The nature of the dwarf population in Abell 868

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ABSTRACT

We present the results of a study of the morphology of the dwarf galaxy population in Abell 868, a rich, intermediate redshift (z=0.154) cluster which has a galaxy luminosity function with a steep faint-end slope (α=-1.26±0.05). A statistical background subtraction method is employed to study the B−R colour distribution of the cluster galaxies. This distribution suggests that the galaxies contributing to the faint-end of the measured cluster LF can be split into three populations: dIrrs with B−R < 1.4; dEs with 1.4≤B−R≤2.5; and contaminating background giant ellipticals (gEs) with B−R ≥ 2.5. The removal of the contribution of the background gEs from the counts only marginally lessens the faint-end slope (α=-1.22±0.16). However, the removal of the contribution of the dIrrs from the counts produces a flat LF (α=-0.91±0.16). The dEs and the dIrrs have similar spatial distributions within the cluster except that the dIrrs appear to be totally absent within a central projected radius of about 0.2 Mpc (H_o=75 km s^{-1} Mpc^{-1}). The number densities of both dEs and dIrrs appear to fall off beyond a projected radius of ≃ 0.35 Mpc. We suggest that the dE and dIrr populations of A868 have been associated with the cluster for similar timescales but that evolutionary processes such as ‘galaxy harassment’ tend to fade the dIrr galaxies while having much less effect on the dE galaxies. The harassment would be expected to have the greatest effect on dwarfs residing in the central parts of the cluster.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: dwarf – galaxies: luminosity function, mass function – methods: data analysis.

1 INTRODUCTION

The galaxy luminosity function (LF) is one of the most direct observational tests of theories of galaxy formation and evolution. Clusters of galaxies are ideal systems within which to measure the galaxy LF down to very faint magnitudes because of the large numbers of galaxies at the same distance that can be observed within a small area of sky. Much work has been done in recent years in measuring the faint-end of the galaxy LF in clusters (e.g. Driver et al. 1994; de Propris et al. 1995; Lobo et al. 1997; Wilson et al. 1997; Valotto et al. 1997; Smith, Driver & Phillipps 1997; Trentham 1997a, 1997b, 1998; de Propris & Pritchett 1998; Driver, Couch & Phillipps 1998b; Garilli, Maccagni & Andreon 1999). These studies have generally used background subtraction procedures and have shown that many clusters are dominated in number by a large population of faint galaxies. The LF of these clusters typically becomes steep faintward of about M_R≈-18.1. The faint-end slope of the LF, α (where α is the slope of dN/dL: α=-1 is flat in a plot of log N vs. magnitude) typically lies in the range -1.2 to -2.2.

Phillipps et al. (1998) noted that the steepness of the faint-end slope appears to be dependent on cluster density, with dwarfs being more common in lower density environments. This is possibly because the various dynamical processes which can destroy dwarf galaxies act preferentially in dense environments. One implication of this is that dwarfs may be less common in the higher density cores of clusters than at larger cluster radii. For example, Lobo et al. (1997) measured α=-1.8 from a large area (1500 arcmin^2) survey of the Coma cluster. However, Adami et al. (2000) derived a flat faint-end LF from a spectroscopic survey of a small area (56 arcmin^2) around the core of the cluster. Driver et al. (1998b) noted a tendency for less evolved clusters (including A868) to have steeper faint-end slopes compared to more evolved clusters (see also Lopez-Cruz et al. 1997). The
implication is that a larger fraction of dwarfs has been destroyed in the more evolved clusters.

Measurements of the field galaxy LF from redshift surveys (e.g. Loveday et al. 1992; Lin et al. 1997; Marzke et al. 1997; Bromley et al. 1998; Muriel et al. 1998) generally give a flat faint-end slope with \( \alpha \simeq -1.0 \pm 0.1 \). However, other recent measurements of the field galaxy LF have found a steeper LF \( \alpha \simeq -1.2 \) (Zucca et al. 1997; Folkes et al. 1999). The LF of the Local Group is flat to \( \simeq \mathcal{L}_* /10000 \) (van den Bergh 1992; Pritch & van den Bergh 1999). Results from nearby diffuse groups (e.g. Trentham, Tully & Verheijen 2001) also give relatively flat faint-end slopes to the LF.

Hierarchical clustering theories of galaxy formation generically predict a steep mass function of galactic halos (e.g. Kauffmann, White & Guideroni 1993; Cole et al. 1994). This is in conflict with the flat galaxy LF measured in the field and in diffuse local groups but not with the steep LFs measured in many clusters. However, in the hierarchical universe, clusters form relatively recently from the accretion of smaller systems. The dynamical processes that operate in clusters are destructive. Ram pressure stripping (e.g. Abadi, Moore & Bower 1999) and gravitational tides/galaxy harassment (e.g. Moore et al. 1996; Moore, Lake & Katz 1998; Bekki, Couch & Shioya 2001) will both tend to fade galaxies by removing gas or stripping stars. These processes are most effective for less massive, less bound systems. Hence, we might expect to see a flattening of the faint-end slope in clusters compared to the field, rather than the observed steepening.

Two selection effects may go some way to resolving this apparent paradox. Firstly, surface brightness selection effects may be seriously affecting the derived LFs both in clusters and the field (see e.g. Impey & Bothun 1997; Cross et al. 2001). Secondly, Valotto, Moore & Lambas (2001) have used a numerical simulation of a hierarchical universe to show that many “clusters” identified from two dimensional galaxy distributions may result principally from the projection of large-scale structure along the line of sight. They suggest that attempts to derive a LF for these “clusters” using the standard background subtraction procedure lead to a derived LF with a steep faint-end slope, despite the fact that the actual input LF had a flat faint-end. Further work needs to be done to establish whether, and to what extent, these effects are biasing measured LFs.

Assuming that selection effects cannot completely explain the dichotomy between the steep LFs seen in clusters and the flat LFs seen in the field and loose groups, then it is vital that the nature of the galaxies causing the steep faint-end slope in clusters be studied in detail. The origin and evolution of these objects may have important consequences for our understanding of galaxy formation and the processes which drive galaxy evolution.

In this paper, we present the results of a study of the colour characteristics of the dwarf population of the cluster A868. A868 is an Abell richness class 3 cluster (Abell, Corwin & Olowin 1989) at redshift \( z = 0.154 \) (Kristian, Sandage & Westphal 1978). Its Bautz-Morgan class is II-III (Leir & van den Bergh 1977). Driver et al. (1998b) measured a steep faint-end slope to the \( (R\text{-}band) \) LF for this cluster. The presence of a giant cD galaxy (Valentijn & Bijleveld 1983) and the richness of this cluster suggest that it is not simply the result of the projection of large-scale structure along the line of sight.

In this paper we use the \( B-R \) colour distribution of the cluster galaxies to derive some broad morphological information about the dwarf population of the cluster. In Section 2 we discuss the observations and data reduction methods employed. In Section 3 we present the derived \( B-R \) colour distribution of the galaxies at the faint-end of the cluster LF. This enables us to separate out the dE and dIrr populations and study their relative contributions to the cluster LF (Section 4). In Section 4 we also discuss the radial distribution of the dE and dIrr populations within the cluster.

Throughout this paper we have adopted a standard flat cosmology with \( \Omega_m = 1, \Omega_{\Lambda} = 0.5, \) and \( H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

2 OBSERVATIONS AND DATA ANALYSIS

2.1 Observations and data reduction

Deep B and R images were obtained of a field centered on the cluster A868 and of a ‘background’ field 74 arcmin east of the cluster centre. A standard Kitt Peak filter set was used. The data were obtained at the f/3.3 prime focus of the 3.9m Anglo-Australian Telescope (AAT) using a \( 1024 \times 1024 \) 24-\( \mu \text{m} \) (0.38-arcsec) pixel thinned Textronix CCD. This detector gave a total field of view of \( \simeq 6.7 \times 6.7 \text{ arcmin}^2 \) (equivalent to a projected size of \( \sim 0.9 \text{ Mpc} \times 0.9 \text{ Mpc} \) at the distance of A868). The R-band data were obtained on 1996 January 25. The B-band data were obtained on 1996 February 15 and 17 with exactly the same observing set-up.

The data were reduced using the Starlink CCDPACK package to de-bias, flat-field, align and co-add the images. The reduced frames were then sky-subtracted to remove any large-scale residual sky gradients. The R-band data were calibrated using observations of standard star fields from the lists of Landolt (1992) putting our photometry on the Johnson (B)-Cousins (R) magnitude system. The total exposure times for the final co-added R-band frames for both cluster and background fields is 90 min. Neither of the nights on which the B data were taken was photometric. These data were calibrated using photometric data obtained on the Jakobus Kapteyn Telescope on La Palma in 2000 November. The total exposure time for the final co-added B-band cluster and background frames are 240 mins and 180 mins respectively.
2.2 Image detection and photometry

The detection and photometry of objects on the final co-added R-band cluster and background frames were conducted automatically using the SExtractor software package (Bertin & Arnouts 1996). A detection limit of $\mu_{R}=26$ mag arcsec$^{-2}$ over 4 connected pixels was used. The magnitudes measured were Kron (1978) types taken within an aperture of radius $= 3.5r_{kron}$. The measured magnitudes were corrected for Galactic extinction using values from the NED Galactic extinction calculator based upon the maps of Schlegel, Finkbeiner & Davis (1998). These values are $A_R=0.09$, $A_B=0.22$ for the cluster frames and $A_R=0.15$, $A_B=0.36$ for the background frames. The positions and apertures defined by SExtractor’s source detection algorithm as run on the R-band frame were then used on the B frames. In this way we measured the apparent $B$ magnitudes for those objects detected on the R frames inside identical apertures.

2.3 Number counts and the luminosity function

Driver et al. (1998b) showed, by comparing the counts from the R-band background data to those of Metcalfe et al. (1995), that these data are complete to at least $R=23.5$ (to Metcalfe et al.’s surface brightness limit of $\approx 25.2$ $R_B$). We actually use data to $R=23.52$ since this is equivalent to $M_R=-15.5$ in our adopted cosmology. To this completeness limit we expect the measured apparent $R$ magnitudes to have a random error of less than $\pm 0.1$ mag (Driver et al. 1998a). However, we expect magnitudes brighter than $R=22.5$ to have a random error of less than $\pm 0.05$ mag.

All of the objects with $R<23.52$ have a measured apparent $B$ magnitude. Objects can be detected on the B frames to about 1 magnitude fainter than on the R frames with similar S/N. Hence, at $R=22.5$ we expect the measured $B-R$ colours to have a random error of around $\pm 0.07$ mag if $B-R=1$, $\pm 0.11$ mag if $B-R=2$ and $\pm 0.21$ mag if $B-R=3$. At $R=23.5$ we expect the measured $B-R$ colours to have a random error of around $\pm 0.14$ mag if $B-R=1$, $\pm 0.23$ mag if $B-R=2$ and $\pm 0.35$ mag if $B-R=3$.

Figure 1 presents an R-band LF derived from the data. This was recovered using the standard method of statistically subtracting the field galaxy counts from those observed towards the cluster (see e.g. Driver et al. 1998b). We have not attempted to apply a k-correction to any of the objects since we do not want to make assumptions about their morphologies before studying the $B-R$ colour distribution. We did make an adjustment for the diminishing field of view available to fainter objects (see Smith et al. 1997). Aside from poisson statistics, we have estimated a further uncertainty of 15% in the number of background counts, to account for field-to-field variance due to large-scale structure. This estimate is based upon Driver et al.’s (1998b) R-band counts for 7 non-cluster fields made during the same run as the A868 R-band images were taken (see their fig. 3). The derived LF shows a sharp upturn faintward of $M_R=-18.0$ ($\alpha=-1.26\pm 0.05$), as noted previously by Driver et al. (1998b).

Figure 2 shows a colour-magnitude ($R$ versus $B-R$) diagram for the cluster frame and for the background frame. The cluster giant elliptical sequence at $B-R\approx 2.2$ is clearly visible. This is the observed $B-R$ we expect for these galaxies using the k-corrections of Coleman, Wu & Weedman (1980) and the redshift of A868 ($z=0.154$).

### 3 THE $B-R$ COLOUR DISTRIBUTION

In this section we consider what the $B-R$ colour data can tell us about the population of galaxies responsible for the upturn seen in the LF at $M_R>-18.0$. Figure 3a presents a histogram of the $B-R$ colours for all objects in the cluster frame with $21.02<R<23.52$ (equivalent to $-18.0<M_R<-15.5$), i.e. the apparent magnitude range covering the upturn in the LF. Figure 3b shows a histogram of the $B-R$ colours for all objects from the same $R$ magnitude range on the background frame. Figure 3c shows the result of subtracting the background frame $B-R$ colour distribution from the cluster frame $B-R$ colour distribution. If one assumes that the population of field galaxies is identical in both frames, not just in its luminosity distribution but also in morphology and hence colour, then the result of the subtraction gives the $B-R$ distribution of the cluster minus the background field population. As with the LF in Fig. 1, no attempt has been made to apply a k-correction to the $B-R$ colours. The error-bars shown in Fig. 3c (and in Fig. 4) take account of poisson statistics and the estimated 15% uncertainty in the background counts due to field-to-field variance.

The background-subtracted cluster $B-R$ colour distribution has a sharp pronounced peak at $B-R\approx 1.1$ and a much broader peak at $B-R\approx 1.8$. Based upon the k-corrections of Coleman et al. (1980) and Trentham (1998) we would expect dIrr galaxies at the distance of A868 to have observed $B-R\approx 1.1$ and dEs to cover a broader range of observed colours $1.6<B-R<2.3$. Clearly, these values match...
FIGURE 3. $B - R$ histograms for galaxies with $21.02 < R < 23.52$ (equivalent to $-18.0 < M_R < -15.5$ at cluster distance) in (a) Cluster frame, (b) Background frame, (c) Cluster - Background.

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4 DISCUSSION AND CONCLUSIONS

In this section we consider the relative contributions to the faint-end of the cluster LF of the three populations of galaxies identified in Section 3. To study this we split the background-subtracted $B - R$ colour distribution shown in
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Figure 5. (a) The solid squares show the R-band LF plotted in Fig. 1. The open squares show the LF derived if objects with $R > 21.02$ (i.e. $M_R > -18.0$ if they are in the cluster) and $B - R > 2.5$ (those identified as background gEs) are excluded; (b) The solid-squares again show the R-band LF plotted in Fig. 1. The open squares show the LF derived if objects with $R > 21.02$ and $B - R < 1.4$ or $B - R > 2.5$ (those identified as cluster dIrrs or background gEs) are excluded.

Fig. 3c into three groups. All galaxies with $B - R < 1.4$ are assumed to be dIrrs. All galaxies with $1.4 \leq B - R \leq 2.5$ are assumed to be dEs. All galaxies with $B - R > 2.5$ are assumed to be background gEs.

Fig. 5a reproduces the LF of Fig. 1 (solid squares). Also shown (open squares) is a LF derived by excluding (for galaxies with $R > 21.02$) all the background gEs. Excluding these objects does not significantly alter the slope of the faint-end upturn in the LF to $\alpha = -1.22 \pm 0.16$. Hence, although there is evidence that background large-scale structure is contributing to the counts at the faint-end of the derived LF for A868, this contribution is nowhere near sufficient to explain, by itself, the steep upturn seen at the faint-end of the cluster LF.

In Fig. 5b, we again reproduce the LF of Fig. 1 (solid squares). However, we now show (open squares) the LF derived by excluding not only the red background gEs but also the dIrr galaxies. Whilst there is significant scatter in these points, it is clear that there is now no evidence for an upturn in the LF of A868 at faint magnitudes ($\alpha = -0.91 \pm 0.16$). The upturn in the cluster LF depends on the presence of both the dE and dIrr populations.

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Figure 6 shows the number of dE and dIrr objects as a cumulative function of projected area from the cluster centre (taken to be the centre of the cD galaxy). These numbers were derived by calculating the number of objects within each $B - R$ range in a series of annuli which linearly increase in projected area. The counts for each annulus were adjusted by subtracting from them the average number of background counts expected in an annulus of that projected area (calculated from the background frame).

Perhaps the most striking feature of Fig. 6 is the apparent absence of any dIrr galaxies inside a projected area of $\simeq 0.12$ Mpc$^2$ (equivalent to a projected radius of $\simeq 0.19$ Mpc). In contrast there is a significant excess of dE galaxies over background counts right into the core of the cluster. This result is consistent with the ‘galaxy harassment’ scenario (Moore et al. 1996, 1998). These simulations show that the morphology of brighter disk systems in a dense cluster can be radically transformed by the effects of close encounters with brighter galaxies and the cluster’s tidal field. Gas and stars are progressively stripped out of the disk systems eventually leaving a spheroidal remnant (Moore et al. 1998). The processes of ‘harassment’ would certainly fade dIrr galaxies by stripping gas and stars from them and may eventually leave a faint dE remnant. In such ‘harassment’ scenarios the material at the cluster centre is older than material in the outer regions. Hence objects in the cluster centre experience ‘harassment’ at earlier times and for longer durations. This could explain the absence of dIrrs in the core of A868.

The second interesting feature of Fig. 6 is that the ratio of dE galaxies to dIrrs appears similar at projected radii $>0.19$ Mpc. This suggests that the population of dIrrs cannot be explained as being due to recent infall. The populations of dE and dIrr would have to have formed part of the cluster for similar timescales in order to achieve similar radial distributions. The dEs numerically dominate down to our completeness limits. However, as can be seen from
Fig. 4b, it is possible that the dIrrs will dominate at fainter magnitudes.

The third point from Fig. 6 is that there appears to be a down-turn in the number densities of both dE and dIrr galaxies beyond a projected area of \( \approx 0.38\) Mpc\(^2\) (projected radii \( > 0.35\) Mpc), although the errors are so large at these radii that any such conclusion has to be tentative. Are we seeing the edge of the cluster’s dwarf halo? At what point do the number densities fall to field levels? Spectroscopic surveys are the best way to study cluster LFs at large cluster radii where the decreasing number of cluster galaxies makes statistical subtraction studies problematical.

Phillipps et al. (1998) noted that the steepness of the faint-end slope of the LF appears to be dependent on cluster density, with the ratio of dwarfs-to-giants increasing in lower density environments. Driver et al. (1998b) noted a tendency for less evolved clusters (including A868) to have steeper faint-end slopes compared to more evolved clusters. A possible scenario is that clusters form with large numbers of both dE and dIrr galaxies and that such unevolved clusters will have LFs with steep faint-end slopes. The various potential dynamical processes in the cluster (e.g. harassment, ram-pressure stripping etc.) preferentially strip gas and stars from the less centrally concentrated dIrr galaxies leading to their gradual fading and with it a lessening of the faint-end slope of the LF. This happens firstly in the cluster core where such processes have had a longer period to operate but ultimately, in very evolved systems, the dIrrs throughout the cluster are ‘faded’ and a flat faint-end slope to the LF at all radii results.

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