THE FAINT END OF THE GALAXY LUMINOSITY FUNCTION IN ABELL 426 AND 539

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ABSTRACT

We derive I-band luminosity functions for galaxies in Abell 426 (Perseus and Abell 539, two rich, low Galactic latitude clusters at moderate redshift. Cluster members are selected via the color-magnitude relation for bright galaxies. We find $\alpha = -1.56 \pm 0.07$ for Perseus over the range $-19.4 < M_I < -13.4$ ($15 < I < 21$) and $\alpha = -1.42 \pm 0.14$ for $-18.5 < M_I < -14$ ($17 < I < 21.5$) for A539. These luminosity functions are similar to those derived in Virgo and Fornax, weakly supporting claims for the existence of a universal luminosity function for galaxies in clusters.

Key words: galaxies: clusters: individual (Abell 426, Abell 539) — galaxies: luminosity function, mass function

1. INTRODUCTION

Dwarfs are the most common type of galaxy in the universe; yet, because of their low luminosity and surface brightness our understanding of these objects is rather limited. Only recently has it become possible to obtain photometry for statistically significant samples of dwarfs, thanks to the availability of wide-field CCD detectors on large telescopes.

Luminosity functions (LFs) for galaxies are a powerful tool to examine galaxy bulk properties, especially where little detailed information is available, as in the case of dwarf galaxies. LFs can be obtained with a modest amount of observing time, are relatively easily corrected for incompleteness, and possess considerable physical meaning. For example, the litmus test of any theory of galaxy formation is how well it reproduces the observed LF.

Clusters of galaxies at moderate redshift ($z < 0.1$) are one of the best environments to study the dwarf LF, because of their high density and the possibility of dealing with contamination statistically. The fact that the nearest clusters are about 5 times as distant as Virgo or Fornax is actually an advantage for dwarf galaxy completeness. This is because low surface brightness galaxies tend to become easier to detect as their angular size decreases. In addition, the ratio of target objects to background galaxies is roughly independent of the distance modulus of the cluster under consideration, but since the angular correlations of fainter galaxies are smaller, field-to-field fluctuations in the background counts are decreased. This gives us greater confidence in the derived LF slope. In addition, it is possible to survey a number of environments by choosing clusters of different densities, richness, Bautz-Morgan class, Rood-Sastry type, or evolutionary stage. These considerations were the basis of the pioneering survey of the Virgo cluster by Sandage, Binggeli, & Tammann (1985).

Recent investigations have revealed large numbers of dwarfs to be present in clusters whose LF slopes are sometimes as steep as $\alpha = -2$ (where $\alpha$ is the slope $dN/dL$; $\alpha = -2$ corresponds to $d \log N/dm = +0.4$, whereas $\alpha = -1$ is flat in a plot of $\log N$ vs. magnitude, where $N$ is the number of galaxies).

We tabulate a compilation of recent results in Table 1: column (1) identifies the cluster, column (2) presents the $\alpha$-values derived and their range, column (3) gives the magnitude limits of the fit, and column (4) identifies the reference. A comparison of these results is somewhat difficult, since the assumption that the LF follows a Schechter (1976) function is no longer tenable. Trentham (1998a) shows that LFs tend to drop rapidly at bright ($M_B < -21$) luminosities, flatten for $-18 < M_B < -16$, and then rise for fainter galaxies, with slopes $-1.3 < \alpha < -1.8$. The above “shape” of the LF may be at the origin of the “dips” and “bumps” seen in the Coma cluster (Lobo et al. 1997) and in A2029 (De Propris, Pritchet, & Eisenhardt 1998b). One further complication is that removal of background galaxies from the cluster counts is carried out in a number of different ways; Bernstein et al. (1995) and Trentham (1997, 1998a, 1998b) compute R-band counts and their variance from observations of background fields. De Propris et al. (1995) use the correlation function to estimate the field-to-field variance in their $B$ and $R$ counts, but they normalize these counts to observations of a background field. Seeker (1996) uses the $B-R$ color-magnitude relation to isolate cluster members, whereas Lobo et al. (1997) adopt $V$-band counts from the ESO-Sculptor Faint Galaxy Redshift Survey (Arnouts et al. 1997). The slopes reported by these authors vary from “shallow” ($\alpha > -1.5$) to very steep ($\alpha \sim -2$), although over different magnitude ranges.

The case of Coma is particularly interesting; Lobo et al. (1997) claim a very steep $V$-band LF ($\alpha \sim -1.8$), whose slope appears to increase outward from the cluster core (Sekiguchi et al. 1997). De Propris et al. (1998a) show that this steep LF persists in the infrared $H$-band and is there-
fore a feature of the mass function of galaxies, in accordance with the hypothesis that starbursts drive the optical LF (Hogg & Phinney 1997), and a steep LF is consistent with a flat mass function for dwarf galaxies.

Lobo et al. (1997) and Sekiguchi et al. (1997) sample their LF to $M_V < -14.75$ and $M_B < -16$, respectively. De Propris et al. (1998a) find a steep upturn for $M_H < -19$, approximately corresponding to $M_B < -16$, whereas Trentham (1998b) reports a shallower slope over this magnitude range. Further, the “depletion” observed by Lobo et al. (1997) near NGC 4889 and NGC 4874 is limited to relatively bright galaxies, whereas Trentham (1998b) reports an increase at fainter magnitudes. This is consistent with earlier observations of A262, where dwarfs appeared to be concentrated in the cluster core (Trentham 1997). It is indeed possible for the dwarf-rich luminosity function to be ubiquitous, with examples found even in the field (Marzke et al. 1994; Loveday 1997). On the other hand, a number of authors disagree and report optical LF slopes $\alpha \simeq -1.5$ (Bernstein et al. 1995; Secker 1996; Lopez-Cruz et al. 1997).

It has often been suggested that the cluster environment should strongly affect the fragile dwarf galaxies. Lobo et al. (1997) find that the LF in the immediate vicinity of NGC 4874 (the cD galaxy in Coma) is shallower. Lopez-Cruz et al. (1997) have proposed that cD galaxies grow at the expense of their dwarf satellites. Trentham (1997) also suggests that the slope of the LF decreases as clusters evolve and dwarfs are subsumed by giants. It is nevertheless possible for the cluster environment to favor the formation or preservation of dwarf galaxies. Dwarfs may be formed during mergers (Krivitvsky & Kontorovich 1997) and are seen to form in tidal tails (Mirabel, Dottori, & Lutz 1992; Yoshida, Taniguchi, & Murayama 1994), with steep LF slopes (Hunsberger, Charlton, & Zaritsky 1996). Silk, Wyse, & Shields (1987) have suggested that dwarfs may accrete gas from the intracluster medium and fuel further bursts of star formation.

Here, we wish to entertain the hypothesis that cluster evolution is responsible for these effects. We have therefore selected targets using the X-ray classification scheme by Jones & Forman (1984). In this model, clusters evolve from loose, spiral-rich, X-ray faint and low density objects, to dense, X-ray luminous and elliptical rich systems. An additional benefit of this scheme is that it allows us to consider the role of gas density (Babul & Rees 1992).

In this paper, we detail observations of two clusters: Abell 426 (Perseus) and Abell 539. Perseus is an old cluster, with high X-ray luminosity and a small core radius. Galaxies are distributed on a large filament that appears to be aligned with surrounding structure. Many of its bright members show signs of nuclear activity (e.g., NGC 1275 is a Seyfert 2 AGN, IC 310 is a WAT radio source). Abell 539 is a rich cluster, dominated by a chain of elliptical galaxies and believed to be undergoing a collision (Ulmer, Wirth, & Kowalski 1992). In the Jones & Forman (1984) classification, this object is slightly more evolved than Virgo.

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**Table 1**

| Cluster | $\alpha$ (2) | Magnitude Range (3) | (JF Type) (4) | Reference (5) |
|---------|--------------|---------------------|--------------|---------------|
| A1367$^a$ | $-1.2 < \alpha < -1.5$ | $-18.9 < M_R < -14.9$ | Un-evolved nXD | 1 |
| Coma | $-1.32$ | $-18.0 < b < -15.0$ | Evolved nXD | 2 |
| Coma | $-1.3 \pm 0.1$ | $-22 < b < -13$ | 3 |
| Coma | $-1.5 \pm 0.13$ | $-18.5 < V < -14$ | 4 |
| Coma | $-1.80 \pm 0.05$ | $-21.5 < V < -14$ | 5 |
| Coma | $\sim -1.7$ | $-15 < R < -11$ | 6 |
| Coma | $-1.42 \pm 0.05$ | $-19.5 < R < -11.5$ | 7 |
| Coma | $-1.42 \pm 0.12$ | $R < -12.5$ | 8 |
| Coma | $-1.41 \pm 0.05$ | $-19.5 < R < -12.5$ | 9 |
| Coma | $-2.0 \pm 0.3$ | $-21 < H < -19$ | 10 |
| Coma | $-1.41 \pm 0.35$ | $-19.5 < K < -16.5$ | 11 |
| A2107$^b$ | $-2.28 \pm 0.30$ | $-15.9 < M_R < -12.9$ | Evolved nXD | 12 |
| A262 | $-1.84 \pm 0.38$ | $-15.4 < M_R < -9.9$ | Un-evolved XD | 13 |
| Virgo | $-2.26 \pm 0.13$ | $-15.9 < M_R < -11.4$ | Un-evolved XD | 14 |
| A539 | $-1.42 \pm 0.14$ | $-18.5 < M_R < -14.0$ | Un-evolved XD | 15 |
| A426 | $-1.56 \pm 0.07$ | $-19.4 < M_R < -13.4$ | Evolved XD | 16 |
| A1795$^a$ | $-1.2 < \alpha < -1.5$ | $-18.9 < M_R < -14.9$ | Evolved XD | 17 |
| A2199 | $-2.16 \pm 0.18$ | $-15.4 < M_R < -10.9$ | Evolved XD | 18 |
| A2199$^c$ | $-1.2 < \alpha < -1.5$ | $-18.9 < M_R < -14.9$ | Evolved XD | 19 |
| NGC 507 Group | $\sim -1.4$ | $-15.6 < M_R < -9.6$ | NA | 20 |
| A665$^a$ | $\sim -2$ | $-19.7 < M_V < -17.7$ | NA | 21 |
| A665$^b$ | $-1.12$ | $-21.7 < M_V < -18.7$ | NA | 22 |
| A663 | $\sim -1.8$ | $-17.0 < M_R < -14.0$ | NA | 23 |
| A1146$^a$ | $-1.2 < \alpha < -1.5$ | $-18.9 < M_R < -14.9$ | NA | 24 |
| A1689$^b$ | $\sim -2$ | $-19.7 < M_V < -17.7$ | NA | 25 |
| A1689 | $\sim -1.2$ | $-21.7 < M_V < -18.7$ | NA | 26 |
| A2052$^a$ | $-2.28 \pm 0.30$ | $-15.9 < M_R < -12.9$ | NA | 27 |
| A2544 | $\sim -1.7$ | $-19.7 < M_R < -16.7$ | NA | 28 |
| A2666$^b$ | $-2.28 \pm 0.30$ | $-15.9 < M_R < -12.9$ | NA | 29 |

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* Combined LF for these three clusters.
* Combined LF for these two clusters.
* Combined LF for these four clusters.

(1) Trentham 1998c; (2) Thompson & Gregory 1993; (3) Biviano et al. 1995; (4) Lobo et al. 1997; (5) Trentham 1998b; (6) Bernstein et al. 1995; (7) Lopez-Cruz et al. 1997; (8) Secker et al. 1997; (9) De Propris et al. 1998a; (10) Mobasher & Trentham 1998; (11) De Propris et al. 1995; (12) Trentham 1997; (13) Phillipps et al. 1998; (14) Wilson et al. 1997; (15) Driver et al. 1994; (16) Smith et al. 1997.
Observing these objects we hope to elucidate the role played by cluster evolution on the dwarf galaxy LF, and to enlarge the sample of well studied clusters.

In this paper, § 2 presents our observations and data reduction. Section 3 introduces our analysis. Section 4 discusses our results. Our conclusions are summarized in § 5. We choose a cosmology with $H_0 = 70$ and $q_0 = 0.1$ throughout.

2. OBSERVATIONS AND DATA REDUCTION

Observations were taken during the nights of 1994 December 4–6 at the prime focus of the Canada-France-Hawaii 3.6 m Telescope, using a $4 \times 4$ K mosaic CCD camera (Cuillandre et al. 1996). Two of the nights were photometric, although the seeing was generally poor (about 1′) for CFHT, whereas the third had to be abandoned because of very poor weather. In the version used in this paper, and now superseded, MOCAM was equipped with four engineering-grade chips. The cosmetic quality of these detectors was generally satisfactory, except for one chip, which was found to be affected by a large defect. Readout times were, however, very long (about 10 minutes each), and this limited our data collecting efficiency considerably. The pixel scale was about $0.21′$ and the total field of view $14′ \times 14′$.

We observed two fields, centered on the giant elliptical galaxies NGC 1275 (Abell 426) and UGC 3274 (Abell 539), in $V$ and $I$. The total exposure times were 1200 s in both filters, suitably split to aid in the removal of cosmic rays.

Data reduction was carried out via the usual techniques of trimming, debiasing and flat-fielding. The CCD mosaic data were split into four component chips before these steps. The cosmetic defect seen to exist in one of the chips proved impervious to any processing procedure, and we were forced to remove this chip from all further analysis. This leaves us with a total observed area of 147 arcmin$^2$.

Because of the long readout times we found it impossible to obtain twilight sky flat fields. Our images were strongly contaminated by bright galaxies and by saturated stars (because of the low Galactic latitude of our targets) and could not be used to build sky flats. Eventually, we decided to use dome flat fields. This may reduce the accuracy of our photometry, but the additional small uncertainty in our photometry is not relevant for our studies of the luminosity function.

Finally, we co-added all data for each cluster to improve our signal-to-noise ratio. The final images are analyzed as discussed below.

3. ANALYSIS

It is immediately apparent, from a cursory examination, that our images are dominated by the two central cluster giants (Figs. 1 and 2). To remove diffuse light from these objects and expose galaxies “hidden” beneath their bulk, we have modeled these galaxies using the IRAF STSDAS routines “ellipse” and “bmodel” and removed them from the images.

To detect objects, we convolved each image with a lowered Gaussian, having full width at half-maximum (FWHM) equivalent to the stellar FWHM, and with a kernel about 4 times as large. Objects that are above a 4 $\sigma$ level from the mean sky are included in our catalog for later photometry. Here $\sigma$ refers to the noise in the sky after convolution with the lowered Gaussian.

For each object, we computed Kron (1980) image moments $r_1$ and $r_{-2}$. The first parameter, $r_1$, is a “size” estimator and is used for photometry, which is carried out in $2r_1$ (radius) apertures. Infante (1987) and Infante & Pritch (1992) show that this procedure encloses most of the light from each object. Naturally, this procedure is not employed for bright members, where the single aperture that we use to measure the image moment is not sufficient. For these objects, we use surface brightness profiles to estimate the best aperture (i.e., one that includes as much light as the Kron apertures used for fainter objects). The $r_{-2}$ parameter is used as a measure of “compactness” in order to discriminate between stars and galaxies. In Figures 3 and 4 we plot $r_{-2}$ vs. $I$; a “stellar” sequence at a constant $r_{-2}$ is clearly visible. This sequence inflects upward at bright magnitudes because of saturation, but these objects are easily identified by inspection. We remove stars from our catalogs, which then consist solely of galaxies.

Photometry is calibrated by observations of stars in M67 by Montgomery, Marschall, & Janes (1993). Because of the low Galactic latitude of our targets we need to correct for foreground extinction. We use the reddening maps by Burstein & Heiles (1982), transformed to the bands of interest using Johnson (1965). Our estimates of foreground extinction agree with those stated in NED and by Weedman (1975). They are equal to 0.54 and 0.40 mag in $V$ and $I$ (respectively) for Perseus, and 0.18 and 0.13 mag for A539.

We select galaxies in the $I$ band, since the LF will be closer to the underlying mass function. For each object we compute $V-I$ colors in $3 \times FWHM$ (radius) apertures. We bin data in 0.5 mag bins to produce galaxy number counts for objects in our fields. These counts consist of a contribution from cluster members and one from foreground and background galaxies. These have to be removed from consideration. We adopt two methods: one is to remove background counts statistically, using estimates from the literature (Lilly, Cowie, & Gardner et al. (Lilly, 1991; Gardner et al. 1996). The other is to use the $V-I$ color-magnitude relation to assess membership, since cluster members tend to lie on a well-defined ridge line. We assume that all objects within $\pm 0.3$ of the color-magnitude relation shown in Figures 5 and 6 (for A426 and A539, respectively) are members (Mazure et al. 1988).

In Figures 7 and 8, we compare counts obtained with these two techniques. It can be seen that the agreement is satisfactory, if not perfect. We have used counts from the literature since the presence of structure in the vicinity of Perseus (as is the case for most clusters) may affect determinations of the background level from nearby “blank” fields. Therefore, counts from the literature may better reflect the true level of background and foreground contamination. Note that these counts are not used for LF determination; they are shown here to demonstrate that the color-selected sample does not bias our result against blue cluster members, which are unlikely to exist in the cluster core.

The shape of the LF is not fitted by a single power law, a composite function being necessary (Trentham 1998a). On the other hand, a power law, despite its lack of physical meaning, is still a concise way of summarizing these data, and we choose to adopt it in this paper, even when, as in Figure 10, a power-law fit does not appear to represent the data very well ($\chi^2 / v = 2.9$).

We show these fits in Figures 9 and 10. For Abell
For Abell 539 we obtain \( a = -1.42 \pm 0.14 \) for \(-18.5 < M_I < -14.0\).

4. DISCUSSION

The slopes we derive for A426 and A539 are broadly consistent with those found in Virgo (Sandage et al. 1985; but see Phillipps et al. 1998) and the Fornax cluster (Ferguson & Sandage 1988). Our derived slopes are only marginally different from each other. Although the slope measured for A426 is slightly steeper than for A539, the difference is not statistically significant. Abell 426 is more evolved than A539, on the Jones (1984) scale, as shown by his preponderantly elliptical population (as opposed to the more spiral-rich A539). Therefore, our results are mildly inconsistent with the hypothesis that cluster evolution results in a flatter LF, but the significance of this is low.

On the other hand, dwarfs may be created in clusters. NGC 1275 is believed to lie at the center of a large cooling flow, which usually associated with star formation. Globular clusters are known to have been formed recently in this galaxy (Holtzman et al. 1992). This may have boosted the LF slope in Perseus. On the other hand, such objects would likely be blue; our color-selection criterion would exclude most of these galaxies, and we may therefore underestimate the slope of the LF in Perseus. The good agreement of the color-selected and background-subtracted counts in Figures 5 and 6 suggests that our LF slope is not affected by this problem.

Note of course that there is some evidence for an environmental effect in the Coma cluster. The brighter Lobo et al. (1997) sample shows fewer galaxies in the immediate vicinity of the two giants and an increase at larger clustercentric distances. Fainter galaxies are instead abundant throughout the cluster and may be concentrated toward the cluster core (Trentham 1998b); this is similar to what has been found in A262 (Trentham 1997). We should not be affected by these environmental dependencies in our analysis.

If the above results are correct, there may exist two
Fig. 2.—$I$-band image of the central region of Abell 539

Fig. 3.—Concentration parameter ($r_{-2}$) vs. $I$ magnitude for Abell 426 (Fig. 1). Objects are plotted as open circles. The adopted star-galaxy separation value is shown as a thick dashed line.

Fig. 4.—Concentration parameter ($r_{-2}$) vs. $I$ magnitude for Abell 539 (Fig. 2). Objects are plotted as open circles. The adopted star-galaxy separation value is shown as a thick dashed line.
Fig. 5.—Color-magnitude diagram for galaxies in A426. The ridge line (thick solid line) shown is derived from the colors of spectroscopic members of the cluster (Chincarini & Rood 1971). Objects within ±0.3 mag of this line are assumed to be members.

Fig. 6.—Color-magnitude diagram for galaxies in A539. Spectroscopic information is taken from Ostriker et al. (1988).

Fig. 7.—Comparison between color-selected (filled circles) and background-subtracted (filled squares) galaxy counts in Abell 426.

Fig. 8.—Same as Fig. 7, but for A539.

Fig. 9.—Luminosity function, derived from color-selected counts, for A426.

Fig. 10.—Luminosity function, derived from color-selected counts, for A539.
for fainter objects continues in distant clusters. (Pryor 1992)

- The mass enclosed in dwarf galaxies would be considerable,
- luminosities comparable to those of Carina or Draco, the
- subject of dwarf galaxy LFs is still disputed.

Clearly, the subject of dwarf galaxy LFs is still disputed and has important theoretical consequences. Steep LFs are, as we pointed out, predicted by cold dark matter scenarios for galaxy formation (see, e.g., White & Frenk 1991), but these are believed to exist in the field rather than in clusters (Dekel & Silk 1986). If the steep LF were continued to luminosities comparable to those of Carina or Draco, the mass enclosed in dwarf galaxies would be considerable, especially if the trend for higher mass-to-luminosity ratios for fainter objects (Pryor 1992) continues in distant clusters. This may reduce the need for a large non baryonic "halo" component to accommodate cluster dynamics.

New panoramic detectors and infrared arrays allow accurate LFs and mass functions to be determined over large fields. These new technologies allow a wide optical-infrared survey to be undertaken, to clarify the shape of the mass and luminosity function in clusters.

5. CONCLUSIONS

We derive I-band luminosity functions for galaxies in Abell 426 and Abell 539. For these clusters we find a good fit to a power law with slope $\alpha = -1.56 \pm 0.08$ for Perseus and $-1.42 \pm 0.14$ for A539. Since A426 is the more evolved of the two clusters, our findings run counter to the idea that cluster evolution destroys dwarf galaxies; on the other hand, star formation may be responsible for boosting the LF slope of dwarf galaxies in this system.

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