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The Faint End of the Galaxy Luminosity Function in Rich Clusters

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Abstract. Recent results on the determination of the shape of the faint end of the galaxy luminosity function in rich clusters are discussed. There is increasing evidence that in many cases the faint end of the function is steep, indicating a large population of dwarf, possibly low surface-brightness, galaxies. In addition, the magnitude at which the turn-up appears is approximately constant with richness and distance. However, it is clear that not all clusters show such a feature.

1. Introduction

It is now almost 25 years since Schechter (1976) empirically fitted an analytic function of the form $\phi_L = \phi^*(L/L^*)^\alpha exp-(L/L^*)$ to the galaxy luminosity function (LF). In this equation, ϕ^* is a normalisation factor related to the number density of galaxies, L^* is the characteristic luminosity and α is the slope of the power-law faint end of the LF. Observations since then have mostly agreed with this general form, with a sharp drop-off at brighter magnitudes leading to very few bright ($M_B < -21$) galaxies whilst the faint end is a power-law of slope α. There is a limitation on the value of α in that if the faint end of the LF is steep then this conflicts with measurements of the intracluster light. In addition, if $\alpha \leq -2$ the Schechter LF diverges and the luminosity density of the Universe becomes infinite. It is expected, however, that the LF must turn-over at very faint magnitudes due to the difficulty of star-formation in very low mass systems, possibly due to photoionization by the ultraviolet background (e.g. Thoul & Weinberg 1996).

The LF is an observable property of the inherent galaxy distribution that can be directly compared to theoretical predictions. Hierarchical clustering mod-

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els (e.g. White & Frenk 1991, Frenk et al. 1996), for example, appear to naturally produce a steep faint end slope of the LF whereas dynamical effects in dense regions may flatten it (e.g. Moore et al. 1996). Due to this close interface between observation and theory, much work has gone into the measurement of the LF, both in the field and in clusters. Original estimates, using magnitude-limited redshift surveys, of α both in the field and clusters were typically around -1.1 (e.g. Efstathiou 1988, Loveday 1992), in direct conflict with the theoretical models proposed at the time (e.g. White and Frenk 1991). However, it is very difficult observationally to measure the dwarf population and hence determine the shape of the faint end of the LF. Selection effects and the form of the LF lead to a strong bias in magnitude-limited samples towards the predominance of galaxies with luminosities close to L^*. Hence to obtain a significant result at magnitudes well away from L^* requires the observation of a very large sample of galaxies. Redshift surveys also have their own inherent problems. Technically it is very difficult to measure the redshift of a faint or low surface-brightness galaxy, especially if its spectrum does not contain emission lines. This will lead to an incompleteness particularly at the faint end of the LF. Due to such difficulties, redshift studies have, until recently, not reached far in to the dwarf regime ($M_B > -17$). Yet it is precisely here that the theoretical models make definite and varying predictions.

2. Photometric studies

The inherent problems with redshift surveys led several groups to search for other techniques to determine the shape of the LF without resort to spectroscopic observations. One possibility is by observing galaxies in clusters. There are several techniques by which cluster membership can be derived, even for the fainter galaxies, without the need for spectroscopy. As the redshift of the cluster can be measured from the brighter galaxies, the faint end of the LF can then be determined.

It must be remembered in the interpretation of results on the LF of clusters that they are dense environments, where the crossing time is less than, or of the order of, the Hubble time. It is well known that environmental effects play a crucial role in the evolution of giant galaxies. At bright magnitudes the dominant population in clusters consists of giant ellipticals whereas in the field late-type galaxies predominate. It is therefore very likely that dynamical effects also have a pronounced effect on the evolution of dwarf galaxies in dense regions, such as through the proposed process galaxy 'harassment' (Moore et al. 1996, these proceedings),. Hence measurement of the LF in clusters might therefore tell us more about cluster-related processes than galaxy formation and evolution in general. This is especially true in the richest clusters, where such effects are expected to be most dominant. Yet it is in the richest clusters where the excess over the background is greatest and therefore the greatest hope of deriving a reliable LF.

The earliest studies of the galaxy population within clusters were necessarily photographic and of nearby clusters - notably Virgo, Fornax and Coma. Photographic plates covered a large enough area of these clusters to obtain a sufficiently large sample of galaxies and also deep enough to reach the dwarf pop-

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ulation. Also, by observing nearby clusters the larger angular size of the dwarfs compared to the background population enabled cluster membership to be determined visually, without the need for any subtraction of the contaminating populations. The initial studies of the three clusters detected large numbers of dwarfs, outnumbering the giants within the clusters (e.g. Binggeli et al. 1985, Ferguson 1989 and Godwin et al. 1983). This implied a steeper faint end of the LF than originally estimated. For example, Sandage et al. (1985) found a value of α of -1.4 for the Virgo cluster. As surveys went deeper and to lower surface brightnesses the number of faint galaxies detected in these clusters increased. Typical values found for the Virgo cluster, for example, increased to $\alpha \sim -1.7$ (Impey et al. 1988). With the advent of more sensitive emulsions and the development of digital stacking techniques it is now possible to push photographic investigations of the dwarf population of nearby clusters down to very faint absolute magnitudes. An example of this technique is presented by Jones et al. in these proceedings. They probe the dwarf population of the Virgo cluster down to a limiting magnitude of $M_R \sim -11$. Unfortunately, it is only in the nearest clusters where the attainable resolution is sufficient to distinguish between cluster and background galaxies using their morphology. To investigate more distant clusters requires a different, statistical, approach.

Using the knowledge that the excess of galaxies seen in the direction of a cluster over that of neighbouring fields is due to cluster members it is possible to derive the LF statistically. Although losing the information as to which galaxies are members such a technqiue allows the LF to be measured for more distant clusters than previous methods. Coupled with the advent of large-format and sensitive, CCD, detectors it is now possible to observe the dwarf population down to faint, $M_R \sim -13$, moderately distant $z \sim 0.2$ clusters. It is then possible to investigate whether the faint end of the LF is generally steep in all clusters and derive any correlation with cluster properties and/or distance. Such studies, however, have their own problems. Even with photographic studies of nearby clusters the removal of the background galaxy population is crucial and this becomes more difficult when there is no morphological information. With $N(M) \propto 10^{-0.4(\alpha+1)}$ from the Schechter LF and, for the number counts, $N(m) \propto 10^{0.4m}$ it is easily possible to get a slope of $\alpha \sim -2$ if the background is not subtracted correctly. There are generally two different techniques for background subtraction - either by observing, with the same instrumental set-up, a background field close to the cluster or using published number counts (e.g. Metcalfe et al. 1995). Each of these have their problems. With the number counts a strongly-varying function of magnitude, an error in the zero-point of the magnitude scale can lead to a significant error. In addition, seeing variations, variable galactic extinction, image-detection algorithm errors can all lead to errors in the background subtraction. Driver et al. (1998a) have used extensive simulations in an effort to quantify the observational limitations to deriving a reliable LF. They find that the reliability is a strong function of cluster richness, seeing and redshift but is relatively independent of the shape of the LF. Driver et al. (1998b) have also shown that both methods of background subtraction (mean number counts or nearby field subtraction) lead to similar shapes of the LF.

3. Recent Results

In the past couple of years there has been an explosion in the number of LFs measured down to faint magnitudes (e.g Driver et al. 1994, Smith et al. 1997, Wilson et al. 1997, Trentham 1997a, 1997b,1998, Driver et al. 1998b). As an example, the cluster Abell 2554 was observed by Smith et al. (1997) using the Thomson CCD on the AAT. This cluster, at a redshift of 0.106, is of Abell richness class 3 and Bautz-Morgan type II. The LF was derived by both methods of background removal - subtraction using the mean number counts of Metcalfe et al. (1995) and also using a nearby offset field observed with the same instrumental set-up. Both techniques produce a LF of similar shape, which is shown in Figure 1. The LF of Abell 2554 is best fit by 2 functions, firstly the giants by a Schechter LF with parameters $M^*_R = -22.5$ and $\alpha = -1.0$ whilst the dwarfs have $\phi(dwarfs) = 2x\phi(giants)$, $M^*_R = -19.5$ and $\alpha = -1.8$.

Comparison with other published results is difficult. Different passbands, different telescopes and instruments, different parameters used in different object detection algorithms, and many other variations in the observational and analysis techniques all lead to uncertainties in any comparison. However, also plotted in Figure 1 are the LFs of two other clusters - Coma and Abell 963. The data for Abell 963 comes from the observations of Driver et al. (1994) using the HitchHiker camera on the WHT whilst that for Coma is from Thompson and Gregory (1993) and Godwin and Peach (1977).

It is interesting to note that the LFs of the three clusters presented here are remarkably similar. The magnitude at which the LF steepens is approximately constant, even though the redshifts of the clusters covers a range of 0.2. Comparison with several other published R-band cluster LFs (e.g. Trentham 1997a,1997b,1998) supports this result. Thus there is tentative evidence that there is little evolution in the dwarf population since z=0.2. How much evolution would be measurable? If the dwarfs in Abell 2554 were all fainter by 0.4 magnitudes then the difference between the measured LFs would be detectable. Is such a variation expected from the various evolutionary scenarios? Two models can be considered. Firstly, if the dwarfs are predominantly dwarf ellipticals, with an old stellar population, then the models for elliptical galaxy evolution (e.g. Gunn & Tinsley 1972, Bruzual & Charlot 1993) can be applied. In elliptical galaxies most of the light originates from red giants and thus their luminosity depends on how many stars have turned off the main sequence on the giant branch. Assuming a Salpeter initial mass function, the luminosity as a function of time is given by $L \propto (t - t_{form})^{2/3}$ or, assuming an early epoch of formation, $\Delta M \simeq -2.5log(1+z)$. Thus by a redhift of 0.2 a brightening of 0.2 magnitudes would be expected. Such a shift would be undetectable in the present data. However, if the dwarf galaxy population is dominated by dwarf irregulars more evolution would be expected. If the last burst of star formation occurred at $z \simeq 0.5$ then $\simeq 0.6$mag of evolution would be expected. The effect would be more noticeable in the blue but the benefit of more sensitive detectors and a small and better known k-correction in the red would be lost. Although this suggests that the dwarfs within rich clusters are primarily ellipticals it is possible that the form of the LF is conspiring to hide any evolution of the dwarfs. For example, if the dwarf component was brighter but less numerous in the past then the two effects would cancel each other out in the observed LF.

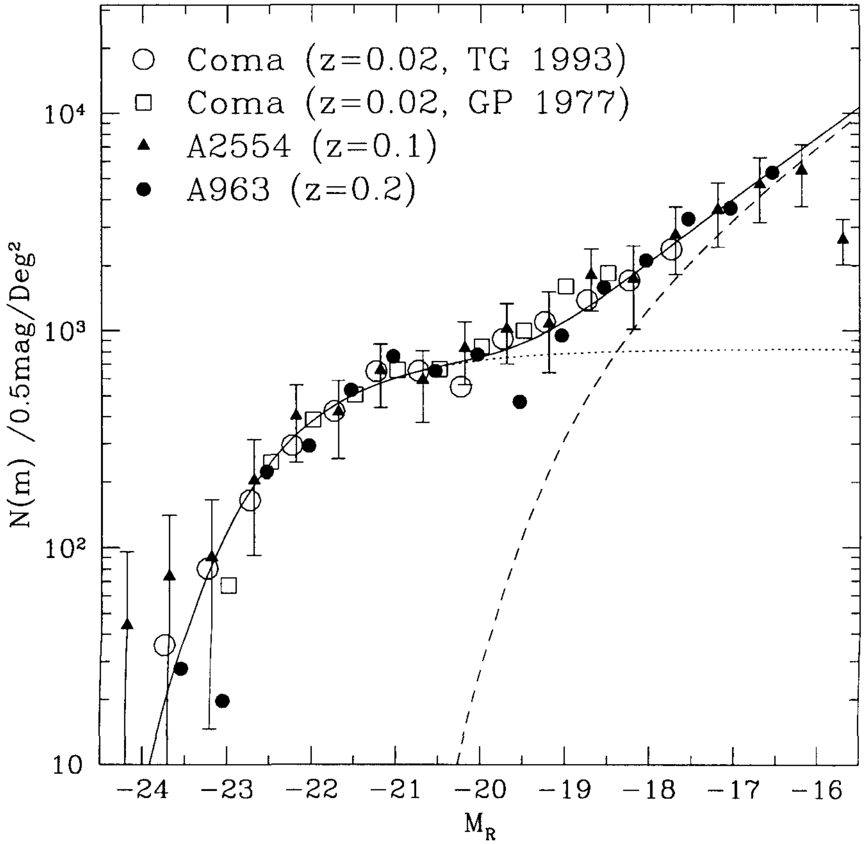

Figure 1. The LF of Abell 2554 compared to that of Coma (Abell 1654) and Abell 963. The dotted line shows a Schechter LF with parameters $M^* = -22.5$ and $\alpha = -1.0$, whilst the dashed line is a Schechter LF with $M^* = -19.5$ and $\alpha = -1.8$. The solid line is the combination of the two LFs.

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The fading irregular model has been successfully applied to explain the faint blue galaxy problem (e.g Phillipps & Driver 1995) and also evolution of the field galaxy LF has been observed in deep redshift surveys (e.g Lilly et al. 1995, Ellis et al. 1996). The similarity between the shape of the cluster LF at varying redshifts hence suggests that there may be a different evolution path for dwarf galaxies in clusters and the field. This has been proposed by Moore et al. (1996, and these proceedings) where the lower luminosity systems are most affected by the strong tidal effects that occur within dense regions leading to galaxy 'harassment'.

The Coma LF plotted in Figure 1 is inconsistent with the results of Bernstein et al. (1995) and Biviano et al. (1995). These studies only sampled the core of the cluster whilst the Thompson and Gregory (1993) and Godwin and Peach (1977) surveys studied a similar area of the cluster to that of Abell 2554. It is therefore likely that the shape of the LF may vary within the cluster. Driver et al. (1998b) have also derived the LFs of a sample of seven Abell/ACO clusters using a very similar technique to that used for Abell 2554. Their results are presented in Figure 2. Although several of their clusters do have a steepening of the LF slope at $M_R \sim -19$ it is clear that it is not a universal feature of all clusters. It is thus apparent that there is not a ubiquitous LF as had been proposed by Smith et al. (1997) and Trentham (1997a, 1997b, 1998) and another parameter is crucial in determining the number of dwarfs within a cluster. Phillipps et al. (1998 and these proceedings) consider this possibility further.

4. Summary

In conclusion, both photographic and CCD studies of rich clusters of galaxies suggest that they contain a very large number of dwarf galaxies. In many clusters, the luminosity function of is not well fitted by a Schechter function as there is a steepening to a slope of $\alpha \sim -1.7$ at about $M_R \sim -19$. From a small sample of clusters, the position of this turn-up is independent of redshift. Comparison with evolutionary models leads to the tentative conclusion that the dwarfs within these clusters are primarily dwarf ellipticals that have undergone little evolution since $z \sim 0.2$. As more observations of rich clusters have been obtained, it has become clear that there is not a ubiquitous form of the LF.

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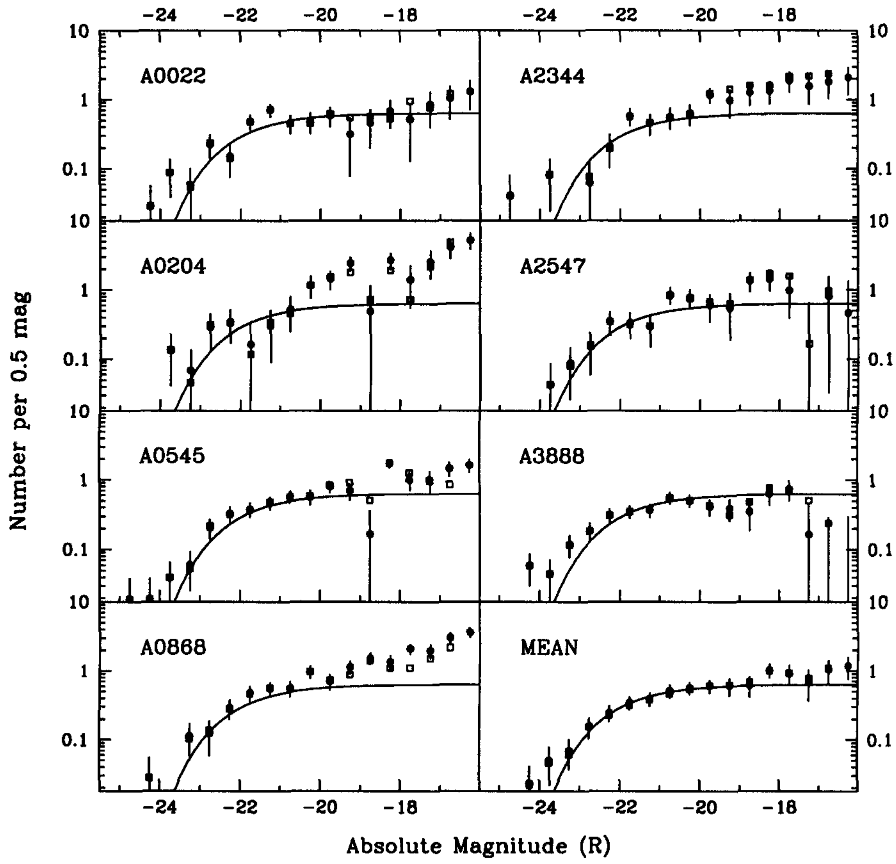

Figure 2. The luminosity functions of 7 Abell/ACO clusters as measured by Driver et al. (1998b). The solid dots and open dots represent differing methods of background/foreground galaxy subtraction.

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