DO CLUSTERS CONTAIN A LARGE POPULATION OF DWARF GALAXIES?

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ABSTRACT

We analyze systematic effects in the determination of the galaxy luminosity function in clusters using a deep mock catalog constructed from a numerical simulation of a hierarchical universe. The results indicate a strong tendency to derive a rising faint end (α ≲ −1.5) in clusters selected in two dimensions, using a galaxy catalog constructed with a universal flat luminosity function with $\alpha \approx −1.0$. This is a result of the projection effects inherent in catalogs of clusters constructed using two-dimensional data. Many of the clusters found in two dimensions have no significant three-dimensional counterparts, and most suffer from massive background contamination that cannot be corrected for by subtracting random offset fields. The luminosity function of high surface brightness galaxies in the field and within small groups follows a Schechter function with a fairly flat faint-end slope, $n(L) \propto L^{\alpha}$, with $\alpha = −0.9$ to $−1.2$. On the contrary, observational studies of clusters constructed using Abell, EDCC, and APM catalogs are systematically found to have steeper luminosity functions with $\alpha = −1.4$ to $−2.0$. This may be attributed to projection effects rather than a dominant population of high surface brightness dwarf galaxies ($M \gtrsim M^{*} + 2$) in clusters. It should be straightforward to confirm our results by measuring redshifts of these faint cluster galaxies.

Subject headings: galaxies: clusters: general — galaxies: luminosity function, mass function — methods: statistical

1. INTRODUCTION

The galaxy luminosity function is one of the most direct observational probes of galaxy formation theories. Hierarchical clustering models generically predict a steep mass function of galactic halos that is in conflict with the field galaxy luminosity function (e.g., Kauffmann et al. 1993; Cole et al. 1994). The discrepancy is resolved by invoking feedback mechanisms to suppress star formation and darken dwarf galaxies. Clusters of galaxies provide the ideal systems with which to measure the galaxy luminosity function down to very faint magnitudes because of the large numbers of galaxies at the same distance that can be observed within a small area on the sky (Schechter 1976).

Measuring the faint-end luminosity function (LF) of galaxies in clusters has been the subject of many detailed research papers in the past few years (e.g., Sandage, Binggeli, & Tammann 1985; Driver et al. 1994; De Propris et al. 1995; Gaidos 1997; Lobo et al. 1997; Lumsden et al. 1997; Lopez-Cruz et al. 1997; Valotto et al. 1997; Wilson et al. 1997; Smith et al. 1997; Trentham 1997, 1998; Driver et al. 1998; Garilli et al. 1999). In most of these studies, these and other authors have demonstrated using background subtraction procedures that galaxy clusters are dominated in number by a large population of faint galaxies. In terms of the faint-end slope of the luminosity function, $\alpha$ lies in the range $−1.4$ to $−2.0$. The nature of these galaxies, their origin, and evolution have important consequences for our current understanding of galaxy formation and the importance of environment in driving morphological evolution.

These results are at odds with observations of the field galaxy luminosity function (e.g., Loveday et al. 1992; Lin et al. 1997; Marzke et al. 1997; Bromley et al. 1998; Muriel et al. 1998) which ubiquitously give a flat faint-end slope with $\alpha \approx −1.0 \pm 0.1$. In other recent works, steeper LF are found ($\alpha \approx −1.2$) (Zuca et al. 1997; Folkes et al. 1999), although significantly flatter than the determinations in clusters. Moreover, galaxies within the Local Group can be observed to more than 10 mag below $L_\ast$, the characteristic break in the Schechter luminosity function (Schechter 1976). Surveys of Local Group galaxies are essentially complete (Mateo 1998), and there is no evidence for a large population of faint dwarfs—the luminosity function is flat to $\approx L_\ast/10000$ (van den Bergh 1992; Pritchet & van den Bergh 1999). The probability that the faint-end slope in the Local Group is as steep as 1.3 is less than 1%. Similarly, redshift surveys of nearby loose groups (Ferguson & Sandage 1990), compact groups (Hunsberger et al. 1998), and isolated ellipticals (Mulchaey & Zabludoff 1999) also show evidence for flat faint-end slopes (but see also Morgan et al. 1998).

The paradox is clear. In the hierarchical universe, clusters form relatively recently from the accretion of systems similar to the Local Group. Dynamical processes that operate in clusters are destructive. Ram pressure stripping (Gunn & Gott 1972; Abadi, Moore, & Bower 1999) and gravitational tides/galaxy harassment (e.g., Moore et al. 1996) both conspire to fade galaxies by removing gas or stripping stars. These processes are most effective for smaller, less bound galaxies, which should manifest itself as a flattening of the faint-end slope rather than the observed steepening.

Surface brightness selection effects complicate these issues. Apart from the Local Group, all of the above surveys are sensitive only to high surface brightness galaxies. Decreasing the limiting isophote for galaxy detection to $\mu_B \approx 27$ mag arcsec$^{-2}$ uncovers a host of previously undetected galaxies (Impey & Bothun 1997). Within nearby clusters, such as Virgo and Fornax, a divergent exponential tail to the galaxy luminosity function cannot be ruled out (Impye et al. 1988; Bothun et al. 1991). A similar situation arises in the field surveys where we know comparatively little about the abundance of low surface brightness objects.

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The observational motivation for this paper are the observations of high surface brightness galaxies, but our results will be applicable to any survey where the clusters are selected from two-dimensional data.

Unlike clusters which provide a large sample of galaxies at the same distance, the field galaxy luminosity function must be determined using redshift information. Even with the advent of large multifiber instruments, the luminosity function of cluster galaxies has not been measured out to the virial radius, nor has it been measured to faint enough magnitudes to constrain the faint-end slope—both vital for comparison with cosmological models. The lack of large compilations of redshifts of faint galaxies imply that most estimates of galaxy luminosity functions in clusters rely critically on background subtraction. The accuracy of this procedure depends on the statistical assumption that galaxy clusters correspond to density enhancements unbiased with respect to the distribution of foreground or background galaxies.

In spite of the lack of deep redshift surveys free from incompleteness and selection effects, several groups have attempted to determine the shape of the galaxy luminosity function from spectroscopic data in cluster fields. By inspection of these papers, it is apparent that flatter faint-end slopes are found over the range of magnitudes where the redshift samples are complete. For instance, spectroscopic analysis of the central region of the Coma cluster shows a flat faint-end galaxy LF ($\alpha \approx -1.1$) for a single Schechter function fit, with the additional claim of a failure of a single Schechter fit at brighter magnitudes $M \approx -18$ to $-17.3$ (Biviano et al. 1995). Similarly, Koranyi et al. (1998) have analyzed a redshift survey in the field of the poor cluster AWM 7. In this case, the galaxy LF shows a steeper faint end ($\alpha = -1.37 \pm 0.16$), although this value is based on a correction to the redshift data that entirely dominates the results at faint magnitudes.

A similar analysis of A2626 and A2440 by Mohr, Geller, & Wegner (1996) gives faint-end slopes $\alpha = -1.16^{+0.18}_{-0.16}$ and $\alpha = -1.30^{+0.26}_{-0.20}$ (90% confidence limits), respectively. The study of A576 by Mohr et al. (1996) also gives a flat galaxy LF in the range of magnitudes where the redshift survey is complete; however, it steepens significantly at fainter magnitudes where a background correction is applied. The most complete published redshift survey of a cluster has been published by Durret et al. (2000) for A496. These authors show that the LF flattens at $M_R \approx -20.5$, where the sample is complete, and at fainter magnitudes ($-20.5 < M_R < -18$), a Schechter function with $\alpha \approx -1.2$, provides a suitable fit to the LF with 79% redshift completeness. In a study of the galaxy LF from the Norris survey of the Corona Borealis and A2069 supercluster regions with spectroscopic information, Small et al. (1997) derive a flat faint-end LF ($\alpha \approx -1.1$) consistent with the field determination. Finally, Adami et al. (1999) analysis of spectroscopic data in the core of Coma cluster imply that the number of low-luminosity galaxies is smaller than expected from previous estimates (Biviano et al. 1995), suggesting a flat faint-end galaxy LF.

To summarize, galaxy LF determinations using spectroscopic data suggest that the steep faint-end slope derived from background subtraction procedures should be taken with caution. However, the spectroscopic surveys are only complete to approximately 2 mag fainter than $M^*$, whereas the photometric surveys can probe 7 mag fainter than $M^*$.

Significant projection effects are found in Abell clusters (e.g., Lucey 1983; Sutherland 1988; Frenk et al. 1990) that can systematically bias the observed correlation function and the mass function of these systems. In fact, van Haarlem et al. (1998) find that a third of Abell clusters are not real physically bound systems but simply projections of galaxies and groups along the line of sight. In this paper we use three-dimensional mock galaxy catalogs to construct samples of rich clusters using just two-dimensional information. Observing these clusters in the same way as published works allows us to quantify how well we can recover the true luminosity function. We will explore the biases due to foreground and background contamination, the dependence of the results on cluster richness, and the effects of the extended halos of clusters.

2. RESULTS

2.1. The Mock Catalog

Mock galaxy catalogs constructed from large $N$-body simulations provide ideal data sets with which to examine selection biases since the full three-dimensional positional and velocity information is available. We have used a deep galaxy catalog kindly constructed by S. Cole that is a mock realization of the APM catalog. The $N$-body simulation and techniques used to construct the catalogs are discussed in detail in Cole et al. (1998); here we just review some of the most relevant details. The $N$-body simulation follows a universe dominated with a closure density of cold dark matter within a periodic box of $345.6 \, h^{-1} \, Mpc$ per side (where $H_0 = 100 \, h \, km \, s^{-1} \, Mpc^{-1}$ throughout). The simulation is normalized to match the observed number density of rich galaxy clusters such that $c_{\sigma} = 0.55$. “Galaxies” are drawn from the mass distribution according to a two-parameter biasing model normalized to fit the observed rms fluctuations in the APM catalog in cubes of side 5 and 20 Mpc $h^{-1}$.

Thus, even though the initial $N$-body simulation is not the currently favored cosmological model, both the amplitude and slope of the “galaxy” correlation function provide a close match to that obtained from the APM survey. Therefore, we do not expect our results to change if the cosmological model included a lambda term, as currently favored. This is, of course, an important point since projection effects may depend on the degree of galaxy clustering present in the mock catalog. Moreover, since the correlations between cluster and galaxy positions are crucial in the present discussion, we have computed the cross-correlation function for clusters and “galaxies” in the mock catalogs as well as the cluster autocorrelation function. The results show reasonable agreement with the observations (Lilje & Efstathiou 1988; Croft et al. 1999; Abadi, Lambas, & Muriel 1998):

\[ [\xi_c g] \approx (r/9.4)^{-1.86}, \quad [\xi_c c] \approx (r/14.5)^{-1.96}, \]

indicating that the statistical properties of the galaxy distribution around the clusters in the mock catalog are in good agreement with the observations. Thus, for the purpose of our analysis the mock catalog used provides a suitable representation of the real universe so that the results derived in this section are robust and not expected to change with other cosmological models that match the observations.

The luminosities of the galaxies are drawn at random according to a Schechter function (Schechter 1976),
unbiased with respect to environment:

\[
\phi(M) = (0.4 \ln 10) \phi^* \left[ 10^{0.4(M^* - M)} \right]^{1+z} \exp \left[ -10^{0.4(M^* - M)} \right].
\]

We adopt the values \( \phi^* = 0.014 h^{-3} \text{Mpc}^{-3} \), \( M^* = -19.5 \), and \( z = -0.97 \), corresponding to the luminosity function of high surface brightness field galaxies (Loveday et al. 1992). The limiting apparent magnitude for the mock catalog (which subtends \( \approx 1300 \) square degrees) is \( B_J = 21.5 \), and the final catalogs contain \( 1.7 \times 10^6 \) comparable to those in the APM Galaxy Survey (Maddox et al. 1990a, 1990b) and Edinburgh/Durham Southern Galaxy Catalog (Heydon-Dumbleton, Collins, & MacGillivray 1989).

2.2. Cluster Selection

We have selected the clusters from the mock catalog, applying a similar procedure as Lumsden et al. (1992) in the construction of the Edinburgh-Durham cluster catalog (EDCC). This corresponds closely to Abell's original criteria (Abell 1958).

First, we project the galaxy catalog on the sky and find cluster centers by searching for galaxy overdensities. The redshift distance of the cluster candidate is measured using the real velocities of the brightest galaxies in the apparent cluster. We then adopt a \( 1.5 h^{-1} \text{Mpc} \) search radius around these centers and we consider galaxies within this radius in the range of magnitudes \( m_3 - m_3 + 2 \) to define cluster richness in a similar way to Abell and EDCC cluster identification procedures. (Note that using this method to determine cluster richness and distances reflects current techniques, rather than Abell's original method that assumed the apparent magnitude of the 10th brightest cluster galaxy was a standard candle.) The final sample of clusters for our analysis comprises 140 objects with redshifts \( z < 0.15 \).

We find that the typical redshift distributions in the field of the identified clusters in the simulations are visually comparable to the observed distribution of radial velocities.

![Fig. 1.—Redshift distribution in the fields of clusters in the simulations: (a) and (c) correspond to a typical cluster selected in projection using the deep mock catalog. For comparison, (b) and (d) show the observed distribution of galaxy redshifts in the field of a cluster selected in three dimensions with no two-dimensional counterparts in the same catalog (see § 2.5).](image-url)
measured for clusters. An example is shown in Figure 1 where we compare the redshift distribution of a typical cluster selected in two dimensions (Figs. 1a and 1c) with the redshift distribution of galaxies in the field of a cluster selected in three dimensions with no two-dimensional counterpart (see § 2.5). Both contain a significant peak of galaxies at one distance that corresponds to a real cluster, but in the two-dimensional case smaller peaks are found at disparate redshifts that are simply groups of galaxies that lie in projection along the line of sight to the cluster. In the absence of redshifts for all the galaxies in the field, these groups provide a significant source of contamination for the cluster membership.

2.3. Luminosity Function Determination

We estimate the mean galaxy luminosity function for the total sample of clusters using only the apparent magnitudes of galaxies and mean cluster redshifts—the same as published observational studies. For a galaxy of apparent magnitude \( m \) associated with a cluster at redshift \( z \), we neglect curvature and assign an absolute magnitude \( M = m - 25 - 5 \log D \), where \( D = zc/H_0 \). The algorithm to determine the composite luminosity function (Valotto et al. 1997; Lumsden et al. 1997; Muriel et al. 1998) in the absence of galaxy radial velocities is based on a background subtraction procedure:

\[
\bar{N}(M) = \frac{1}{n_{\text{clus}}} \sum_{i=1}^{n_{\text{clus}}} N_i(M),
\]

where \( \bar{N}(M) \) is the composite luminosity function in the magnitude bin centered in \( M \) and \( N_i(M) \) is the background-corrected number of galaxies with magnitude \( M \) of the \( i \)th cluster; \( R_i \) is the richness count of the \( i \)th cluster in the range of magnitudes \( -21 < M < -19 \) within the projected radius \( r = 1.5 \ h^{-1} \) Mpc, and \( n_{\text{clus}} \) is the number of clusters contributing to the composite luminosity function.

In order to explore the galaxy LF at faint absolute magnitudes we compute the composite LF for the nearest 22 clusters with redshift \( z_{\text{clus}} < 0.07 \), using galaxies brighter than \( M_{\text{lim}} = -15 \). The background decontamination is performed by considering a mean local background around each cluster defined as the number of galaxies in a ring at projected radius \( r_1 < r_p < r_2 \). The results shown in Figure 2 correspond to \( r_1 = 4 \) Mpc and \( r_2 = 6 \) Mpc.

Figure 2 shows the resulting galaxy luminosity function in the simulated clusters, the solid lines correspond to a best fitting Schechter function estimated using a minimum \( \chi^2 \) method. The dotted lines correspond to the imposed Schechter function (eq. [1]). The error bars are calculated according to Poisson statistics. The estimated galaxy LF is significantly steeper, \( \alpha = -1.41 \pm 0.11 \) and \( M = -20.0 \pm 0.1 \), than the actual LF \( \alpha = -0.97 \) and \( M = -19.5 \). When we take a deeper sample of clusters surveyed to fainter magnitudes \( (M_{\text{lim}} = 16) \), we find an even steeper faint-end slope \( \alpha = -1.52 \pm 0.07 \) and \( M = -20.0 \pm 0.2 \).

2.4. Radial and Richness Dependence

Can we detect any trends in how the recovered luminosity function depends on the limiting radius used to identify clusters or the cluster richness? Smaller radii would probe higher overdensities and would reduce the chance of background contamination. In Figure 3 we show the results

![Figure 2](image_url)  
**Fig. 2**—Composite cluster luminosity function derived from the mock catalog. (See § 2.3 for details on the normalization of the cluster galaxy luminosity function.) The best fitting Schechter function is shown as a solid line (\( \alpha = -1.52 \) and \( M_\alpha = -20.5 \)). The dashed line shows the original input luminosity function used to construct the mock catalog (\( \alpha = -0.97 \) and \( M_\alpha = -19.5 \)).

![Figure 3](image_url)  
**Fig. 3**—Composite cluster luminosity function for different cluster radii: (a) \( r = 1.0 \) Mpc \( h^{-1} \), (b) \( r = 0.75 \) Mpc \( h^{-1} \), (c) \( r = 0.5 \) Mpc \( h^{-1} \), (d) \( r = 0.25 \) Mpc \( h^{-1} \). Solid lines correspond to the fit to the projected data shown in Fig. 2.
corresponding to model 1 for \( r = 0.5 \, h^{-1} \) Mpc, \( r = 0.75 \, h^{-1} \) Mpc, and \( r = 1.0 \, h^{-1} \) Mpc. This figure shows a similar behavior, with steeper faint-end slopes than expected, although fits to a Schechter function show a tendency for lower values of \( \alpha \) with decreasing cluster radius (see Table 1).

In order to examine any possible dependence of the results with cluster richness we have divided the cluster samples according to their richness counts, \( R \), defined in equation (2). In Figure 4 we show the results for the samples of different \( R \), and we detect a trend of increasing negative slope as poorer clusters are included.

### 2.5. Analysis of Projection Effects

For each cluster we have considered galaxies within 1000 km s\(^{-1}\) of the cluster mean radial velocity from the mock

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**TABLE 1**

| Number of Clusters | \( M_{\text{lim}} \) | \( z_{\text{clus}} \) | Cluster Radius (Mpc \( h^{-1} \)) | \( \alpha \) | \( M^* \) | Comments |
|--------------------|----------------|----------------|----------------------------------|-------|--------|-----------|
| 22 .................. | -15            | 0.07            | 1.50                             | -1.41 ± 0.11 | -20.0 ± 0.1 | Total sample |
| 32 .................. | -16            | 0.08            | 1.50                             | -1.52 ± 0.07 | -20.5 ± 0.2 | Total sample |
| 22 .................. | -15            | 0.07            | 1.00                             | -1.44 ± 0.12 | -20.1 ± 0.1 | ... |
| 22 .................. | -15            | 0.07            | 0.75                             | -1.31 ± 0.23 | -19.8 ± 0.2 | ... |
| 10 .................. | -15            | 0.07            | 1.50                             | -1.42 ± 0.23 | -20.1 ± 0.1 | \( R \geq 40 \) |
| 15 .................. | -15            | 0.07            | 1.50                             | -1.29 ± 0.16 | -19.8 ± 0.1 | \( R \geq 30 \) |
| 19 .................. | -15            | 0.07            | 1.50                             | -1.27 ± 0.12 | -19.8 ± 0.2 | \( R \geq 10 \) |
| 22 .................. | -15            | 0.07            | 1.50                             | -1.10 ± 0.06 | -20.5 ± 0.1 | \( V_{\text{gal}} < V_{\text{clus}} + 1000 \, \text{km} \, \text{s}^{-1} \) |
| 22 .................. | -15            | 0.07            | 1.50                             | -1.61 ± 0.10 | -20.5 ± 0.1 | \( V_{\text{clus}} - 1000 \, \text{km} \, \text{s}^{-1} < V_{\text{gal}} \) |
| 22 .................. | -15            | 0.07            | 1.50                             | -1.07 ± 0.10 | -19.1 ± 0.1 | \(| V_{\text{clus}} - V_{\text{gal}} | < 1000 \, \text{km} \, \text{s}^{-1} \) |
| 13 .................. | -14            | 0.06            | 1.50                             | -0.96 ± 0.05 | -19.7 ± 0.1 | Fake clusters |
| 21 .................. | -15            | 0.07            | 1.50                             | -1.08 ± 0.09 | -19.3 ± 0.2 | Three-dimensional clusters |

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**Fig. 5.**—Composite luminosity function for three different cuts in the redshift distribution. (a) \( V_{\text{gal}} < V_{\text{clus}} + 1000 \, \text{km} \, \text{s}^{-1} \), (b) \( V_{\text{clus}} - 1000 \, \text{km} \, \text{s}^{-1} < V_{\text{gal}} \leq V_{\text{clus}} + 1000 \, \text{km} \, \text{s}^{-1} \), (c) \( V_{\text{clus}} - 1000 \, \text{km} \, \text{s}^{-1} < V_{\text{gal}} < V_{\text{clus}} + 1000 \, \text{km} \, \text{s}^{-1} \). The solid curves correspond to the fit shown in Fig. 2, and the dashed curve shows the input galaxy luminosity function.
We can easily examine if the systematic rise in the derived galaxy LF shown in Figure 2 is mainly due to foreground or to background contamination. We split the sample of cluster galaxies (identified in projection from model 1) into two: (1) for each cluster we consider only galaxies with radial velocities $V_{\text{gal}} < V_{\text{clus}} + 1000$ km s$^{-1}$ (thus considering only foreground contamination) and (2) $V_{\text{gal}} < V_{\text{clus}} - 1000$ km s$^{-1}$ (thus considering only background contamination). When we repeat the procedure to recover the LF, i.e., applying the same decontamination procedures described to the foreground case $V_{\text{gal}} < V_{\text{clus}} + 1000$ km s$^{-1}$, we find a flat galaxy LF, entirely consistent with that originally imposed to create the galaxy catalog. On the other hand, a significantly steeper LF is derived by considering galaxies with $V_{\text{gal}} < V_{\text{clus}} - 1000$ km s$^{-1}$ ($\alpha = -1.5$) consistent with that obtained from the total mock catalog (see Fig. 2 and Table 1). The results of these tests are shown in Figure 5, which demonstrate that the artificial steep faint-end slopes arise entirely because of projection of background galaxies into the field of view of the cluster.

The observed distribution of galaxies closely matches the clustering pattern of galaxies in our mock catalogs. We can therefore test the role of large-scale correlations and the filamentary structure of the galaxy distribution in creating projection effects. We construct a spherically symmetric model cluster that resembles real bound objects in the mock catalog. Thirteen clusters are added to the galaxy catalog, we use a friends-of-friends algorithm with linking length $l = 1.7d_{\text{c}} = 0.5 h^{-1}$ Mpc. We select the most massive systems corresponding to a mean number density of $2.2 \times 10^{-5} h^3$ Mpc$^{-3}$, roughly the abundance of $R > 1$ Abell clusters. We compute the galaxy LF in these samples of clusters using the same background subtraction procedures as in § 2.3. The results are shown in Figure 7 demonstrating that the clusters selected in three dimensions can be used to recover the input luminosity function. The Schechter fit of the galaxy LF of the three-dimensional cluster sample has parameters $\alpha = -1.08 \pm 0.09$ and $M^* = -19.3 \pm 0.2$ (Table 1).

When we compare the richness of the two-dimensional selected clusters with the largest physically selected three-dimensional cluster along the same line of sight, we find a large scatter, with the richness count typically in error by a factor of 2.

2.6. Quantifying the Effects of Extended Halos

In the previous sections we have demonstrated the importance of the correlation between cluster and galaxy positions in the determination of the galaxy LF parameters in these systems. Taking into account these results we now consider the effects of the extended halos of clusters on the background subtraction procedure. The virialized halos of clusters extend to several Mpc and the turnaround region is much larger than this. This produces an excess of galaxies
near to the cluster that appear in projection, on the cluster core. A “Malmquist”-like bias will cause foreground galaxies to be preferentially “observed in the cluster.”

The estimated luminosity function $\psi(M)$ satisfies

$$\psi(M) \propto \int_0^\infty \phi(M) \xi_{cg}(r) R^2 dR, \quad (3)$$

where $M'$ is the absolute magnitude of each galaxy assumed to be at the mean cluster redshift. The distances in the calculation satisfy

$$r^2 = R^2 + R_0^2 - \frac{R}{R_0} \left( \frac{Rr^2}{R_0^2} \right),$$

where $r$ is the distance between the galaxy to the cluster center, $R$ is the distance of the galaxy to the observer, $R_0$ is the distance of the cluster to the observer, $r_p$ is the projected distance galaxy-cluster center, $\phi(M)$ is the true galaxy luminosity function for which we adopt a Schechter function with the same parameters as for our mock catalog, and $\xi_{cg}(r)$ is the cluster-galaxy cross-correlation function.

We adopt a power-law model for the cluster-galaxy cross-correlation function with parameters $r_0 = 10 \, h^{-1}$ Mpc, $\gamma = -2.0$, and an effective cutoff at $r_{max} = 40 \, h^{-1}$ Mpc which provides a reasonable fit to the observations (Lilje & Efstathiou 1988; Merchau et al. 1998).

The results for a typical cluster at $R_0 = 100 \, h^{-1}$ Mpc and $m_{lim} = 21.5$ are $\alpha = -1.0$ and $M^* = -21.8$, indicating that the extended cluster halos of clusters do not bias the resulting LF at the faint end. This calculation shows that the effect of extended halos is mainly to increase the estimated value of $M^*$ by the inclusion of foreground galaxies.

3. CONCLUSIONS

We have analyzed several sources of systematic effects present in observational determinations of the galaxy luminosity function in clusters. We use a deep mock catalog derived from a numerical simulation of a hierarchical universe models dominated by cold dark matter to identify clusters of galaxies in two dimensions. Galaxies and clusters in the mock catalog have autocorrelations and cross-correlation functions, in agreement with the observations so that the distribution of galaxies and clusters relative to the position of clusters resemble those actually observed. This fact provides confidence that our analyses on the mock catalog gives reliable results that apply to the real universe. The clusters are identified in projection from the galaxy distribution in a similar way as performed to create the EDDC and Abell catalogs. The galaxy LF in the clusters is obtained by performing a background subtraction procedure identical to that applied to observational data. Our results are summarized here:

1. Clusters identified in projection suffer from projection effects that conspire to produce artificially steep faint-end slopes, mimicking the presence of a large population of dwarf galaxies. With an input Schechter function with a slope $\alpha = -0.97$ we recover $\alpha \approx -1.5$.

2. We show that the projection effects result almost entirely from background galaxies—many of the clusters selected in two dimensions have no significant counterpart in three dimensions and most suffer from massive amounts of projection that is responsible for the steep faint-end slopes.

3. Unbiased estimates of mean galaxy luminosity function in clusters may be obtained with background subtraction methods only for samples of clusters selected in three dimensions, such as may be obtained from an X-ray- or lensing-selected sample.

4. We examined the effects of the extended halos and infall regions surrounding clusters on the background subtraction procedure. Neglecting these effects leads to a bias in the determination of $M^*$ to brighter magnitudes, but does not affect the estimation of the faint-end slope $\alpha$.

These results indicate that caution should be taken when interpreting the observed steep faint end of the LF with a large population of faint galaxies associated with cluster environments—radial velocity data for cluster galaxies are crucial for analyzing their faint galaxy populations, and typically half of the apparent cluster galaxies will be background objects.

We note that Abell, EDDC, and APM clusters exhibit on average a steep galaxy LF with $\alpha \approx -1.4$ to $-1.8$ (Valotto et al. 1997; Lumsden et al. 1997), showing that the particular choice of cluster-finding algorithms in two-dimensional catalogs is not biasing the resulting LF. On the other hand, the observed mean galaxy LF of groups that avoid cluster neighborhoods is found to be quite flat (Muriel, Valotto, & Lambas 1998) which suggest that either clusters have a contaminated galaxy LF or that the relative excess of faint galaxies arises at very high densities. We also note here that the galaxy LF is steep in irregular systems (Lopez-Cruz et al. 1997) and flat in dense relaxed clusters, a result supported by recent spectroscopic observations in the Coma cluster core (Adami et al. 1997). The mounting evidence of flat galaxy LF results from spectroscopic surveys with reasonable completeness adds to the above considerations, and we suggest that irregular clusters may owe their irregularity to projection effects which bias the LF to steeper slopes. Our results support the idea of a similar galaxy luminosity function in clusters and the field.

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