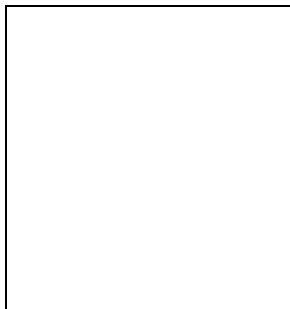


# THE FAINT END OF THE LUMINOSITY FUNCTION IN CLUSTERS

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## Abstract

I review recent measurements of the faint end of the galaxy luminosity function in galaxy clusters. Evidence is presented that the luminosity function of galaxies in the central parts of clusters is remarkably constant between clusters and that this luminosity function is steep at bright and faint magnitudes and shallow in-between. The curvature is highly significant – neither a power-law nor a Schechter function is consistent with the data. At no magnitude does  $\alpha = -1$  fit the data well. The faintest galaxies in all clusters that have been studied are dwarf spheroidal galaxies.

## 1 Introduction – luminosity functions

The luminosity function (LF)  $\phi(L)$  of galaxies is defined as the number density of galaxies per unit luminosity  $L$ : the number of galaxies in volume  $dV$  with luminosity between  $L$  and  $L + dL$  is  $\phi(L)dLdV$ .

The LF represents one of the most direct interfaces between studies of dwarf galaxies and cosmology, the two subjects of this conference. This statement follows directly from the form of the fluctuation spectrum – most plausible theories of structure formation (e.g. cold dark matter [3]) predict a fluctuation spectrum whose power spectrum  $|\delta(k)|^2 \propto k^n$  has index  $n \sim -2$  on scales of galaxies. This value of  $n$  simultaneously requires that low-mass systems be far more numerous than high-mass ones, so that the statistical properties of low-mass systems are a powerful probe of galaxy formation theories.

Consequently one of the most fundamental predictions of models of galaxy formation and evolution is the LF, particularly at faint magnitudes (e.g. refs. 6,13,48–50). These models generally assume a power spectrum of primordial dark matter fluctuations (say, from CDM theory) and then adopt prescriptions for the behavior of the baryonic component (specifically,

things like the effects of gas dissipation, star-formation efficiencies, feedback from supernovae, and the temperature-density structure of the intergalactic medium need to be quantified).

Significant differences in the theoretical luminosity functions from different models are seen, even when similar dark matter power spectra are assumed, because of differing prescriptions for the behavior of the baryonic component. For example Babul & Ferguson [2] suggest a faint-end slope of  $\alpha \sim -2.6$  at faint magnitudes, whereas White & Kauffmann [49] compute values more like  $\alpha \sim -1$  for their dwarf suppression models (here  $\alpha$  is the logarithmic slope of the LF:  $\alpha = d \log \phi(L)/d \log L$ ). Therefore measuring  $\alpha$  as accurately as possible at faint magnitudes seems like a worthwhile exercise.

## 2 Introduction – dwarf galaxies

I will introduce this section of the review by referring to the absolute magnitude vs. central surface-brightness plot that at this conference was referred to as the Binggeli diagram. As Figure 1 of Binggeli’s 1994 review paper [5, see also 14,15] shows, stellar systems generally fall into four distinct regions on this diagram:

**(1) Elliptical galaxies and bulges.** These form a sequence of decreasing central surface-brightness with increasing luminosity. Absolute magnitudes range from about  $M_B \sim -25$  (e.g. cD galaxies in the centers of clusters like NGC 6166 in Abell 2199, which have faint central surface-brightnesses) to  $M_B \sim -15$  (compact low-luminosity ellipticals like M32 which have bright central surface-brightnesses).

**(2) Globular clusters.** These have high central surface-brightnesses ( $\mu_B \leq 18$  mag arcsec<sup>-2</sup>), like ellipticals and bulges but have much fainter absolute magnitudes ( $M_B > -10$ ). These form a sequence of higher central surface-brightness with increasing luminosity, which is in the opposite sense to the correlation for ellipticals and bulges.

**(3) Disks of spirals and S0 galaxies.** These have absolute magnitudes  $-21 < M_B < -17$ , and central surface-brightnesses close to  $21.6 B$  mag arcsec<sup>-2</sup> (Freeman’s law [11]), which is fainter than the central surface-brightness of almost any sequence (1) ellipticals. At faint magnitudes  $M_B > -18$ , this sequence blends into the dwarf galaxy sequence – see (4) below.

**(4) Dwarf Galaxies.** These have  $M_B > -18$  and form a sequence of fainter central surface-brightness with decreasing total luminosity. They are also increasingly dark matter dominated at fainter magnitudes [25,16]: the faintest dwarfs like Draco and Ursa Minor have mass-to-light ratios  $\sim 10^2$  within their core-fitting radii [1] and total mass-to-light ratios that are probably much larger than this [28]. It is because of their high dark matter content that a link between the mass functions of these faint dwarfs and the power spectrum of primordial fluctuations on small scales is suggested. Dwarf galaxies are typically one of two morphological types: (i) dwarf irregulars (dIrr) or (ii) dwarf spheroidals (dSph, alternatively called dwarf ellipticals, or dE). These types of galaxies have similar scaling laws (they occupy the same region on the Binggeli diagram), but dwarf irregulars have bluer colors and more disturbed morphologies. Familiar examples in the Local Group are the LMC (dIrr), NGC 205 (a bright dSph with  $M_B \sim -15$ ), and Draco (a faint low surface-brightness dSph with  $M_B \sim -8$ ).

There do exist other, rare galaxies which do not fit into the classifications above. Examples are huge low surface-brightness giants like Malin 1, and blue compact dwarfs, which appear to have been caught in a short burst of extreme star formation. Throughout the rest of this paper, by “dwarf galaxy”, I will mean sequence (4) objects.

Figure 1: The velocity dispersions and redshifts for some clusters with recent LF determinations

### 3 Introduction – clusters

Clusters of galaxies have proved a popular environment for determining the LF. This is because the distances to the galaxies there are known (at least in a statistical sense) so that the LF can be determined by photometry alone and spectroscopic redshifts are not needed. This in turn means that the LF can be measured down to very faint limits.

But there is a price to be paid for the cosmologist. Cluster galaxies are in dense environments where the crossing time plus age is less than or comparable to the Hubble time. These galaxies have therefore had their properties shaped by cluster-related processes e.g. ram-pressure stripping of gas from the galaxies. Measurements of the galaxy LF in clusters might then tell us more about these cluster-related processes than about cosmological parameters like the shape of the power spectrum on small mass scales. This is particularly true of very dense environments like the centers of rich clusters with large fractions of elliptical galaxies. It is less true of diffuse spiral-rich environments and the outer parts of clusters.

In Figure 1, for a sample of clusters with LF determinations, I present the velocity dispersion (an indication of the mass of the cluster) as a function of the cluster redshift  $z$ . Also shown on this figure are lines corresponding to 200 kpc = 10 arcmin – this is where a rich cluster core roughly fits into a single 2K CCD frame on a 2 to 4 meter telescope – and corresponding to where a typical dSph galaxy with  $R = 24$  has a scale-length (as inferred from the Binggeli plot) of 1 arcsec – to the right of this line, most faint cluster galaxies detected have intrinsic scale-lengths smaller than the seeing and so cannot be readily discriminated from background galaxies on morphological grounds.

The techniques used to determine the LF in a particular cluster are determined by its position on Figure 1. In simplest terms, clusters are either on the left of the dashed lines

(hereafter I call these “nearby clusters”) or between or to the right of the dashed lines (I call these “distant clusters”).

Most early work in this subject that reached absolute magnitudes faint enough to probe dwarf galaxies (those in sequence (4) of the Binggeli diagram) were photographic measurements of nearby clusters e.g. Virgo [29] and Fornax [10]. Clusters significantly more distant than Coma (see e.g. ref. 35 for a large photographic survey of Coma) could not be studied in this way because (i) photographic plates were not sensitive enough to probe the bulk of the dwarf population, and (ii) cluster members could not be readily distinguished from background/foreground galaxies.

However, the advent of 2K CCDs on 2 – 4 m telescopes allowed very precise statistical determinations of field galaxy counts down to very faint magnitudes (e.g. refs. 43 and 17). Background/foreground contamination in cluster fields could then be estimated and corrected for down to  $R = 25$ , and the LFs of several rich clusters out to  $z = 0.2$  were measured. The main limitation of these studies was that the errors at the faintest magnitudes were quite large because of uncertainty in the field-to-field variance of the background. However, large samples of clusters could be studied, and these errors reduced when combining samples of similar clusters. In Section 5, some results of this type will be presented and discussed.

These 2K CCDs are not well suited to studies of nearby clusters, although individual dwarfs can easily be identified and no background subtraction is needed. This is because the CCDs are small and each exposure can only cover a negligible fraction of the cluster core (we are to the left of the 200 kpc = 10 arcmin line in Figure 1). Counting statistics are then crippling – a typical 2K CCD field in the center of the Virgo Cluster will have no or at most 1 or 2 dwarfs brighter than  $R = 22$ .

More recently, 8K and larger CCDs have become available on 4 m telescopes (e.g. the UH 8K mosaic on the 3.6 m CFHT [23]). Large samples of galaxies in nearby clusters can now be obtained and the LFs measured accurately down to very faint magnitudes. Because no background subtraction is required, the only errors at faint magnitudes come from counting statistics – the errors are consequently much smaller than the errors at the faint end for the distant clusters, at least for reasonably dense nearby clusters like Virgo and Fornax. An alternative approach has been employed by Phillipps et al. [27] who use sensitive median-stacked UK Schmidt plates [32] to measure the Virgo cluster LF down to  $M_R \sim -11.5$  (see the paper by Jones et al. in these proceedings – this was one of the most significant new results at this meeting). A project in collaboration with B. Tully (University of Hawaii) has been undertaken to measure the Ursa Major LF but this cluster is sufficiently diffuse that counting statistics are still a significant problem.

## 4 Techniques

For the distant clusters, a number of specialized techniques have evolved [9,4,38] that optimize the accuracy to which the LF can be measured at faint magnitudes. A recurrent theme is the importance of characterizing the background/foreground contamination and its uncertainty, as this is the main source of the error in the faintest points of the LF. The contamination is severe: the background/foreground galaxy counts are comparable to or greater than the cluster counts at  $R > 19$ , even in the centers of rich clusters like Coma. For example, high photometric accuracy in the zero-point needs to be achieved because the background counts are a strongly-varying function of magnitude and we must be sure that we are subtracting exactly the right amount of background galaxies at each magnitude. Other systematic sources of error (e.g. Galactic extinction, possible extinction from dust in the clusters, stellar contamination,

Figure 2: The  $R$ -band luminosity functions of A 262 ( $z = 0.016$ ), Coma ( $z = 0.023$ ), A 1795 ( $z = 0.063$ ), and A 665 ( $z = 0.182$ ). In converting apparent to absolute magnitudes, I assume  $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $\Omega_0 = 1$ .

globular cluster contamination, giant galaxy halo substructure, distortion of the background counts by gravitational lensing by the cluster dark matter) are important too and all need to be considered. The reader is referred to the papers listed above for details.

Measurements of nearby clusters as outlined in Section 4 pose different problems. Background subtraction is no longer a major problem because the faintest dwarfs have scale-lengths that are significantly larger than the seeing so that cluster members can be identified by their morphologies. Therefore the LF of Virgo measured by Phillipps et al. [27] is very well constrained at the faint end. Measurements in diffuse groups like Ursa Major are more difficult because counting statistics there are poor. Also, the surface density of low-surface-brightness (LSB) field galaxies which look similar to cluster dwarfs needs to be well characterized (for Virgo this is not a serious problem because the cluster dwarfs outnumber background LSB galaxies by a large factor in this relatively dense cluster – see the paper by Jones et al. in these proceedings).

## 5 The luminosity functions of the cores of rich clusters

In Figure 2, I present four LFs from my earlier work [38 – 41]. Other published LFs (in addition to the ones already listed) are presented in references 12, 19, 20, 33, 34, and 47.

For A 262 (a poor cluster at  $z = 0.016$ ), signs of a turn-up at the faint-end ( $M_R < -14$ ) are seen, but the LF is not well-constrained at bright magnitudes here because the galaxy density is too low. In Coma, a richer cluster at approximately the same distance as A 262, a similar turn-up at the faint-end is seen, but a far more shallow LF is observed at brighter magnitudes.

Figure 3: Composite  $R$ -band luminosity function of rich clusters (derived using the LFs from Coma, A 2199, A 1795, A 1146, A 665, and A 963). This represents the weighted average of the individual LFs, normalized to a projected galaxy density corresponding to that of a typical Abell richness 2 cluster. Local values of  $\alpha(M_R)$  derived by measuring the slope between  $M_R - 1$  and  $M_R + 1$ , and their uncertainties, are given too. Slopes corresponding to  $\alpha = -1$  and  $\alpha = -2$  are also shown.

In both cases, the statistics are poor at the faint-end because the field-to-field variance of the background is so large – nevertheless, in both cases the turn-up at the faint-end is statistically significant and the LF is not fit by either a power-law or a Schechter function [30] over the entire range  $-20 < M_R < -11$ ). For the more distant clusters, A 1795 and A 665, a flatter LF is seen but the very faint magnitudes at which the turn-up is seen in A 262 and Coma are not probed in these clusters.

The approximate similarity of the form of the LFs in the four clusters in Figure 2 suggests that it might be productive to combine the individual cluster LFs in order to improve the statistics. This is done in Figure 3. When performing this calculation, I found that each individual cluster LF is consistent with the composite LF to a high degree of statistical significance. This is suggestive that the LF of galaxies in the cores of rich clusters is remarkably constant. Also, the Fornax LF of Ferguson [10] is also consistent with this composite function at a high level of significance down to  $M_B = -13$  (see ref. 42 – this is particularly intriguing because the errors in the Fornax sample at the faint end come only from counting statistics and are quite small).

The composite LF in Figure 3 has much better statistics than the LFs shown in Figure 2, now that a sample of clusters have been combined. The composite LF shows the following properties:

1) the LF shows significant curvature at both the bright and faint-ends. Neither a power-law

nor Schechter function [30] provides a good fit to the data. A similar conclusion was made for the Coma LF in Figure 2, but the smaller error bars in Figure 3 now make this true at a far higher level of confidence.

2) at no magnitude is  $\alpha = -1$  a good fit to the data. We note however the peculiar result that the LF is flattest ( $\alpha = -1.2$ ) at about  $M_R = -19$ , which is the transition magnitude between giants ellipticals and dwarfs in the Binggeli diagram (most giant galaxies in the centers of rich clusters are ellipticals). This is suggestive of a conspiracy in which the giant galaxy LF is falling by an amount almost exactly compensated for by the rise in the dwarf galaxy LF at  $M_R = -19$ .

3) the turn-up at the faint-end appears to be very steep. The new results for Virgo (ref. 27, Jones et al. these proceedings) suggest a value of  $\alpha = -2.1$  at  $M_R = -12$ . The statistics that Phillipps, Jones and collaborators got for Virgo are significantly better than I show for A 262 or Coma in Figure 2, because in Virgo a background subtraction is not required.

On theoretical grounds, this steep LF is not predicted to extend to indefinitely faint magnitudes because we expect photoionization from the UV background to suppress the conversion of gas into stars in very low mass systems [36]. On observational grounds, we arrive at the same prediction from the requirement that the integrated light from small galaxies not overproduce the measured intracluster light (see Section 8 below). It is, however, interesting to note that between about  $M_R = -13$  and whenever this turnover occurs, the LF has approximately the same shape ( $\alpha \sim -2$ ) as the mass function predicted [49] from Press-Schechter theory (i.e. if Press-Schechter theory is valid in this context, then over this magnitude range, the combined efficiency of all the baryonic processes which convert gas to stars is independent of the mass of the galaxy).

An important caveat is that the LFs presented in Figures 2 and 3 are only valid for the cores of rich clusters, which are dense elliptical-rich environments. Perhaps the agreement between the composite LF and the Fornax LF outlined above suggests that it is the elliptical galaxy fraction, not the total galaxy density, that is important (Fornax is anomalously elliptical-rich). There is good evidence [8] that the ellipticals evolve differently from all other giant galaxies (including S0s) in clusters, so it is perhaps unexpected if the global form of the LF is the same in elliptical-rich and elliptical-poor environments.

## 6 Comparison between clusters and the field

The largest sample of field galaxies to date is the Las Campanas Redshift Survey (LCRS; ref. 18), which has  $1.9 \times 10^4$  galaxies. For  $-18 < M_R < -16$  (approximately  $-16.5 < M_B < -14.5$ ), the LCRS has a slope of  $\alpha = -1.39 \pm 0.11$ . The cluster slope over the same magnitude range is  $\alpha = -1.44 \pm 0.13$ .

There are, however, differences. Most of the faintest galaxies seen in the LCRS are emission-line galaxies where as most of the faintest galaxies in clusters are gas-poor dSph galaxies. Therefore, even though the LF slope is similar in the two environments for  $-18 < M_R < -16$ , the LF is dominated by the contributions from different types of galaxies in each.

Also, the field and cluster LFs are probably very different much fainter than  $M_R = -14$ . The steep turn-up seen in Virgo [27] for  $M_R > -14$  certainly does not happen in the Local Group [45], for example. Although the Local Group may have several undiscovered low surface-brightness members at the very faintest magnitudes like  $M_R \sim -9$  (the magnitude of Draco and Ursa Minor), it probably does not have many brighter than  $M_R = -12$ . Therefore incompleteness is not the reason for the discrepancy in the LFs here.

## 7 The types of the faintest galaxies in rich clusters

In the previous two sections, I have presented evidence that supports the presence of a large number of faint galaxies in clusters, but have not shown what type these galaxies are. The scale-lengths are consistent with either a dSph or dIrr interpretation (recall from Section 2 that these galaxies occupy the same part of the Binggeli diagram). They are not consistent with the faintest galaxies being low luminosity compact ellipticals like M32. These faint galaxies have scale-lengths comparable to or smaller than the seeing, so that their detailed morphologies cannot be used to tell whether they are dSphs or dIrrs.

The best discriminant between these galaxy types in the absence of spectroscopic information is the color of the galaxies. In all the distant clusters shown on Figure 1, I found that the colors of the faintest galaxies were consistent with them being dSphs and not dIrrs (the K corrections are given in ref. 41). Other authors (see the list of references in Section 5) conclude similarly. In Virgo, the galaxies are sufficiently nearby that morphological information can be used – both Sandage et al. [29] and Phillipps et al. [27] find that the faintest galaxies that they detect are dSphs as well.

## 8 The lowest surface-brightness galaxies

With measurements of this type there is always the long-standing worry that we are missing many LSB galaxies and so are underestimating the cluster galaxy counts at each magnitude [7]. Then the LF that we derive could be seriously in error.

In all clusters I studied (the distant clusters in Figure 1), I found that on going to fainter magnitudes, I did not find systematically more galaxies that had surface-brightnesses close to my detection threshold. This is indicative that I am not missing many galaxies because they have surface-brightnesses too low to be detected, but is far from being a rigorous statement to this effect. There may be, for example, an entire population of extremely LSB galaxies with surface-brightnesses far lower than my detection threshold. A more formal analysis is suggested.

So let us define (as Phillipps and Disney [26] did for spiral galaxies) a bivariate surface-brightness / luminosity distribution function in the usual way:  $\phi(\mu, L)d\mu dL$  is the number density of galaxies with surface-brightnesses between  $\mu$  and  $\mu + d\mu$  and luminosities between  $L$  and  $L + dL$ . When we measure a LF (as in the rest of this paper), what we are really measuring is the contraction of this bivariate function over high surface-brightnesses:  $\phi(L)_{\text{measured}} = \int_{\mu_c}^{\infty} \phi(\mu, L)d\mu$  where  $\mu_c$  is the detection threshold.

There is a constraint on the other side of this contraction (i.e. over low surface-brightnesses):  $\int_0^{\infty} \int_0^{\mu_c} L\phi(\mu, L)d\mu dL$  must not exceed the intracluster background light (e.g. refs. 22 and 37, and more recently refs. 31, 44, and 46). This is only a limit because much of the intracluster background light might come from stars that have been tidally stripped from the giant galaxies; such stars are not associated with LSB galaxies. This constraint is however severe enough to rule out extremely steep LFs in clusters (e.g. the steep ( $\alpha \sim -2.8$ ) LF recently proposed by Loveday [21] for the field would not work in the Coma cluster because of this constraint).

## 9 The mass function

Everything presented so far in this review has dealt with the luminosity function of galaxies, which is not the same as the mass function (by mass function here I am referring to total



mass, where the dark matter content of individual galaxies is included). The two, however, probably are fairly similar, unless there exist a significant dispersion in the mass-to-light vs. light distribution function for galaxies in clusters. Clusters of galaxies possess a great deal of dark matter so that it is not impossible that they contain many galaxies that are almost completely dark. The mass function would be a useful probe of the fluctuation spectrum, since it bypasses all the complex physics of the baryonic component outlined in Section 1 (in the cores of rich clusters, however, there remains the caveat that the dark-matter properties of galaxies might be significantly affected by cluster-related processes e.g. tidal stripping).

The mass function is not straightforward to measure. The best hope is to determine it through gravitational lensing measurements, for example (i) galaxy-galaxy strong lensing, or (ii) the Natarajan-Kneib [24] method, which attributes granularity in the weak lensing shear map to lensing by individual galaxy halos. In the upcoming age of 8 and 10 m telescopes, it is likely that these kinds of measurements will provide important constraints.

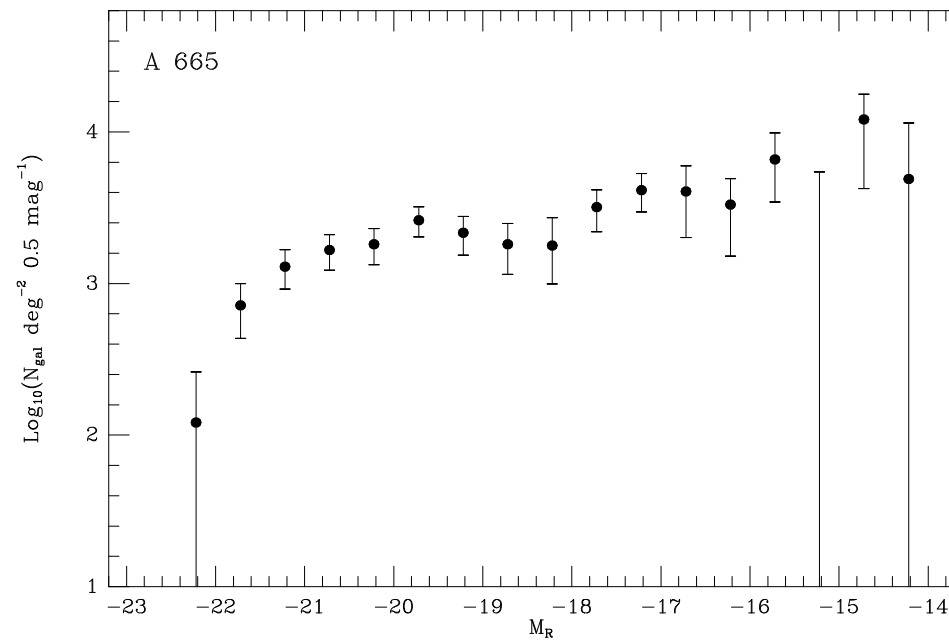
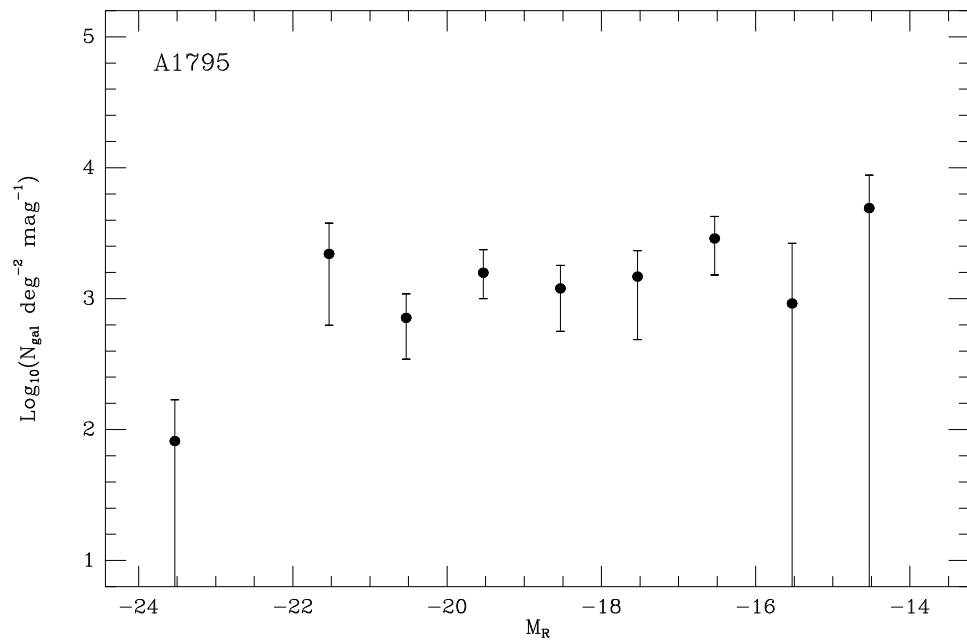
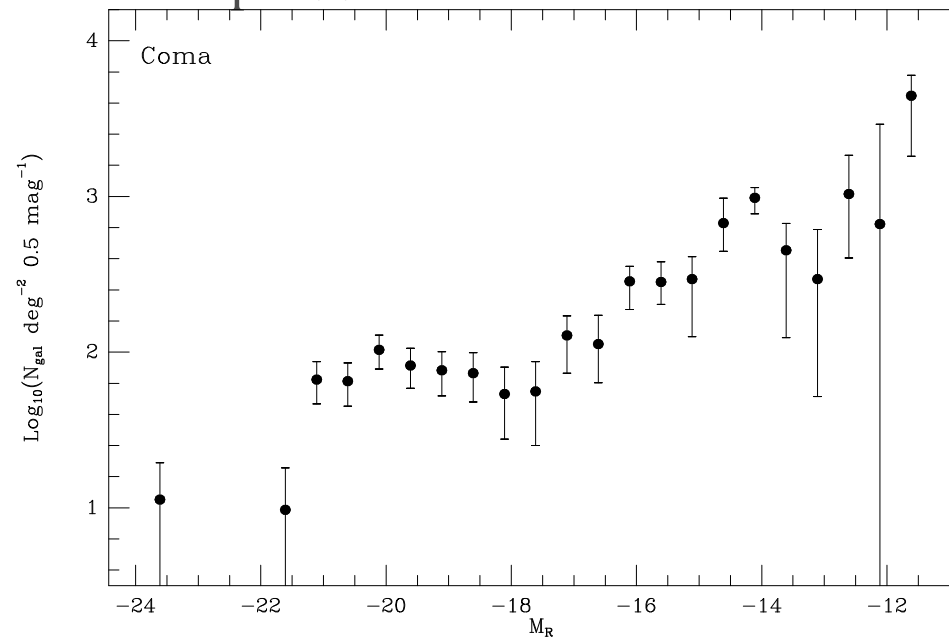
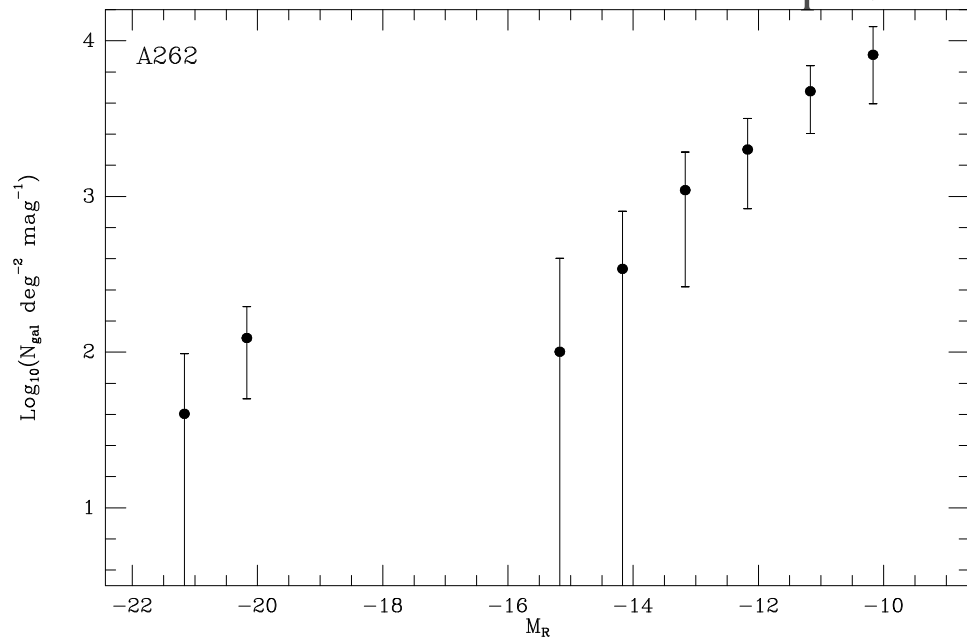
## References

- [1] Armandroff T. E., Olszewski E. W., Pryor C., 1995, *Astron. J.* **110**, 2131
- [2] Babul A., Ferguson H. C., 1996, *Astrophys. J.* **458**, 100
- [3] Bardeen J. M., Bond J. R., Kaiser N., Szalay A. S., 1986, *Astrophys. J.* **304**, 15
- [4] Bernstein G. M., Nichol R. C., Tyson J. A., Ulmer M. P., Wittman D., 1995, *Astron. J.* **110**, 1507
- [5] Binggeli B., 1994, in *Conference and Workshop Proceedings No. 49: Dwarf Galaxies* p. 13, eds Meylan G., Prugneil P., ESO
- [6] Cole S., Aragón-Salamanca A., Frenk C. S., Navarro J. F., Zepf S. E., 1994, *MNRAS* **271**, 781
- [7] Disney M. J., 1976, *Nature* **263**, 573
- [8] Dressler A., Oemler A., Couch W. J., Smail I., Ellis R. S., Barger A., Butcher H., Poggianti B. M., Sharples R., 1997, *Astrophys. J.* **490**, 577
- [9] Driver S. P., Phillipps S., Davies J. I., Morgan I., Disney M. J., 1994, *MNRAS* **268**, 393
- [10] Ferguson H. C., 1989, *Astron. J.* **98**, 367
- [11] Freeman K. C., 1970, *Astrophys. J.* **160**, 811
- [12] Gaidos E. J., 1997, *Astron. J.* **113**, 117
- [13] Kauffmann G., White S. D. M., Guideroni B., 1993, *MNRAS* **264**, 201
- [14] Kormendy J., 1985, *Astrophys. J.* **295**, 73
- [15] Kormendy J., 1987, in *Nearly Normal Galaxies* p. 163, ed Faber S. M., Springer-Verlag
- [16] Kormendy J., 1990, in *The Edwin Hubble Centennial Symposium: The Evolution of the Universe of Galaxies* p. 33, ed Kron R. G., ASP
- [17] Lilly S. J., Cowie L. L., Gardner J. P., 1991, *Astrophys. J.* **369**, 79
- [18] Lin H., Kirshner R. P., Shectman S. A., Landy S. D., Oemler A., Tucker D. L., Schechter P. L., 1996, *Astrophys. J.* **464**, 60
- [19] Lobo C., Biviano A., Durret F., Gerbal D., Le Fevre O., Mazure A., Slezak E., 1997, *Astr. Astrophys.* **317**, 385
- [20] Lopez-Cruz O., Yee H. K. C., Brown J. P., Jones C., Forman W., 1997, *Astrophys. J.* **475**, L97

- [21] Loveday J., 1997, *Astrophys. J.* **489**, 29
- [22] Melnick J., White S. D. M., Hoessel J., 1977, *MNRAS* **180**, 207
- [23] Metzger M. R., Luppino G. A., Miyazaki S., 1995, *Bull. Amer. Astr. Soc.* **187**, 73.05
- [24] Natarajan P., Kneib J.-P., 1997, *MNRAS* **287**, 833
- [25] Persic M., Salucci P., 1988, *MNRAS* **234**, 131
- [26] Phillipps S., Disney M., 1986, *MNRAS* **221**, 1039
- [27] Phillipps S., Parker Q. A., Schwartzberg J. M., Jones J. B., 1997, *preprint* (astro-ph/9712027)
- [28] Pryor C., Kormendy J., 1990, *Astron. J.* **100**, 127
- [29] Sandage A., Binggeli B., Tammann G. A., 1985, *Astron. J.* **90**, 1759
- [30] Schechter P., 1976, *Astrophys. J.* **203**, 297
- [31] Scheick X., Kuhn J. R., 1994, *Astrophys. J.* **423**, 566
- [32] Schwartzberg J. M., Phillipps S., Parker Q. A., 1996, *Astr. Astrophys. Suppl. Ser.* **117**, 179
- [33] Secker J., Harris W. E., 1996, *Astrophys. J.* **469**, 628
- [34] Smith R. M., Driver S. P., Phillipps S., 1997, *MNRAS* **287**, 415
- [35] Thompson L. A., & Gregory S. A., 1993, *Astron. J.* **106**, 2197
- [36] Thoul A. A., Weinberg D. H., 1995, *Astrophys. J.* **442**, 480
- [37] Thuan T. X., Kormendy J., 1977, *Publ. Astr. Soc. Pacific* **86**, 499
- [38] Trentham N., 1997a, *MNRAS* **286**, 133
- [39] Trentham N., 1997b, *MNRAS* **290**, 334
- [40] Trentham N., 1998a, *MNRAS* **293**, 71
- [41] Trentham N., 1998b, *MNRAS* **295**, 360
- [42] Trentham N., 1998c, *MNRAS* **294**, 193
- [43] Tyson J. A., 1988, *Astron. J.* **96**, 1
- [44] Uson J. M., Boughn S. P., Kuhn J. R., 1991, *Astrophys. J.* **369**, 46
- [45] van den Bergh S., 1992, *Astr. Astrophys.* **264**, 75
- [46] Vilchez-Gomez R., Pello R., Sanahuja B., 1994, *Astr. Astrophys.* **283**, 37
- [47] Wilson G., Smail I., Ellis R. S., Couch W. J., 1997, *MNRAS* **284**, 915
- [48] White S. D. M., Frenk C. S., 1991, *Astrophys. J.* **379**, 52
- [49] White S. D. M., Kauffmann G., in *The Formation and Evolution of Galaxies* p. 455, eds Munoz-Tunon C., Sanchez F., CUP
- [50] White S. D. M., Rees M. J., 1978, *MNRAS* **183**, 321

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