Color and Evolution

The color measurements can be used to search for other physical effects, and McGaugh & Bothun (1994) explored the possibility (see also Bothun et al. 1991) that most LSBs exist because they are ordinary galaxies that have faded to produce low surface brightness systems. In this scenario (which McGaugh & Bothun did not confirm in their data set), the fainter a galaxy is, the older, and hence redder, it is. Then, for the B−V color, McGaugh & Bothun estimated a reddening of 0.25 for every 1 magnitude decrease in central surface brightness. This estimate was based on standard stellar evolution models (Tinsley 1972). Since B_j−R is larger for the same stellar type, we would expect the effect to be even more pronounced in the B_j−R versus central surface brightness plane. And we can see in Figure 6b that there could be ~ 0.1 – 0.2 magnitudes of reddening per 2 magnitudes of fading, but the data are also consistent with no reddening. Given the relatively large non-statistical scatter in the data we cannot provide a valid (low chi-squared) best-fit gradient to these data. Combining our data with that of McGaugh & Bothun, however, we conclude that there is no evidence for color fading as the origin of LSBs. This conclusion is consistent with another test for such an effect (also performed by McGaugh & Bothun), i.e., color versus exponential scale, which is shown in Figure 6c.
3.7. **LSB M/L and Missing Mass**

Another attribute that could be related to the origin of LSBs is their mass to light ratio (M/L) and their relationship to the overall cluster mass. We can make an estimate of their masses by assuming that they have lasted the age of the cluster. Then the calculations of Bernstein et al. (1995) apply, and the $M/L_R$ we estimate has a lower bound\(^2\) of about $60 \, M_\odot/L_\odot$ which is consistent with dEs in general (cf. Pryor 1992)\(^3\). We can estimate the total mass contribution to the cluster by using the fraction of light that these objects contribute to the cluster as a whole, which is about $1/400$ (cf. Bernstein et al.). We use a value for the optical luminosity for the cluster as a whole, of $10^{13} \, L_\odot$ (Abell 1977). Then, we find that the total contribution to the cluster mass is a relatively small $10^{12} \, M_\odot$ [compared to the mass required to virialize the cluster, i.e., about $10^{15} \, M_\odot$ (cf. Sarazin 1986)], and even though LSBs dominate over ordinary large galaxies in number, they do not contribute a dynamically significant amount of mass to the cluster. As LSBs are difficult to detect, they potentially could have been a source for the missing mass in Coma, but this is not the case. Even if we had missed objects due to selection or crowding effects, these “missed” objects would have contributed to the diffuse light we detected in our image, and as shown by Bernstein et al., there is not enough diffuse light to account for the missing mass as long as $M/L$ is less than several hundred. Thus the search for sources of the missing mass in Coma must continue.

\(^2\)This is a lower bound in the sense that a mass greater than this would produce stability. This is, however, an upper bound if considered in terms of the required lifetime of the galaxy in the cluster. For, as the age of the galaxy is reduced, so is its required (stable) mass.

\(^3\)Here we have assumed that the color of a typical elliptical galaxy is such that the difference between $V$ and $R$ is less than 10%.
3.8. LSB Formation Via Supernova Mass Ejection  

Finally, we consider the hypothesis that the existence of dEs/LSBs in rich clusters is due to large (90%) mass loss due to supernova driven winds. We cannot directly test this hypothesis, but we can show that if dEs were initially 10 times more massive and lost all this excessive mass to the intra-cluster medium (ICM), then it is just possible to explain the presence of iron in the ICM (Henriksen & Mushotsky 1986). The argument goes as follows: an estimate of gas in the cluster is about $10^{14} \, M_\odot$ (White et al. 1993) over approximately the same volume as the total light estimate of $10^{13} \, L_\odot$ (i.e. about a 3 to 4 Mpc radius). Then if the LSBs (or dEs) have lost $10^{13} \, M_\odot$ total to the ICM with solar abundance, this would produce about 0.1 solar abundance in the cluster. Within the accuracy of the estimates and measurements (the iron abundance in the ICM of Coma is between approximately 0.2 and 0.4 times solar, with 90% confidence limits; Henriksen & Mushotsky), then, this is good agreement between hypothesis and observation. In this calculation, however, we have implicitly assumed that most of the current mass of the dEs is baryonic, since we also assumed that 10 times the current mass has been ejected into the ICM, and that this ejected mass was baryonic. Thus, we deem this scenario unlikely, but we can neither disprove it nor an alternative explanation of lower baryonic mass loss of enriched material (i.e., higher amounts of iron and other heavy elements relative to solar abundance). A future line of investigation could be to compare the iron abundance in the ICM with dE densities, but as most rich X-ray bright clusters are farther away than Coma (cf. Sarazin 1986), this task will be difficult to carry out.

4. SUMMARY AND CONCLUSIONS

In summary, we have found 36 extremely low surface brightness dwarf galaxies in the core of the Coma cluster. We find no statistically significant evidence to relate the origin or
evolution of the LSBs to: fragmentation via galaxy-galaxy interactions; the spiral fraction; the presence of D galaxies, as the Coma LSBs seem typical of LSBs found in other clusters that do not contain D galaxies; or, long-lived color fading. There is also no statistically significant dependence on color with respect to the projected distances of the LSBs from key locations such as the D galaxies or the X-ray center. Furthermore, these LSBs probably do not contribute significantly to the overall mass of the cluster or to the iron in the hot intra-cluster medium. Thus, the origin and evolution of LSBs and their relationship to rich clusters remain unclear. Observations of other rich clusters and observations farther from the Coma cluster core are necessary to help solve the mystery. Finally, although numerous, LSBs (or faint objects in general) that were missed in previous surveys of Coma cannot make up for the missing dynamical mass in the cluster.

5. ACKNOWLEDGEMENTS

We thank M. Bell for her programming support. Thanks to P. Teague for assistance in the Coma observing run, and to P. Guhathakurta for allowing us to commandeer images from other projects for use as control fields. GMB was generously supported by AT&T Bell Laboratories and the Bok Fellowship from Steward Observatory during the tortuously extended duration of this work. Ulmer thanks A. Sandage for discussions at the inception of this project, and Northwestern University and NASA for partial support. We thank the referees, K. O’Neil and G. Bothun, for useful and insightful comments. We also thank A. Ulmer for providing useful comments.
Table 1: LSBs’ Positions and Exponential Parameters

| id# | h  | m  | s  | d  | m  | m  | s  | S  | S  | α  | α  |
|-----|----|----|----|----|----|----|----|----|----|----|----|
| 18  | 12 | 57 | 3.46| 28 | 6  | 11.0| 21.50| 22.66| 23.82| 25.10| 1.06| 1.24|
| 18L | 12 | 57 | 4.53| 28 | 6  | 8.6 | 23.69| 25.11| 25.66| 26.94| 0.92| 0.88|
| 17  | 12 | 57 | 5.47| 28 | 10 | 2.6 | 21.66| 23.67| 23.88| 25.38| 1.25| 1.45|
| 16  | 12 | 57 | 5.90| 28 | 7  | 37.2| 21.39| 22.38| 23.69| 24.75| 1.26| 1.30|
| 17L | 12 | 57 | 7.02| 28 | 8  | 39.3| 23.52| 25.29| 26.40| 27.19| 1.95| 1.34|
| 16L | 12 | 57 | 7.45| 28 | 11 | 49.1| 25.17| 26.66| 25.97| 29.58| 0.85| 1.71|
| 15L | 12 | 57 | 8.17| 28 | 11 | 11.6| 23.41| 25.01| 25.93| 26.71| 1.46| 1.14|
| 14L | 12 | 57 | 8.46| 28 | 6  | 20.8| 23.41| 24.48| 25.61| 26.63| 1.36| 1.13|
| 15  | 12 | 57 | 8.68| 28 | 6  | 5.0 | 22.15| 23.95| 23.88| 26.41| 0.96| 1.51|
| 13L | 12 | 57 | 8.96| 28 | 8  | 38.3| 24.10| 24.73| 25.65| 27.08| 0.93| 1.38|
| 14  | 12 | 57 | 9.43| 28 | 11 | 16.6| 21.75| 22.77| 24.09| 25.37| 1.27| 1.45|
| 12L | 12 | 57 | 10.58| 28 | 8  | 57.0| 23.38| 24.48| 25.97| 26.69| 1.50| 0.99|
| 13  | 12 | 57 | 10.87| 28 | 11 | 51.4| 21.83| 23.20| 24.10| 25.32| 1.25| 1.27|
| 12  | 12 | 57 | 11.38| 28 | 6  | 49.5| 22.23| 24.14| 23.81| 26.42| 0.80| 1.47|
| 11  | 12 | 57 | 12.85| 28 | 12 | 7.1 | 20.46| 21.49| 23.80| 25.03| 2.04| 2.37|
| 11L | 12 | 57 | 15.66| 28 | 10 | 28.7| 22.51| 23.54| 25.31| 26.81| 1.50| 2.34|
| 10  | 12 | 57 | 16.16| 28 | 10 | 4.8 | 21.49| 22.38| 24.44| 25.71| 1.75| 2.10|
| 9   | 12 | 57 | 17.10| 28 | 10 | 51.9| 21.15| 22.04| 23.09| 24.51| 1.04| 1.44|
| id# | h  | m  | s  | d  | '  | " | m$_R$ | m$_{B_j}$ | S$_R$ | S$_{B_j}$ | $\alpha_R$ | $\alpha_{B_j}$ |
|-----|----|--|--|--|--|--|--|--|--|--|--|--|
| 10L | 12 | 57 | 18 | 00 | 28 | 10 | 30.1 | 23.62 | 24.64 | 25.71 | 26.74 | 1.05 | 0.52 |
| 8   | 12 | 57 | 19.87 | 28 | 5  | 58.0 | 21.92 | 22.78 | 23.93 | 25.25 | 1.19 | 1.47 |
| 7   | 12 | 57 | 21.24 | 28 | 6  | 29.2 | 22.51 | 23.42 | 24.49 | 25.81 | 1.22 | 1.28 |
| 9L  | 12 | 57 | 21.60 | 28 | 11 | 36.2 | 23.34 | 24.53 | 25.14 | 26.76 | 0.98 | 1.24 |
| 6   | 12 | 57 | 22.75 | 28 | 7  | 17.0 | 21.39 | 22.73 | 23.50 | 24.87 | 1.26 | 1.42 |
| 8L  | 12 | 57 | 23.58 | 28 | 5  | 51.5 | 22.40 | 23.66 | 25.10 | 26.20 | 1.47 | 1.27 |
| 7L  | 12 | 57 | 24.08 | 28 | 8  | 51.3 | 22.68 | 23.87 | 24.58 | 25.87 | 1.07 | 1.17 |
| 5   | 12 | 57 | 25.20 | 28 | 8  | 52.5 | 22.08 | 22.83 | 23.76 | 25.27 | 0.82 | 1.30 |
| 6L  | 12 | 57 | 25.70 | 28 | 10 | 4.6  | 22.40 | 23.33 | 25.63 | 26.83 | 1.84 | 2.02 |
| 5L  | 12 | 57 | 27.21 | 28 | 9  | 28.3 | 22.83 | 24.82 | 26.02 | 26.96 | 1.85 | 1.38 |
| 4   | 12 | 57 | 27.86 | 28 | 9  | 35.6 | 21.38 | 22.40 | 23.70 | 24.98 | 1.37 | 1.54 |
| 3   | 12 | 57 | 27.97 | 28 | 11 | 29.3 | 22.83 | 23.32 | 24.58 | 25.84 | 1.25 | 1.49 |
| 2   | 12 | 57 | 29.31 | 28 | 12 | 25.2 | 22.21 | 22.71 | 23.67 | 24.91 | 0.71 | 1.25 |
| 4L  | 12 | 57 | 29.95 | 28 | 8  | 49.2 | 22.62 | 23.69 | 24.89 | 26.12 | 1.33 | 1.33 |
| 3L  | 12 | 57 | 30.35 | 28 | 7  | 33.8 | 23.19 | 24.41 | 25.30 | 26.62 | 1.24 | 1.23 |
| 2L  | 12 | 57 | 33.66 | 28 | 10 | 59.8 | 23.01 | 23.95 | 24.89 | 26.45 | 0.97 | 1.49 |
| 1L  | 12 | 57 | 35.93 | 28 | 5  | 45.4 | 23.48 | 24.91 | 25.49 | 27.29 | 1.03 | 1.39 |
| 1   | 12 | 57 | 36.29 | 28 | 9  | 5.7  | 22.27 | 23.37 | 23.87 | 25.31 | 0.87 | 1.15 |
Notes to Table 1
Column 1: identification number; Columns 2–7: RA and Dec in 1950 equinox; Columns 8 and 9: total magnitudes in R and Bj based on integrating the best fit exponential model to infinity for the R and Bj images; Columns 10 and 11: the central surface brightness (also denoted $\mu_0$ elsewhere) for R and Bj; and, Columns 12 and 13: the exponential angular scale factor in arcseconds for R and Bj. The estimated uncertainties in the central surface brightness and scale factors increase from the brighter to the fainter objects as follows: the average uncertainty in the angular scale of the LSBs is 0.03 to 0.05 (R) and 0.04 to 0.06 (Bj) arcseconds, and for the central surface brightnesses 0.06–0.08 (R) and 0.04–0.06 (Bj). The estimated uncertainties in total magnitudes are typically less than 0.2 (see text).
Table 2: Fixed Aperture Magnitudes and Colors

| id# | $m_R$ | $m_{Bj}$ | $B_j - R$ | $AR^{\prime\prime}$ | $SR^{\prime\prime}$ |
|-----|-------|----------|-----------|---------------------|---------------------|
| 18  | 21.35 | 22.52    | 1.17      | 4.73                | 7.57                |
| 18L | 23.54 | 25.39    | 1.85      | 4.07                | 6.15                |
| 17  | 21.53 | 22.56    | 1.03      | 4.49                | 7.57                |
| 16  | 21.51 | 22.40    | 0.89      | 4.73                | 7.57                |
| 17L | 23.69 | 24.87    | 1.17      | 4.54                | 6.15                |
| 16L | 24.50 | 27.93    | 3.43      | 3.07                | 5.91                |
| 15L | 23.60 | 25.20    | 1.60      | 4.02                | 5.91                |
| 14L | 23.21 | 24.33    | 1.12      | 4.02                | 6.15                |
| 15  | 22.01 | 23.87    | 1.86      | 5.20                | 7.57                |
| 13L | 24.00 | 24.67    | 0.66      | 3.55                | 4.73                |
| 14  | 21.84 | 22.94    | 1.10      | 4.97                | 7.57                |
| 12L | 23.69 | 24.39    | 0.70      | 4.73                | 5.91                |
| 13  | 22.09 | 23.10    | 1.01      | 4.73                | 7.57                |
| 12  | 22.17 | 23.77    | 1.60      | 5.68                | 8.04                |
| 11  | 20.45 | 21.47    | 1.02      | 7.80                | 9.22                |
| 11L | 22.40 | 23.47    | 1.07      | 4.82                | 6.15                |
| 10  | 21.45 | 22.45    | 1.00      | 7.80                | 9.22                |
| 9   | 20.93 | 22.06    | 1.13      | 6.39                | 8.04                |
Table 2 (cont.)

| id# | $m_R$ | $m_{B_j}$ | $B_j - R$ | AR (") | SR (") |
|-----|-------|-----------|----------|--------|--------|
| 10L | 23.67 | 25.77     | 2.11     | 4.78   | 5.91   |
| 8   | 21.65 | 22.72     | 1.07     | 4.97   | 7.09   |
| 7   | 22.47 | 23.86     | 1.39     | 5.20   | 7.57   |
| 9L  | 23.27 | 24.50     | 1.23     | 5.16   | 7.09   |
| 6   | 21.33 | 22.46     | 1.13     | 3.55   | 5.44   |
| 8L  | 22.37 | 23.77     | 1.40     | 5.44   | 7.57   |
| 7L  | 22.49 | 23.85     | 1.37     | 4.49   | 7.57   |
| 5   | 21.95 | 22.91     | 0.96     | 5.91   | 7.33   |
| 6L  | 22.36 | 23.50     | 1.15     | 7.76   | 8.99   |
| 5L  | 23.20 | 25.47     | 2.27     | 7.09   | 8.51   |
| 4   | 21.37 | 22.53     | 1.15     | 7.57   | 8.99   |
| 3   | 22.11 | 23.31     | 1.20     | 4.49   | 7.57   |
| 2   | 22.06 | 22.77     | 0.71     | 3.78   | 7.57   |
| 4L  | 22.51 | 23.79     | 1.28     | 4.49   | 7.09   |
| 3L  | 23.11 | 24.67     | 1.56     | 4.59   | 7.57   |
| 2L  | 22.96 | 23.66     | 0.71     | 5.34   | 7.57   |
| 1L  | 23.37 | 25.57     | 2.20     | 4.49   | 7.57   |
| 1   | 22.17 | 23.27     | 1.10     | 4.73   | 7.57   |
Notes to Table 2
Column 5 is the radius in arcseconds of the aperture used for photometry. Sky was determined in an annulus from this radius to the “sky radius” in column 6. The uncertainties in total magnitudes and colors are dominated by the choice of the background, and scatter in the background, rather than by counting statistics. The errors in color correspond to less than 0.1 magnitudes for the brighter objects, and increase up to about 0.5 magnitudes for the fainter objects in the sample. The estimated uncertainties in total magnitudes are typically less than 0.2 (see text).
REFERENCES

Abell, G. O. 1977, ApJ, 213, 327

Abell, G. O., Corwin, H. G., & Olowin, R. P. 1989, ApJS, 70, 1

Bernstein, G. M., Nichol, R. C., Tyson, J. A., Ulmer, M. P., & Wittman, D. 1995, AJ, 110, 1507

Binggeli, B., & Cameron, L. M. 1991, A&A, 252, 27

Binggeli, B., & Cameron, L. M. 1993, A&AS, 98, 297

Bothun, G. D., Caldwell, N., & Schombert, J. M. 1989, AJ, 98, 1542

Bothun, G. D., Impey, C. D., & Malin, D. F. 1991, ApJ, 376, 404

Bothun, G. D., Impey, C. D., Malin, D. F., & Mould, J. R. 1987, AJ, 94, 23

Caldwell, N., Armandroff, T. E., Seitzer, P., & da Costa, G. S. 1992, AJ, 103, 840

Cole, S. 1991, ApJ, 367, 45

Davies, J. I., Phillipps, S., & Disney, M. J. 1989, MNRAS, 239, 703

Dressler, A. 1980, ApJS, 42, 565

Ferguson, H. C., & Binggeli, B. 1994, A&A Rev., 6, 67

Gilmore, G., King, I. R., & van der Kruit, P. C. 1989, The Milky Way as a Galaxy (Mill Valley, California: University Science Books)

Godwin, J. G., & Peach, J. V. 1982, MNRAS, 200, 773

Henriksen, M. J., & Mushotzky, R. F. 1986, ApJ, 302, 287

Impey, C., Bothun, G., & Malin, D. 1988, ApJ, 330, 634
Kormendy, J. 1985, ApJ, 295, 73

McGaugh, S. S., & Bothun, G. D. 1994, AJ, 107, 550

Phillipps, S., Disney, M., Cawson, M., & Kibblewhite, E. 1987, MNRAS, 229, 505

Pryor, C. 1992, in Morphological and Physical Classification of Galaxies, ed. G. Longo, M. Capaccioli, & G. Busarello (Dordrecht: Kluwer), 163

Sarazin, C. L. 1986, RMP, 58, 1

Tinsley, B. M. 1972, A&A, 20, 383

Turner, J. A., Phillipps, S., Davies, J. I., & Disney, M. J. 1993, MNRAS, 261, 39

Tyson, J. A. 1986, J. Opt. Soc. Am., 3, 2131

Ulmer, M. P., Wirth, G. D., & Kowalski, M. P. 1992, ApJ, 397, 430

Valdes, F. 1989, in First ESO/ST-EF Data Analysis Workshop, ed. P. J. Grosbol, F. Murtagh, & R. W. Warmels

van der Kruit, P. 1987, A&A, 173, 59

White, S. D. M., Navarro, J. F., Evrard, A. G., & Frenk, C. S. 1993, Nature, 366, 429

This manuscript was prepared with the AAS \LaTeX\ macros v4.0.
6. FIGURE CAPTIONS

Fig. 1 (1a): average surface brightness versus gaussian best fit $\sigma = \text{“radius”}$; diamonds are the LSBs culled from examining all objects above the horizontal line. (1b): central surface brightness versus exponential scale factor; the diamonds are the same objects as shown in 1a. The vertical lines demark the initial (dashed) and final (solid) selection limit of our sample (see text).

Fig. 2 - Thirty-six separate plots showing the radial intensity profiles of the LSBs (R images only) we found, along with both the gaussian (dotted curves) and exponential best fits. The right hand corner of each plot contains the ID numbers related to Tables 1 and 2. The bottom X-axes are in kpc, the top are in arcseconds. The best fit local background has been subtracted from these data.

Fig. 3 - Images of the sample LSBs from our survey. Best fit local background has been subtracted. The designation of these objects in Tables 1 and 2 are, reading clockwise from the top left corner, 2L, 4L, 13L and 7L. The spatial scale on these plots is arcseconds. The surface brightness scale given below each plot is in R magnitudes per square arcsecond. The pixel size is 0.′′473.

Fig. 4 - The total brightness in blue versus the central surface brightness. The crosses are from Bothun et al. (1991). The asterisks are our data and assume $H_0 = 75$ km/sec-Mpc. The open diamonds are our sample corrected to the distance of Fornax. The solid curves show the selection function that relates the limiting central surface brightness, and the limiting diameter of the object, to the exponential scale factor given by $B_{tot} = -0.6689 + 5.0 \times \log[(\mu_{lim} - \mu_0)/\theta_{lim}] + \mu_0$, where $\mu_{lim}$ is the limiting isophotal magnitude, $\theta_{lim}$ is the limiting diameter in arc seconds, and $\mu_0$ is the observed central surface brightness (see also Bothun et al.; Gilmore, King & van der Kruit 1989, page 259). The arrows show the direction of motion on the central surface brightness total apparent magnitude plane.
based on a correction for distance.

Fig. 5 — The absolute surface brightness versus absolute blue magnitude for various classes of galaxies, shown with plusses, are from Ferguson & Binggeli (1994). The open diamonds are our LSBs.

Fig. 6 — Top (6a) color versus distance from NGC 4874. Center (6b): average LSB color (from Table 2) versus central surface brightness in the blue (from Table 1). Bottom (6c): color versus exponential scale factor in arcseconds. In all of these plots LSB 16L has been excluded due to the faintness, and hence large uncertainty, in the B$_j$ value.
Figure 1b

\( \alpha \text{ (arcsec)} \)

\( \mu_{0}R \text{ (mag/sq arcsec)} \)
Figure 2
Figure 2 (cont)
Figure 2 (cont)
Figure 2 (cont)
Figure 2 (cont)
Figure 4

-theta limits:

-θ_{lim} = 3.0
-μ_{lim} = 28.8
-θ_{lim} = 16.
-μ_{lim} = 27.3
Figure 5

Central Surface Brightness (B arcsec\(^2\))

Absolute Blue Magnitude

- Es + bulges
- globulars
- DWARFS
Figure 6