Dissecting the luminosity function of the Coma cluster of galaxies by means of CFHT wide field images

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Abstract. By means of wide–field (42 × 28 arcmin) CCD images of the Coma cluster of galaxies and of control fields, taken at the Canada–France–Hawaii telescope with the CFH12K and UH8K cameras, we determine the luminosity function bi–variate in central brightness. We found a clear progression for a steeping and weakening of the FL going from high surface brightness galaxies ($\mu \sim 20$ mag arcsec$^{-2}$) to galaxies of very–faint central brightnesses ($\mu \sim 24.5$ mag arcsec$^{-2}$). Compact galaxies, usually rejected in the star/galaxy classification, are found to be a minor population in Coma. A huge population of low surface brightness galaxies red and faint are discovered, representing the largest contributor to the LF at faint magnitudes. Among them, there could be the remnant of high redshift starbursting galaxies responsible for the Butcher–Oemler effect.

1. Introduction

The luminosity function (LF hereafter), i.e. the number density of galaxies having a given luminosity, is critical to many observational and theoretical problems (see e.g. Binggeli, Sandage & Tammann 1988). From an observational point of view, the LF is the natural “weight” of all those quantities which need to be weighted against the relative number of objects in each luminosity bin. Furthermore, due to the role played by luminosity and surface brightness in the inclusion of objects in any observed sample (faint objects or low surface brightness galaxies are often excluded or under–represented), the knowledge of the LF and the LF bi–variate in brightness is fundamental to compute the selection function and is needed to derive the actual galaxy properties from the measured quantities (see, for example, the discussion on the field LF steepness by Sprayberry et al. 1997).

The LF buries under its foots the true problem (Sandage 1994): the LF is likely the sum of the LFs of the specific types, or of any other physically based galaxy classes. Galaxies can be classified on the bases of their central brightness, and in fact depending on their central brightness they lay in different parts of
the Fundamental Plane (e.g. Bender, Burstein & Faber 1997), showing that this classification is not an aesthetical one but reflects some physical difference between the classes. Therefore, “it would be of great importance to know what the luminosity function looks like when divided into classes of surface brightness” (Kron 1994).

In the present paper we shortly present the LF bi–variate in surface brightness of a sample of galaxies in the Coma cluster of more than 4000 members and in three filters, down to the magnitude of three bright globular clusters, complete in surface brightness down to the brightness of the faintest cataloged LSB galaxies, spread up over the largest cluster area ever observed with CCDs. The interested reader may found details in Andreon & Cuillandre (2000).

2. The CFHT data

$B$, $V$ and $R$ Coma cluster observations have been taken during the CFH12K (Cuillandre et al. 2000, see also Cuillandre et al. in this proceeding) first light at the Canada–France–Hawaii telescope prime focus in photometric conditions. CFH12K, the third generation wide-field imager at CFHT, is a 12K $\times$ 8K backside-illuminated CCD mosaic camera, offering a field of view of $42 \times 28$ arcmin$^2$ with a pixel size of 0.206 arcsec. A total of 12 mn were accumulated in each filter, split in four dithered 3 mn exposures to remove blemishes and cosmic rays and most importantly to fill the 6 arcseconds gaps between the CCDs. The data were reduced using standard CCD data reduction procedures (additive and multiplicative components, alignment and combination) implemented in a software specially optimized for fast processing of large CCD mosaics data at CFHT (FLIPS, Cuillandre 2001).

The control fields have been observed with the same telescope, with the same camera ($B$) during the same night, and using the UH8K ($V$ and $R$) in 1998. UH8K, a 8K $\times$ 8K frontside-illuminated CCD mosaic camera was the second generation wide-field imager at CFHT. The $B$ data is a deep (2 hours integration) empty field nearby the galaxy NGC 3486, a field standing at a similar galactic latitude as the Coma cluster. The $V$ and $R$ (3 hours and 2 hours resp. of integration) data are centered on the SA 57 field, also at a similar galactic latitude to Coma. The control fields were reduced in an identical way as the Coma cluster data, and then the properties (noise and PSF) of these images are matched to those of Coma.

3. The bi–variate luminosity function

The bi–variate LF is computed as the statistical difference between counts in the Coma and control field directions, in order to remove the background contribution from counts in the Coma direction. Figure 1 shows the $R$ and $V$ bi–variate LF. This is the first so far accurately computed for any environment, to our best knowledge. Brightness bins are 1 mag arcsec$^{-2}$ wide. The previous larger effort in this direction is presented in de Jong (1996), which study a sample of 86 field galaxies, while our sample includes $\sim$ 3000 cluster member galaxies. Central brightness is the actual galaxy central brightness convolved with the seeing disk
Figure 1. Bi–variate LF of Coma galaxies in the $R$ and $V$ bands. There is a clear progression from flat and bright LFs of HSB galaxies to steep and faint LFs of LSB. Errorbars are as in Figure 3.
(whose FWHM correspond to $\sim 1$ kpc to the Coma cluster distance) and then measured in a 0.25 kpc aperture.

At all brightness bins, galaxies occupy a bounded range. Although a distribution with a finite width is expected, we can now quantify it for the first time. Galaxies of very large size or very flat surface brightness profile (i.e. near the left end of each bi–variate LF plot) are uncommon, with a relative frequency distribution presented in Figure 1.

At the bright end, galaxies more than 4 mag brighter than their central brightness are very uncommon. Bi–variate LFs are bounded at the faint end too, because any object can be fainter (and smaller) than an unresolved point source (star) of the same central (apparent) brightness. An arrow in the plots marks this magnitude. Seldom the point at the pointed magnitude, i.e. objects that are as compact as the seeing disk, is on the extrapolation of points at brighter magnitudes. The rarity of galaxies at the arrow magnitude, when compared to the expected location based on the trend at brighter magnitudes, is not due to the fact that compact galaxies are removed in the star/galaxy classification or implicitly supposed not to exist, because our derivation of the LF does not follow this path: at the difference of most previous works, we have not removed compact dwarfs in the star/galaxy classification or implicitly supposed that they do not exist. The found rarity of compact galaxies means that most of the galaxies at the Coma distance are extended sources at our resolution.

Lacking a field bi–variate LF, it is difficult to say whether the Coma cluster is effective in harassing LSB galaxies, as advocated by Moore et al. (1996; 1999) or the bi–variate LF is the same in the two environments and it tells us more on galaxy formation and evolution in general.

The comparison of Figure 1 panels shows that LSB dominate the LF at faint magnitudes, while high surface brightness (HSB) galaxies dominate the bright end. High surface brightness galaxies ($\mu_0 < 20.0$ mag arcsec$^{-2}$) have a shallow LF ($\alpha \sim -1$), while LSB galaxies have a steep and fainter LF. There is a clear trend for a steepening and weakening of the FL going from high surface brightness galaxies to faint and very faint central brightnesses.

From the comparison of the Coma LF at different wavelengths, we found that faint Coma galaxies are red (Andreon & Cuillandre 2000; Andreon, Cuillandre & Pelló 2000). Faint galaxies are mostly of low surface brightness (LSB), and therefore in Coma faint galaxies are red and of LSB. In the field, LSB galaxies dominate the LF at faint magnitudes (Sprayberry et al. 1997) and are preferentially blue (de Blok et al. 95; van der Hoek et al. 2000). However, red LSB have been recently discovered in a survey targeting mainly two nearby clusters (O’Neil, Bothun & Cornell 1997), but the large majority are still blue. Therefore LSBs in Coma and in the field have quite different colors.

The existence of a large population of red LSB galaxies in the Coma cluster has a significant impact in the context of the Butcher–Oemler (1978, 1984) effect. It has been argued by Rakos & Schombert (1995), and then by many other authors later, that unobserved descendents of the large population of starbursting high redshift galaxies represent a problem for the Butcher–Oemler effect. LSB galaxies has been excluded as descendent because they have not the properties of failed galaxies, lacking, for example, the expected correlation between color and brightness for a fading population (Bothun, Impey & McGaugh 1997).
However, the LSB galaxies disclaimed to be failed galaxies are blue and in the field while exhausted galaxies should be red and in cluster, as Coma LSB galaxies are. Therefore, we suggest a too premature dismiss of the LSB galaxies as a remnant of high redshift starburst galaxies. There is ample room among several thousand red LSBs in the Coma cluster for accounting for a few tens of faded remnants and therefore Coma could be, from this point of view, the descendent of clusters with high blue fractions. In this context, we are assuming that the Butcher–Oemler effect is still a measure of the galaxy evolution, even if it could be largely plagued by selection effects, as shown by Andreon & Ettori (1999).

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