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The $z \leq 0.1$ surface brightness distribution

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Abstract. The surface brightness distribution (SBD) function describes the number density of galaxies as measured against their central surface brightness. Because detecting galaxies with low central surface brightnesses is both time-consuming and complicated, determining the shape of this distribution function can be difficult. In a recent paper Cross et al. suggested a bell-shaped SBD disk-galaxy function which peaks near the canonical Freeman value of 21.7 and then falls off significantly by 23.5 B mag arcsec^{-2}. This is in contradiction to previous studies which have typically found flat (slope = 0) SBD functions out to 24–25 B mag arcsec^{-2} (the survey limits). Here we take advantage of a recent surface-brightness limited survey by Andreon & Cuillandre which reaches considerably fainter magnitudes than the Cross et al. sample (M_B reaches fainter than -12 for Andreon & Cuillandre while the Cross et al. sample is limited to $M_B < -16$) to re-evaluate both the SBD function as found by their data and the SBD for a wide variety of galaxy surveys, including the Cross et al. data. The result is a SBD function with a flat slope out through the survey limits of 24.5 B mag arcsec^{-2}, with high confidence limits.

1. Introduction

The Surface Brightness Distribution (SBD) function – a measure of the number density of galaxies broken into bins of decreasing central surface brightness – provides a quantitative description of the galaxy population within the Universe. The first attempt at quantifying the local ($z \leq 0.1$) disk-galaxy SBD was done by Freeman (1970) who found a Gaussian distribution with $\langle \mu_B(0) \rangle = 21.65 \pm 0.30$ mag arcsec^{-2}. In the years since Freeman's distribution was published a significant quantity of galaxies have been found with central surface brightnesses more than 10σ from Freeman's canonical value, showing that Freeman's distribution clearly underestimated the number of galaxies at faint surface brightness. Indeed it is fairly certain that the distribution seen by Freeman was due to selection effects imposed by the considerable noise inherent in imaging techniques at the time, which effectively eliminated the possibility of seeing galaxies with $\mu_B(0) \geq 23$ mag arcsec^{-2}.

In the thirty years since Freeman's (1970) results were published, a number of attempts have been made to describe the local SBD. Adding on to the work done first by Disney (1976) and then McGaugh (1996), O'Neil & Bothun (2000) found that the SBD of galaxies at $z < 0.1$ is described by a curve which rises steeply from 20 to 22 B mag arcsec^{-2} and then remains flat through the survey limits of 25.0 B mag arcsec^{-2}. This implies that the majority of galaxies in the local Universe are low in surface brightness, and that LSB galaxies should play a significant role in studies of the local baryon density, damped Lyman-α systems, and in theories of galaxy formation and evolution.

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Recently, though, the belief in a flat SBD out to $\geq$25 mag arcsec^{-2} has been questioned. Using a subsample of galaxies taken from the 2dF Galaxy Redshift Survey, Cross et al. (2001) found the local SBD to be best represented by a broadened version of Freeman's (1970) original SBD. If this is correct it would have far-reaching implications. First, a SBD which falls off before $\mu_B(0) = 24.0$ mag arcsec^{-2}, as the Cross et al. distribution does, would imply that LSB galaxies are extremely rare and thus are rarely the cause of phenomenon such as damped Lyman-α systems. Additionally, though, the Cross et al. distribution suggests that, as surveys can now readily reach surface brightnesses fainter than 25.0 B mag arcsec^{-2}, we have now seen the entire range of galaxies which exist at this epoch.

As the Cross et al. (2001) results are both highly significant and seem in contradiction to the studies done by, e.g. O'Neil & Bothun (2000) and McGaugh (1996), further investigation is clearly warranted. With this in mind we have taken the recent results from a Canada-France-Hawaii Telescope (CFHT) deep survey of the Coma cluster (Andreon & Cuillandre 2002) to obtain an independent measure of the local SBD. Our results are then combined with previous SBD measurements and compared with that given by Cross et al.

2. The data

B, V, and R observations of the Coma Cluster using the CFHT were obtained by Andreon & Cuillandre (2002), and details about the observations and data reduction are given within that reference. All observations were taken on 12 January, 1999 with the Canada-France-Hawaii Telescope and CFH12K instrument (Cuillandre et al. 2001). The fields were centered on the Coma cluster and had a usable area (observed field minus vignetting, etc.) of 0.29 degrees sq. in V and R, and 0.20 degrees sq. in B. The total integration time was 720 s for the B and V images, and 480 s for the R image. The seeing was found to be 0.88″, 1.23″ and 1.04″ for the B, V, and R images, respectively.

For completeness, the sample was cut at central surface brightnesses 1.0–1.5 mag arcsec^{-2} brighter than the lowest detectable objects. That is, the sample is complete to the cutting central surface brightnesses of 23.75, 24.25, and 23.75 mag arcsec^{-2}, where the limiting detection brightnesses are $\mu(0)$ = 25.0, 25.5, 24.5 mag arcsec^{-2} in B, V, and R, respectively. At the cut-off limits the measured signal-to-noise ratio is ∼20.

Foreground and background galaxies were eliminated from the sample by comparing counts of galaxies within the observed field and within a control field which crosses the Coma supercluster. Errors incurred in this method are discussed in detail in Andreon & Cuillandre (2002) and are included in the error estimates for this data with the minor difference that possible over–Possonian number galaxy fluctuations are not taken into account for lack of knowledge on the fluctuation amplitudes.

As described in Andreon & Cuillandre (2002), central surface brightnesses were determined by finding the magnitude within the 0.25 kpc aperture and dividing that by the area (in arcsec) of that aperture. (All analysis was done on images convolved with the seeing disk.) For the purpose of this article, the galaxies were then separated into bins 0.5 mag arcsec^{-2} wide, and counts were made to the number of objects in each bin. The R band image proved to be the most reliable, having a definitive counts of ∼1000 galaxies (after elimination of background sources, etc.), with bins containing between 16–200 galaxies/bin in the $\mu_R(0)$ = 20–23.5 mag arcsec^{-2} range. The V and B images had total counts of 404 and 157 galaxies, respectively, with bins containing 13–26 galaxies/bin in $\mu_V(0)$ = 20–24 mag arcsec^{-2} and 8–40 galaxies/bin in $\mu_B(0)$ = 20.5–23.5 mag arcsec^{-2}, respectively. The considerably higher counts in the R band are due to a combination of lower sky noise, high CCD quantum efficiency, low galaxy background contamination, and larger field size. As a result, the SBD determined for the R band is by far the most reliable.

3. Finding the surface brightness distribution

3.1. The Andreon & Cuillandre data

Unlike many previous SBD studies (bar that of Cross et al. 2001), the data from Andreon & Cuillandre (2002) contains not just disk systems, but galaxies ranging from E and S0 through pure disk systems. As a result, at the bright end (e.g. between 18–21 B mag arcsec^{-2}) the sample is predominantly bulge-dominated (Fig. 1). Fortunately, the contribution of bulge-dominated galaxies at the surface brightness regime of interest (e.g. $\mu_B(0) \geq 21.5$ mag arcsec^{-2}) is extremely small. To account for this, all subsequent analysis of the Andreon & Cuillandre (2002) data will take into account only those data points with $\mu_B(0) \geq 21.5$ mag arcsec^{-2} or $\mu_R(0) \geq$ 20.0 mag arcsec^{-2}.

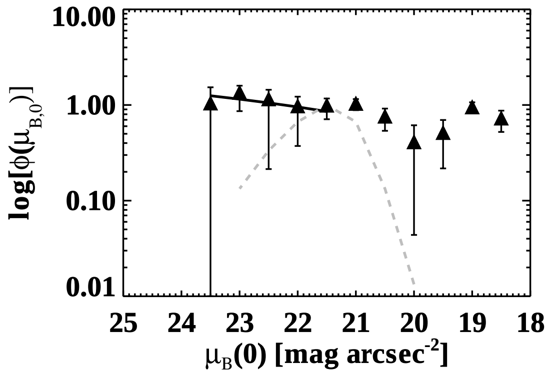

Fig. 1. Plot of the data from Andreon & Cuillandre (2002). The best fit line for the $\mu_B(0) \geq 21.5$ mag arcsec^{-2} data is given by the solid line, while the distribution of Cross et al. (2001) is given by the dashed line. The data has been normalized so that it has a value of 1.0 at $\mu_B(0)$ = 21 mag arcsec^{-2}. The Cross et al. line cuts off at 23.0 mag arcsec^{-2}, after which Cross et al. state that a lack of data points makes their curve unreliable.

Obtaining a best-fit line to the $\mu_B(0) \geq 21.5$ mag arcsec^{-2} data of Andreon & Cuillandre (2002) gives a line whose slope is marginally *increasing* with decreasing central surface brightness (slope = 0.08). This is in marked difference to the results shown by Cross et al. (2001) which shows an almost Gaussian distribution to the SBD (Fig. 1). As the error bars for the Andreon & Cuillandre (2002) distribution are fairly large, though, it is conceivable that the Cross et al. distribution could describe Andreon & Cuillandre's B band data.

Strong support can be given to the argument that Andreon & Cuillandre's B band data is best fit by a roughly horizontal line by looking at the SBD in V and R (the more reliable datasets) – Fig. 2. As discussed above, the errors for Andreon & Cuillandre's V and R SBD are considerably smaller than for their B band data. In particular, the R band data has >200 galaxies/bin in the lower ($\mu_R(0) \leq 21.52$ mag arcsec^{-2}) bins. As can be seen, both the V and R band data have similar fits to the B band fit, giving strong credence to the argument that the Cross et al. curve is not an accurate description of the Andreon & Cuillandre data.

3.2. Combining datasets

Another simple way to determine whether the Cross et al. (2001) distribution represents the true galaxy population at $z \leq$ 0.1 is to combine all previous data sets obtained for studying the local SBD function, and then obtain a best-fit curve to the data. Figure 3 shows all data points used for the SBD functions of McGaugh (1996), O'Neil & Bothun (2000), and Cross et al. (2001) with the $\mu_B(0) \geq 21.52$ mag arcsec^{-2} points from Andreon & Cuillandre (2002) overlaid. A best-fit line, weighted by the errors of the data points, is also shown. To allow for the natural fall-off in central surface brightness at $\mu_B(0) \leq 21.7$ mag arcsec^{-2}, two different lines were fit to the data – one for $\mu_B(0) \geq 21.7$ mag arcsec^{-2} and one for $\mu_B(0) < 21.7$ mag arcsec^{-2}. In this case the distribution again

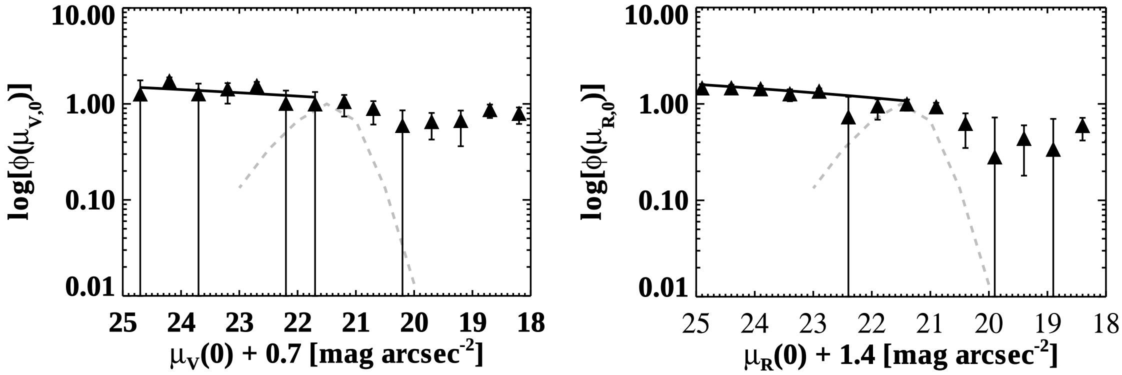

Fig. 2. Plot of the V and R band data from Andreon & Cuillandre (2002). Again, the distribution of Cross et al. (2001) is given by the dashed line. All data has been normalized so that it has a value of 1.0 at $\mu_B(0) = 21.6$ mag arcsec^{-2}.

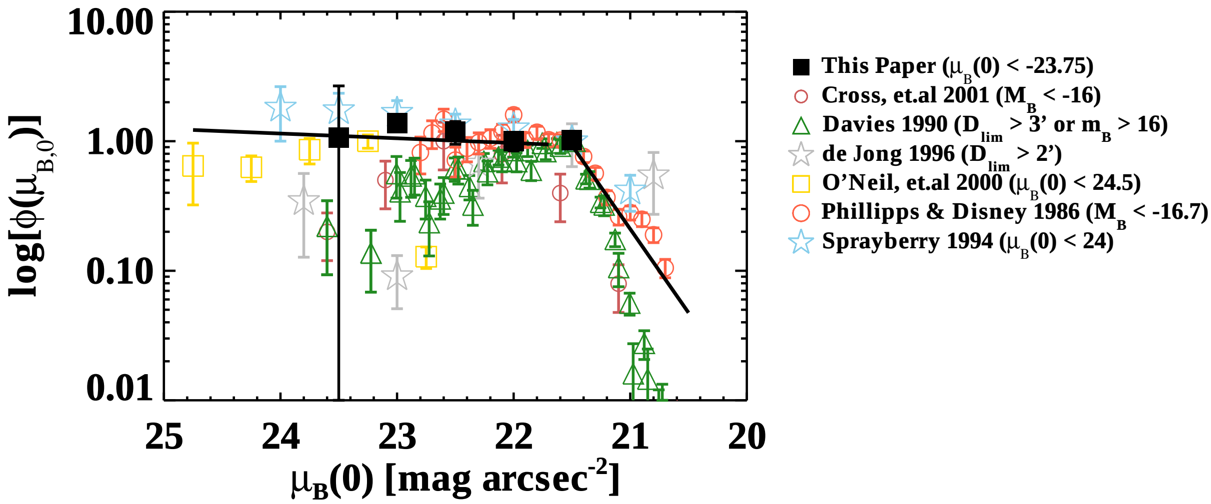

Fig. 3. Plot of the data from a variety of galaxy surveys. The associated surveys, the survey limits, and the approximate magnitude limits of the surveys are given at the right. The two lines are the best-fit lines to all the data, broken into that data with $\mu_B(0) < 21.7$ mag arcsec^{-2} and $\mu_B(0) \geq 21.7$ mag arcsec^{-2}.

shows a slight upwards slope at lower surface brightnesses (slope = 0.03).

Finally, perhaps the most accurate fit to the data is obtained by re-binning and statistically averaging the data points from all previous studies, and obtaining a best-fit line to this new data set. In this case, the data was placed into 0.5 mag arcsec^{-2} bins. The mean (and error) were calculated, with each data point weighted inversely by its own variance. The results of this re-binning are shown in Fig. 5. Two best-fit lines, again separated at the $\mu_B(0) = 21.7$ mag arcsec^{-2} mark, are shown. In this case, the slope for the lower surface brightness regime has a slightly downward angle (slope = −0.1). To insure that limiting the fit to a line did not force an artificial flattening of the SBD function, we also attempted to fit a second order function to the data. Not surprisingly, given the shape of the data, attempting to fit a bell-shaped curve to the seemingly flat data was unsuccessful.

3.3. Magnitude and measurement differences

One possible reason for the discrepancy between the Cross et al. (2001) SBD and that presented in this paper is that the selection criterion and method for determining $\mu(0)$ for the two surveys are quite different. The Cross et al. survey uses an absolute magnitude cut-off at $M_B < -16$ and determines $\mu(0)$ by assuming an exponential profile and extrapolating $\mu(0)$ from the measured isophotal magnitudes and areas. In contrast, the Andreon & Cuillandre (2001) sample uses a surface brightness limit and obtains all surface brightness measurements through finding the total magnitude within a central 0.25 kpc aperture and dividing that by the area of that aperture (Sect. 2).

In the Coma sample, only 30 galaxies out of the 405 with $\mu_0(B) < 23.5$ mag arcsec^{-2} also have $M_B < -16$. As a result it is not practical try to mimic the Cross et al. survey limits (Fig. 4). Instead, we can look at a variety of surveys undertaken and the limits inherent in those surveys. Figure 3 shows the SBD for a number of surveys, each having different survey limits. As with the Andreon & Cuillandre data, the majority of these surveys do not have explicit magnitude limits but instead have a surface brightness and diameter limit. We can, though, determine a rough magnitude limit for the surveys. Having done so (Fig. 3), it is notable that no trend is clearly seen between the fall-off in the SBD and the magnitude limit of the survey. This re-emphasizes the idea that *any complete*

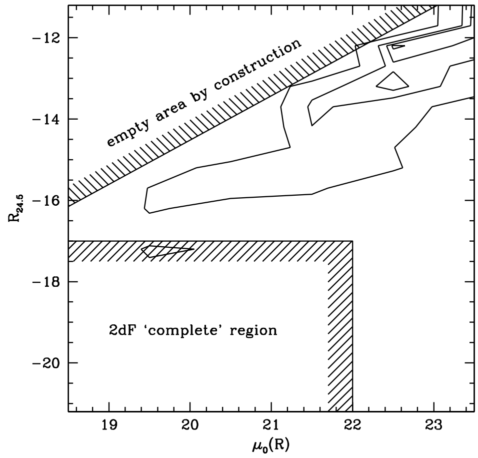

Fig. 4. Contours of the galaxies in the Andreon & Cuillandre (2001) sample showing the number of galaxies in 0.5 R mag arcsec^{-2} and 1 R magnitude bins. The first contour line indicates 10 galaxies and the lines are spaced by 40 galaxies/bin. The enclosed area labeled "2dF complete region" demarcates the completeness region for the Cross et al. (2001) sample. The region in the upper left corner of the plot, labeled "empty area by construction" demarcates the minimal galaxy size to be included in the the Andreon & Cuillandre sample.

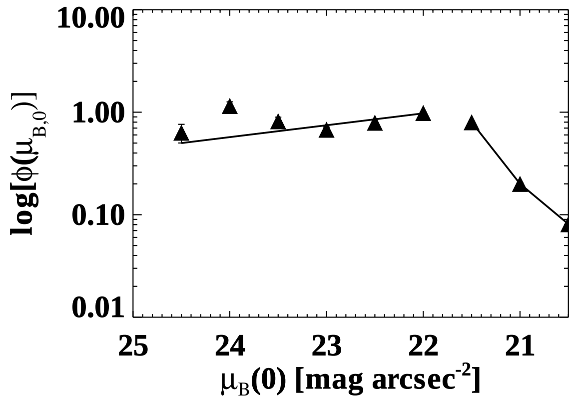

Fig. 5. The same data as in Fig. 3 re-binned and averaged into 0.5 mag arcsec^{-2} bins. The best fit lines to this data are shown, where again the lines are separated at the $\mu_B(0)$ = 21.7 mag arcsec^{-2} mark.

survey of galaxies is defined not by a limiting magnitude, but by the combination of a limiting magnitude and diameter. That is, by a surface brightness limit.

4. Discussion

The SBD described herein, obtained though combining a wide variety of survey data (including that of Cross et al. 2001), is in clear agreement with the studies of both McGaugh (1996) and O'Neil & Bothun (2000). That is, up to the general survey limits of 24.5 B mag arcsec^{-2}, our data conclusively shows that the SBD for the Andreon & Cuillandre sample does *not* decrease significantly between the canonical Freeman (1970) value of 21.7 and the survey limits of 24.5 mag arcsec^{-2}. Within the errors of this data, the line can be best described as have a slope of 0.0 ± 0.1. This is in clear contrast to the SBD determined by Cross et al. (2001). It is possible that the reason for the difference in the two surveys is due to a much higher magnitude cut-off for the Cross et al. sample than that of Andreon & Cuillandre. If this is correct it would imply that although low surface brightness galaxies may numerically dominate the number counts of galaxies in the local Universe, they do not play an important role in measures of either the total light or mass at $z < 0.1$. It is important to note, though, that by combining a wide variety of survey data, we attempted to minimize systematic errors induced by individual surveys and techniques. That is, we have included both samples which are purely volume limited (e.g. the Andreon & Cuillandre sample) and samples which are magnitude and/or diameter limited (e.g. Sprayberry 1994) and no trend is clearly seen between the fall-off in the SBD and the magnitude limit of the survey.

It seems plausible that the SBD given in Fig. 5 is an accurate representation of the SBD in the $z < 0.2$ Universe. Due to a dearth of data, though, the shape of the SBD in the $\mu_B(0) > 25.5$ mag arcsec^{-2} range cannot currently be determined, as finding the true form of the SBD at lower central surface brightnesses will only happen as survey sensitivities increase. We can gain a hint of what be be found through examining some recent findings in the literature. There have been a number of discoveries over the past few years of galaxies detected at 21-cm which which cannot be identified down to optical limits of 25−27 mag arcsec^{-2} (Boyce et al. 2001; Ryder et al. 2001; Kilborn et al. 2000; Rosenberg & Schneider 2000). Although none of these detections can make any statement as to the number density of extremely low surface brightness galaxies, the fact that any galaxies have been found so far below current survey limits argues that we still are not seeing a complete picture of the local galaxy population.

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