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On the universality of the type-dependent luminosity functions

S. Andreon

Osservatorio Astronomico di Capodimonte, Via Moiariello 16, I-80131 Napoli, Italy (email: andreon@na.astro.it)

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Abstract. We find that the bright part ($M_B < -18.5$ mag) of luminosity function of each Hubble type has the same shape in three poor clusters (Virgo, Fornax and Centaurus) and in two rich clusters (Coma and Cl0939+4713). The fact that these type-dependent luminosity functions are invariant in shape from poor to rich environments gives support to the hypothesis that they may be universal. We also present in tabular form improved type-dependent luminosity functions, based on a much larger sample than previous works.

Key words: galaxies: elliptical and lenticular, cD – galaxies: spiral – galaxies: luminosity function, mass function

1. Introduction

Luminosity functions (hereafter LFs) are powerful tools for studying the evolution of galaxies, and a lot of attention has been devoted to their determination and to the study of their dependence on environment (e.g. Lugger 1989, Oegerle & Hoessel 1989). Even more powerful is the study of bivariate type-luminosity functions, i.e. the luminosity function of each Hubble type (hereafter LFT), since the study of each galaxy population can be approached separately. For example, using the morphological classification, Abraham et al. (1995) have shown that only a specific part of the field population is strongly evolving.

In a seminal paper, Binggeli et al. (1988) suggested that it is unlikely that the shape of the LF is universal, since it is the sum of the LFTs, and the morphological composition varies from cluster to cluster and with respect to the intercluster field. From the study of galaxies in the local field, in small groups and in two poor clusters, Virgo and Fornax, Binggeli et al. (1988) suggested the LFTs could be universal. It is clear, however, that this statement needs to be tested in a wide variety of environments.

A first comparison between LFTs determined in very different environments dates back to Binggeli (1986), who compared the V-band LFTs of Coma, as measured by Thompson & Gregory (1980), to his B-band LFTs of Virgo. This comparison assumes the same color for all galaxies and that galaxies have been classified in the same morphological scheme (whereas instead Thompson & Gregory (1980)'s morphological classes are not perfectly coincident with Hubble classes). Sandage et al. (1985), Binggeli et al. (1988), Jerjen & Tammann (1997, hereafter JT) and Andreon (1997a), have compared LFTs measured in environments which are possibly not different enough to support the claim that LFTs are universal.

A more robust conclusion can be drawn from a comprehensive study of the LFTs in very different environments, where the galaxy densities differ by 4 orders of magnitude or more.

In Sect. 2 we explore the universality of the LFTs. In Sect. 3 we address some objections to our claim. We build composite LFTs in Sect. 4. The results are discussed in Sect. 5.

2. Are the LFTs universal ?

JT have recently determined FLTs in poor clusters for a sample of galaxies including the samples of Binggeli et al. (1988) and Sandage et al. (1985) and composed of galaxies in Virgo, Fornax and Centaurus, grouped together in order to increase the rather poor statistics of giant galaxies in each sample, particularly of Es and S0s. The relative distances of these clusters are still a matter of debate and therefore we expect that their composite LFTs will be broadened by uncertainties in the relative distances of the clusters.

For poor clusters we adopt the LFTs read from Figs. 5 and 6 in JT. We verified that these magnitudes were on the RC3 (de Vaucouleurs et al. 1991) B_T magnitude system by comparing magnitudes of galaxies in common. Between the magnitudes in the two systems we found a typical scatter of $\sim 0.15-0.30$ mag and systematic differences in the range 0 to 0.13 mag. Absolute magnitudes were computed by JT assuming an *apparent* distance modulus for Virgo, Fornax and Centaurus of 31.7, 31.9, and 33.8 mag, respectively.

LFTs have also been measured in two rich clusters of galaxies: Coma (Andreon 1996) and Cl0939+4713 (Andreon et al. 1997a). For Coma galaxies, magnitudes are taken from Godwin et al. (1983, hereafter GMP) and linked to the RC3 B_T system comparing magnitudes of common galaxies. We found:

$$b_{GMP} = B_{RC3} + 0.12 \quad \sigma = 0.15 \text{ mag.}$$

Our choice of the distance modulus of Centaurus and the assumption that this cluster is at rest with respect to the Hubble flow, give $H_0 = 65.5$ km s^{-1} Mpc^{-1} and a distance modulus for Coma of 35.14 mag. For the morphological types of Coma galaxies we have two samples at our disposal: one complete

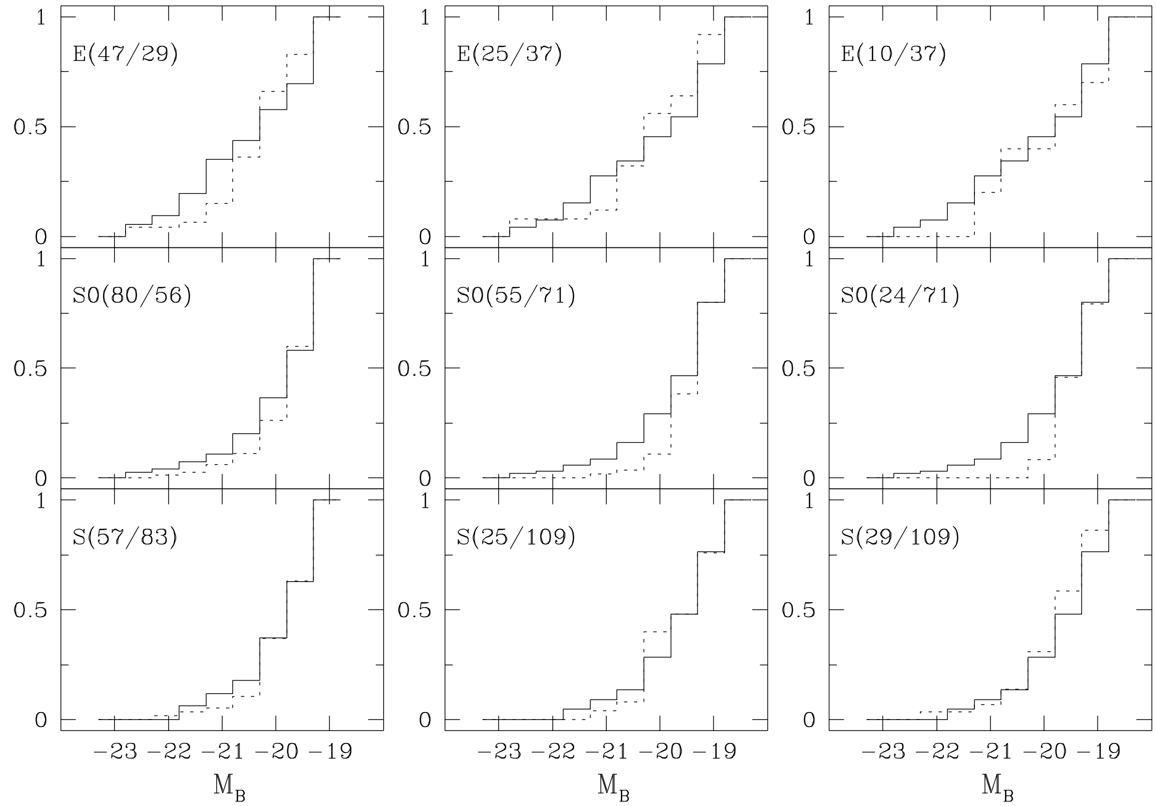

Fig. 1. Comparison between the cumulative type-dependent luminosity functions in poor clusters (continuos lines) with those measured in the central region of Coma (left panels, dashed lines), in the whole Coma cluster (central panels, dashed lines) and the Cl0939+4713 cluster (right panels, dashed lines). We binned our LFTs, as done by JT for their data, to compare our data to theirs. Numbers in parenthesis give the number of galaxies of each type in the comparison clusters and in the poor clusters, respectively

down to $b_{GMP} = 16.5$ mag with an almost complete spatial coverage of the cluster and another complete down to $b_{GMP} = 17$ mag including only galaxies in the cluster core (see Andreon et al. 1996 for details). Rest frame b_{GMP}-like magnitudes of Cl0939+4713 galaxies (see Andreon et al. 1997a for details) are linked to B_T assuming for them the same transformation that holds for Coma galaxies. Morphological types are taken from Andreon et al. (1997a). We assume a distance modulus of 41.57 mag for Cl0939+4713.

To summarize, for all galaxies we have $J-$like magnitudes converted to B_T system, as usual for such studies, and good estimates of the morphological types.

The left-hand and central panels of Fig. 1 compare cumulative LFTs in poor clusters and in the two Coma samples. Coma and the poor clusters differ by 2 orders of magnitude in central density. LFTs of the poor clusters are statistically indistinguishable from Coma ones, down to the adopted magnitude limits (-18.75 mag for the whole Coma cluster and -18.25 mag for its central part). A two-side Kolmogorov-Smirnov test to reject the null hypothesis that the compared distributions are extracted from the same parent distribution gives at most 30 % probability (we need 95 % for calling them different at the 2 σ confidence level). This agreement is highly satisfactory, given the scatter between adopted and RC3 magnitudes, and the poor knowledge of the relative apparent distance moduli of Virgo, Fornax and Coma. If anything, the LF of Es in poor clusters seems more skewed toward bright magnitudes than the Coma one (note the excess at $M_B \sim -22$ mag and the consequent deficit at $M_B \sim -20$ mag), but at an insignificant statistical level[1].

Therefore, the shape of LFTs is the same not only among poor clusters, all similar in terms of galaxy densities, but in Coma as well, where the galaxy density is significantly different.

The right-hand panels of Fig. 1 show a comparison of LFTs in poor clusters and in the Cl0939+4713 cluster, which is the most distant ($z \sim 0.4$, Dressler & Gunn 1992) ACO (Abell, Corwin & Olowin 1990) cluster and one of the richest known (Oemler et al. 1997). Besides this, there are no other clusters whose LFTs have been measured in a J-like filter. The distant sample is complete in absolute magnitude down to $M_B = -18.0$ mag.

Again, the LFTs of Cl0939+4713 are statistically indistinguishable from those of poor clusters, as it could be expected due to the similarity of the LFTs in Coma and in Cl0939+4713 (Andreon et al. 1997a).

The results of these comparisons give a clear indication that the shape of LFTs, down to $M_B \sim -18.5$ mag, is invariant in clusters *of different richness* (we compare the average of three

[1] A similar excess has also been noted by Capaccioli et al. (1992) from the comparison of the Virgo E+S0 LF with a Gaussian.

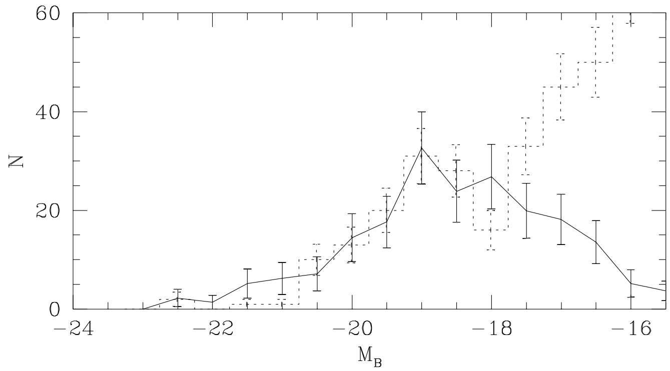

Fig. 2. Real and synthetic luminosity functions of Coma (histogram and spline, respectively), neglecting Coma dwarf galaxies and the background contribution to the total counts, which start to be important at $M_B > -18$ mag.

richness 0 clusters to one richness 2 cluster and one of the richest clusters), and even at different epochs.

3. Two possible objections to the universality of the LFTs

Previously (Andreon 1996), we noted that the V band LF for S0s in Perseus may be qualitatively different from that of their counterparts in Coma in the J band. In order to improve our comparison of LFTs in the two clusters we recompute LFTs of Coma galaxies in V using our morphological types and photometry by Godwin & Peach (1977). Morphological types of Perseus galaxies have been taken from Poulain et al. (1992) and we correct Perseus V magnitudes (from Bucknell et al. 1979) for Galactic absorption using reddening maps by Burstein & Heiles (1984). Godwin & Peach (1977)'s V catalog of Coma is not ideal for this comparison, since it covers a smaller area than that studied in Andreon (1996), it is not deep enough and V and b_{GMP} magnitudes show a large scatter, up to 0.75 mag. Lacking better catalogs, we adopt them, but in this way our sample of Coma galaxies becomes smaller (67 galaxies) and complete at a rather bright magnitude (-20.25 M_V mag $\sim$ -21.25 M_B mag), brighter than the magnitude at which the LF of S0s seems different in Coma and Perseus. A statistical comparison of LFTs shows that, in fact, they are consistent at the 50 % confidence level, down to our magnitude completeness limit. Given the small magnitude range involved in the comparison, this result should not be taken as conclusive.

The second possible objection to the universality of the LFTs concerns the LF of Coma. It shows a bump a $b_{GMP} = 16$ mag and a dip a $b_{GMP} = 17$ mag, as already shown, for complete samples, by Godwin & Peach (1977).

Fig. 2 shows that the sum of the LFTs *as determined in poor clusters*, weighted by the morphological composition of Coma computed from the data of Andreon et al. (1996, 1997b), reproduces the bump and the dip of the Coma LF down to $M_B \sim -18$ mag. At $M_B > -18$ mag, the synthetic LF does not match the Coma LF, because it neglects the existence of dwarfs and of background/foreground galaxies. The rise of the LF for $-18 < M_B < -16$ can be easily modelled with a Schechter (for dwarfs) +powerlaw (for background) functions given the small magnitude range and the large number of free parameters for the functions.

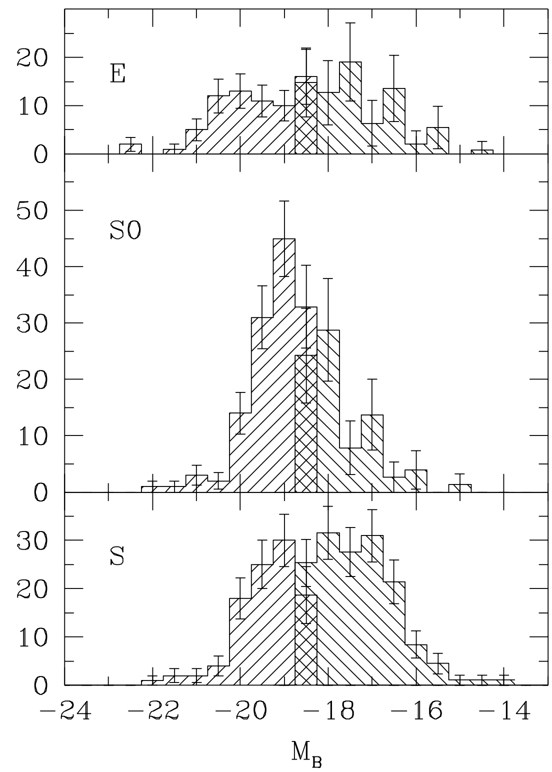

Fig. 3. The luminosity function of Es, S0s and Ss. The two shadings highlight what part of the LFTs are built using rich and poor clusters (bright and faint parts of the LFTs, respectively). The numbers in ordinate are the observed numbers of galaxies per half-magnitude bin, down to $M_B = -18.75$ mag in our composite sample. For fainter magnitudes, see text.

The maximum of the bump in the Coma LF matches well the synthetic LF. The bump is not sharper or shallower in the real LF than in the synthetic one. A slight excess at $M_B \sim -22$ mag is present in the synthetic LF but the significance is null, due to the large errorbars. The observed dip at $M_B \sim -18$ mag is less than 1 σ deeper than the one expected, giving a null statistical significance to this difference. This is at variance with the conclusions of Biviano et al. (1995) and Lobo (1997), but their studies were based on less accurate comparisons. The qualitative agreement of the shape of the B LFTs in Coma and Virgo claimed by Andreon (1996) is thus confirmed on a quantitative basis.

4. Improved LFTs

Having shown that LFTs in different clusters are compatible among themselves, we can now add them up. The number of early-type galaxies at bright magnitudes in the newly added clusters (Coma and Cl0939+4713) is more than twice those previously present in the sample.

Table 1. Improved LFTs

B	n_E	ε_{n_E}	n_{S0}	$\varepsilon_{n_{S0}}$	n_S	ε_{n_S}
-23.0	0	0	0	0	0	0
-22.5	2	1.4	0	0	0	0
-22.0	0	0	1	1	1	1
-21.5	1	1	1	1	2	1.4
-21.0	5	2.2	3	1.7	2	1.4
-20.5	12	3.5	2	1.4	4	2
-20.0	13	3.6	14	3.7	18	4.2
-19.5	11	3.3	31	5.6	25	5
-19.0	10	3.1	45	6.7	30	5.5
-18.5	15.5	4.4	29.1	5.5	22.6	3.8
-18.0	12.7	6.6	28.8	9.1	31.5	5.5
-17.5	19.0	8.1	7.9	4.8	27.6	5.1
-17.0	6.3	4.7	13.7	6.3	31.0	5.4
-16.5	13.5	6.9	2.6	2.8	21.4	4.5
-16.0	2.1	2.7	3.9	3.4	8.4	2.8
-15.5	5.5	4.4	0	0	4.5	2.1
-15.0	0	0	1.3	1.9	1.1	1.0
-14.5	0.8	1.7	0	0	1.1	1.0
-14.0	0	0	0	0	1.1	1.0

At bright magnitudes, because of larger photometric errors in poor clusters, poor statistics and the open question of their relative distances, we privileged the Coma and Cl0939+4713 LFTs determinations, whereas at faint magnitudes we adopted LFTs in poor clusters, since data for clusters with well known distance moduli are missing. To be more specific, down to $M_B = -18.75$ mag, we add the entire Coma cluster data to Cl0939+4713. For $M_B > -18.25$ mag we adopt the poor cluster LFTs, after normalizing the number of galaxies brighter than $M_B = -18.75$ to the one of the Coma and Cl0939+4713 clusters together. For the half-magnitude bin centered on $M_B = -18.50$ mag we add the samples of galaxies in Cl0939+4713, in the central part of Coma and in poor clusters, after normalization, as above.

The LFTs are plotted in Fig. 3, and the data are listed in Table 1. The shape of the LFTs computed in JT is confirmed (and therefore their comments hold for our LFTs too), except that the skewness of the E LF found by JT is now much reduced for our much larger E sample. Es, S0s, and Ss have LFTs which largely overlap in luminosity. The E LF shows a distribution broader than the S0s. It is for this reason that, in samples complete down to intermediate magnitudes ($M_B \sim -18$ mag), Es appear to be brighter than S0s (e.g. Binggeli et al., 1988; Andreon 1996). S0s have the narrowest distribution in luminosity, followed by Ss.

The presented LFTs provide an indispensable ingredient for computing synthetic galaxy counts, expected redshift distributions, the observability of galaxies in voids and many other quantities which involve the break down of the sample in populations with less heterogeneous observational properties (k-corrections, visibility, etc.) or the normalization at zero redshift of type-dependent quantities.

5. Conclusions

We found that the bright part ($M_B < -18.5$ mag, roughly M^*+3) of the LFTs is the same in three poor clusters and in two rich clusters, one of which (Cl0939+4713) is the most distant of the Abell, Corwin, & Olowin (1990) catalog and one of the richest known clusters, and the other (Coma) is the prototype of rich clusters (Jones & Forman 1984, Sarazin 1986) and is perhaps the best studied one.

We have thus verified the invariance of the shape of the LFTs in a large range of environments from as poor as the local field, where the measured LFTs are compatibles with the ones in poor clusters (Binggeli et al. 1988), to those of the Coma cluster and Cl0939+4713 cores (this work), several orders of magnitude denser than the local field. We have also verified that the observed luminosity function of Coma is equal to the synthetic computed assuming universal LFTs and the observed Coma morphological composition, down to $M_B \sim -18.5$ mag.

This suggests, in general, that differences in the LF of clusters are more likely due to differences in morphological compositions rather than in environment, and that the shape of LFs of each giant galaxy type (Es, S0s, Ss) is universal. This conclusion enlarges on a previous result by Binggeli et al. (1988) which was based on a smaller range of environments, and confirms the results of a less direct comparison between Coma and Virgo LFTs by Binggeli (1986).

The over-simplified approach of studying the evolution of galaxies at different look-back times or in different environments by comparing their LFs or the characteristic magnitudes of the Schechter (1976) function fit to their LF, should now be abandoned in favor of an approach that considers the possibility that the environments being compared have different morphological mixtures.

Improved LFTs are given, for a much larger sample of giant galaxies than previous works. They are quite useful for many statistical and theoretical studied.

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