NoSOCS in SDSS. IV. The Role of Environment Beyond the Extent of Galaxy Clusters

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ABSTRACT

We are able to extend the investigation of the color-morphology-density-radius relations, for bright and faint galaxies, to $R \gtrsim 3 \times R_{200}$ and to very low density regions, probing the transition region between cluster and field galaxies, and finding a smooth variation between these two populations. We investigate the environmental variation of galaxy properties (and their relations), such as color, spectral type and concentration. Our sample comprises 6,415 galaxies that were previously selected as cluster members from 152 systems with $z \leq 0.100$. This sample is further divided in complete subsamples of 5,106 galaxies with $M_r \leq M^* + 1$ (from clusters at $z \leq 0.100$) and 1,309 galaxies with $M^* + 1 < M_r \leq M^* + 3$ (from objects at $z \leq 0.045$). We characterize the environment as a function of the local galaxy density and global cluster related parameters, such as radial distance, substructure, X-ray luminosity and velocity dispersion. For a sample of field galaxies we also trace their environmental dependence using a local galaxy density estimate. Our main findings are: (i) The fraction of discs is generally higher than the ones for blue and star-forming galaxies, indicating a faster transformation of color and star-formation compared to structural parameters. (ii) Regarding the distance to the cluster center we find a small variation in the galaxy populations outside the virial radius. Once within that radius the fractions of each population change fast, decreasing even faster within $R \sim 0.3 \times R_{200}$. (iii) We also find a small increase in the fraction of blue faint galaxies within $R \sim 0.4 \times R_{200}$, before decreasing again to the most central bin. (iv) Our results do not indicate a significant dependence on cluster mass, except for the disc fraction in the core of clusters. (v) The relations between galaxy properties also point to no dependence on cluster mass, except for the scatter of the color stellar mass relation. Our results corroborate a scenario on which pre-processing in groups leads to a strong evolution in galaxy properties, before they are accreted by large clusters.

Key words: surveys – galaxies: clusters: environment – galaxies: evolution.

1 INTRODUCTION

Galaxies in the local Universe can be classified in two broad types, according to their structure or properties related to their star formation history. Elliptical and S0 galaxies tend to be redder, to be bulge-dominated and show little star formation, being called early-type galaxies. Spirals are bluer, show high star formation rate (SFR) and are termed late-type. The presence of these two main types have a strong correlation with environment, with the former being predominant in the most dense regions of the Universe (central parts of groups and clusters of galaxies), while the latter are more common in low-density environments, called field (Oemler 1974, Dressler 1980). Those results can arise from differences in the intrinsic galaxy formation process (galaxy properties also show strong dependence on stellar mass). Another natural interpretation of this morphology-density relation is that galaxies are transformed as they move from the field to the central parts of clusters. Several different processes acting within groups and clusters could be important for the transformation of late-type into early-type galaxies as they move from low

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to high density regions. These include ram-pressure stripping, strangulation, mergers and tidal stripping from the cluster potential (Toomre & Toomre 1972; Caldwell et al. 1993; Gunn & Gott 1972; Abadi, Moore, & Bower 1999; Boselli & Gavazzi 2000). The open question regarding all these mechanisms is to know where they become relevant, as we consider infalling galaxies into groups or clusters. As these systems’ boundaries are hard to place it is nearly impossible to mark the transition between the field and groups/clusters.

Recent work has shown that the variation of galaxy types extend to very low density regions where the cluster influence should be minimal (Mateus & Sodré 2004; Balogh et al. 2004; Bahé et al. 2013). These results became possible after the very large projects such as the 2dF Galaxy Redshift Survey (2dFGRS) and Sloan Digital Sky Survey (SDSS) became available. According to these works there is a critical density for which the connection between SFR and environment first takes place. As this critical density is compatible with regions outside the cluster virial radius, it is suggested that galaxies are first processed in groups (Balogh et al. 2004). Besides this pre-processing (Bahé et al. 2013) also suggests that overshooting (Ludlow et al. 2004; another indirect mechanism) is responsible for transforming galaxies, as well as ram pressure due to low density gas in the outskirts of clusters.

The morphology-density (and color-density) relation is known to have a strong dependence on mass, with red early-type objects being the most massive. That agrees with the scenario of hierarchical growth of structure, from which we expect the most massive halos to be in the most dense parts of the Universe. As a consequence we expect the morphology-density relation to be a morphology-halo mass relation. However, results in the literature are contradictory. For instance, De Lucia et al. (2012) and Valentiniuzzi et al. (2011) find no dependence on the fraction of early-type galaxies (bulge-dominated and red galaxies), and properties of the cluster red-sequence (RS), with parent halo mass. On the other hand, Calvi et al. (2012) find a small dependence between morphology and halo mass. These differences may be associated to different halo mass ranges. The work of De Lucia et al. (2012) is based on a narrow cluster mass range (14 \leq \log M_H/\hmpc^2 \leq 14.8), using simulated data, while the results of Valentiniuzzi et al. (2011) are restricted to clusters with 500 \leq \sigma_v \leq 1100 km s^{-1}. Calvi et al. (2012) consider systems spanning a much wider mass range (12 \leq \log M_H/\hmpc^2 \leq 15). Another recent work (Howie et al. 2012) based on even more massive systems than Calvi et al. (2012) (13 \leq \log M_H/\hmpc^2 \leq 15.8; but a different lower mass cut) find no significant variation of galaxy type fraction with halo mass.

This work is the fourth of a series aiming to investigate cluster and galaxies’ properties at low redshifts (z \leq 0.1). Our main goal is to study galaxy properties in a variety of environments, from the central parts of groups/clusters to the field. For that we obtain the variation of the fractions of galaxy populations (traced by different properties) with local and global environment, characterized by the local galaxy density, distance to the center of the parent cluster, cluster mass (traced by the velocity dispersion and X-ray luminosity) and substructure. Besides investigating the environmental variation of the galaxy populations we check its dependence on galaxy cluster mass. We also investigate the differences in the field and group/cluster galaxies and the transition between such populations. All the analysis is performed on two different luminosity ranges (M_\star \leq M^* + 1 and M^* + 1 < M_\star \leq M^* + 3), so that we can assess the impact of environment for giant and dwarf galaxies separately.

The environmental influence is also investigated in different ranges of galaxy stellar mass.

This paper is organized as follows: §2 has the description, where we also discuss the local galaxy density estimates, the field sample and the separation of the galaxy populations. In §3 we present the environmental variation of different galaxy populations according to different environment tracers. In §4 we show how the relations between different galaxy properties depend on environment. In §5 we summarize and discuss our main results. The cosmology assumed in this work considers \Omega_M =0.3, \Omega_\Lambda =0.7, and \H_0 = 100 h \kms/\Mpc, with h set to 0.7. For simplicity, in the following we are going to use the term “cluster” to refer loosely to groups and clusters of galaxies, except where explicitly mentioned.

2 DATA

In the first paper of this series (hereafter paper I, Lopes et al. 2009a) we defined a cluster sample from the supplemental version of the Northern Sky Optical Cluster Survey (NoSOCS; Lopes 2003; Lopes et al. 2004). For that we used data from the 5th Sloan Digital Sky Survey (SDSS) release. This sample comprises 7,414 systems well sampled in SDSS DR5 (details in paper I). NoSOCS has its origin on the digitized version of the Second Palomar Observatory Sky Survey (POSS-II; DPOSS, Djorgovski et al. 2003). In Gal et al. (2004) and Odewahn et al. (2004) the photometric calibration and object classification for DPOSS, respectively, are described. The supplemental version of NoSOCS (Lopes et al. 2004) goes deeper (z \sim 0.5), but covers a smaller region than the main NoSOCS catalog (Gal et al. 2006; 2009).

For a subset of the 7,414 NoSOCS systems with SDSS data we extracted a subsample of low redshift galaxy clusters (z \leq 0.1). This subsample comprises 127 clusters, for which we had enough spectra in SDSS for spectroscopic redshift determination, as well as to select cluster members and perform a virial analysis, obtaining estimates of galaxy velocity dispersion, physical radius and mass (\sigma_v, R_{500}, M_{500}, M_{200}; details in paper I). This low-redshift sample was complemented with more massive systems from the Cluster Infall Regions in SDSS (CIRS) sample (Rines & Diaferio 2006, hereafter RD06). CIRS is a collection of z \leq 0.100 X-ray selected clusters overlapping the SDSS DR4 footprint. The same cluster parameters listed above were determined for these 56 CIRS clusters.

In the second paper of this series (hereafter paper II, Lopes et al. 2009b) we investigated the scaling relations of clusters using this combined sample of 183 clusters at z \leq 0.100, except for three systems that are not used for having biased values of \sigma_v and mass due to projection effects. These 3 clusters are Abell 1035B, Abell 1291A, and Abell 1291B. We plan to investigate the properties of these interacting clusters in detail in a future work. Details about this low-
redshift sample and the estimates obtained for the clusters can be found in papers I and II. For the clusters with at least five galaxy members within $R_{200}$ we also have a substructure estimate, based on the DS, or $\Delta$ test (Dressler & Shectman 1988). Details about this test can be found in paper I.

The redshift shift limit of the sample ($z = 0.100$) is due to incompleteness in the SDSS spectroscopic survey for higher redshifts, where galaxies fainter than $M^* + 1$ are missed, biasing the dynamical analysis (see discussion in section 4.3 of Lopes et al. 2009a). We eliminated interlopers using the “shifting gapper” technique (Fadda et al. 1996), applied to all galaxies with spectra available within a maximum aperture of 2.50 h$^{-1}$ Mpc. We also estimated X-ray luminosity ($L_X$, using ROSAT All Sky Survey data), optical luminosity ($L_{opt}$) and richness ($N_{gal}$, Lopes et al. 2009a). The centroid of each NoSOCS cluster is a luminosity weighted estimate, which correlates well with the X-ray peak (see Lopes et al. 2006).

In Ribeiro et al. (2013) (hereafter paper III) we investigated the connection between galaxy evolution and the dynamical state of galaxy clusters, indicated by their velocity distributions. Here we focus on the investigation of the variation of galaxy properties (and their relations), such as color, spectral class, stellar mass, and concentration, with the environment. Note that we only use galaxies that are selected as cluster members by the “shifting gapper” technique.

For the current work, we have also implemented one modification to the “shifting gapper” technique, regarding the radial offset between two consecutive galaxies. In previous papers of this series, if this quantity was greater than the radial offset between two consecutive galaxies. We proceeded as follows. For every galaxy member we compute its projected distance, $d_s$, to the 5th nearest galaxy found around it, within a maximum velocity offset of 1000 km s$^{-1}$ (relative to the velocity of the galaxy in question). The local density $\Sigma_5$ is simply given by $5/r_d\Sigma^2$, and is measured in units of galaxies/Mpc$^2$. Density estimates are also obtained relatively only to galaxies brighter than a fixed luminosity range, which we adopt as $M^* + 1.0$. On what regards the global environment we consider the distance to the center of the parent cluster and its mass (traced by the X-ray luminosity and velocity dispersion). We also inspect possible differences relative to the dynamical state of clusters, indicated by the substructure estimate.

2.1 Local Galaxy Density Estimates

When comparing literature results regarding the environmental dependence of galaxy properties one central issue is the definition of environment. That can be local (associated to the galaxy neighborhood) or global (related to the large scale structure). The galaxy environment measure is further complicated by different selection criteria, issues related to the survey geometry, as well as luminosity limits. Blanton & Berlind (2007) investigate the impact of group environment on different scales, concluding that not only the surrounding density matters. Wilman, Zibetti & Budavari (2010) present a multiscale model-independent approach to measure the galaxy density. Their method is used to investigate the variation of the galaxy $(u - r)$ color distribution (with $-21.5 \leq M_r \leq -20$) on multiscale density.

Muldrew et al. (2012) compare the results from twenty different published environment definitions. They classify the methods to measure environment in two groups, those based on nearest neighbours and those using fixed apertures. They conclude that the local environment is best probed by nearest neighbours methods, while the large-scale environment is best measured by apertures.

Considering the results from Muldrew et al. (2012) we decide to adopt a nearest neighbour method to estimate the local environment. The authors also mention that the choice of $n$ - the rank of the density-defining neighbour - is very important, as the environment measure may lose power in the case $n$ is larger than the number of galaxies residing in the halo. Hence, we chose to work with the $\Sigma_5$ local galaxy density estimator, as $n = 5$ is typically smaller than the number of galaxies we have per cluster and is a common estimate in the literature. To estimate local galaxy densities we proceed as follows. For every galaxy member we compute its projected distance, $d_s$, to the 5th nearest galaxy found around it, within a maximum velocity offset of 1000 km s$^{-1}$ (relative to the velocity of the galaxy in question). The local density $\Sigma_5$ is simply given by $5/r_d\Sigma^2$, and is measured in units of galaxies/Mpc$^2$. Density estimates are also obtained relatively only to galaxies brighter than a fixed luminosity range, which we adopt as $M^* + 1.0$. On what regards the global environment we consider the distance to the center of the parent cluster and its mass (traced by the X-ray luminosity and velocity dispersion). We also inspect possible differences relative to the dynamical state of clusters, indicated by the substructure estimate.

2.1.1 Correction for the fiber collision issue

The fiber collision issue affects the SDSS spectroscopic sample and the derived density estimates. Due to a mechanical restriction spectroscopic fibers cannot be placed closer than 55 arcsecs on the sky. An algorithm used for target selection randomly chooses which galaxy gets a fiber, in case of a conflict (Strauss et al. 2002). This problem is reduced by spectroscopic plate overlaps, but fiber collisions still lead to a ~ 6% incompleteness in the main galaxy sample. Our approach to fix this problem is similar to the one adopted by Berlind et al. (2006) and La Barbera et al. (2010). For galaxies brighter than $r = 18$ with no redshifts we assume the redshift of the nearest neighbour on the sky (generally the galaxy it collided with). This may result in some nearby galaxies to be placed at high redshift, artificially increasing their estimated luminosities. Due to that the collided galaxies also assume the magnitudes of their nearest neighbours, resulting in an unbiased luminosity distribution. Notice that the fraction of fixed galaxies is quite small (at most 6%, at highest densities); the above correction procedure has been shown to accurately match the multiplicity function of groups in mock catalogues (Berlind et al. 2006); and the velocity distribution (relative to group centre) of the original and fixed samples are consistent (La Barbera et al. 2010).
Hence, the local galaxy density estimates take in account
the fiber collision issue. For every galaxy we want to esti-
mate density, either group member or belonging to the field
(see next section) in the original spectroscopic sample, we
use the fixed sample to find \( d_5 \) and estimate \( \Sigma_5 \).

### 2.1.2 Field sample

Besides computing local galaxy densities to group/cluster
members we also do that for a galaxy field sample. This sam-
ple is constructed as follows. From the whole DR7 data set
we select galaxies that would not be associated to a group
or cluster, considering the cluster catalog from \( \text{Gal et al. (2009)} \). To be conservative, we consider a galaxy to belong
to the field if it is not found within 4.0 Mpc and not hav-
ing a redshift offset smaller than 0.06 of any cluster from
\( \text{Gal et al. (2009)} \). We select more than 60,000 field galaxies,
but work with a smaller subset (randomly chosen) for which
we derived local density estimates. In the end we use 2,986
field galaxies at \( z \leq 0.100 \) with \( M_r \leq M^* + 1 \), and 1,829 at
\( z \leq 0.045 \) with \( M^* + 1 < M_r \leq M^* + 3 \) (the same order of
cluster galaxies). For these objects we compute density
estimates in the same way as done for the cluster members.

### 2.2 Absolute Magnitudes and Colors

For the current work we consider the stacked properties of
cluster and field galaxies (in this case, regarding local density
only). We do that considering the radial offset (in units of
\( R_{200} \)), absolute magnitudes, colors and local densities of all
member galaxies coming from the 152 clusters (or the field).
Our sample consists of 5,106 bright member galaxies with
\( M_r \leq M^* + 1 \) (at \( z \leq 0.100 \) ), 1,309 faint members with
\( M^* + 1 < M_r \leq M^* + 3 \) (at \( z \leq 0.045 \) ), 2,986 bright field
galaxies \( (M_r \leq M^* + 1, z \leq 0.100) \) and 1,829 faint field
galaxies \( (M_r^* + 1 < M_r \leq M^* + 3, z \leq 0.045) \).

To compute the absolute magnitudes of each galaxy
(in ugr bands) we consider the following formula:
\( M_x = m_x - DM - kcorr - Qz \) \( (x \text{ is one of the four SDSS bands we}
considered, where DM is the distance modulus (considering the
redshift of each galaxy), \( kcorr \) is the \( k \)-correction and \( Qz \) \( (Q = -1.4) \)).
\( \text{Ye e & López-Cruz (1999)} \) is a mild evolution-
ary correction applied to the magnitudes (for each galaxy
redshift). The \( k \)-corrections are obtained directly from the
SDSS database, for every object in each band. Rest-frame
colors are also obtained for all objects.

### 2.3 Separation of Galaxy Populations

Galaxies can generally be separated in two groups according
to their structure and star formation activity. Early-type (E
and S0) galaxies are redder, have little star formation and
high concentration, while late-type galaxies are bluer, show
active star formation and are less concentrated. Here we use
three galaxy parameters to separate galaxies in two popu-
lations and investigate the variation of the fraction of each
population (specified by each of the three parameters) with
environment. We use the \( (u-r) \) color, the concentration
index \( C \) (defined as the ratio of the radii enclosing 90 per
cent and 50 per cent of the galaxy light in the r-band, \( R_{90}/R_{50} \))
and a spectral classification called \( c_{\text{class}} \) (which is based on
a PCA analysis of the SDSS spectrum database). We call
blue/red galaxies those with \( (u-r) \) values smaller/greater
than 2.2 \( \text{[Strateva et al. (2001)]} \). Galaxies are considered to
have low-concentration (and are called disc-dominated ob-
jects) if they have \( C < 2.6 \) (blue-dominated galaxies have
values greater than 2.6). The parameter \( c_{\text{class}} \) ranges from
about \(-0.35 \) to 0.5 for early- to late-type galaxies (or pas-
sive to star-forming), with the former having values typi-
cally below \(-0.05 \) (spectra with lower-temperature absorp-
tion features). Late-type objects have spectra with higher
temperature features or emission lines. Note that the sepa-
ration value for \( C \) is in agreement to what was adopted by
\( \text{Strateva et al. (2001)} \) and \( \text{Kauffmann et al. (2004)} \).

In Fig. 1 we show the correlation between \( (u-r) \) color
with \( c_{\text{class}} \) and \( C \) for bright galaxies \( (M_r \leq M^* + 1) \) in the
groups/clusters regions \( (i.e., \text{all galaxies, members and in-
terlopers}) \). The horizontal lines indicate the color separa-
tion, while the vertical lines indicate the median values (for
\( c_{\text{class}} \) and \( C \) ) of galaxies with \( (u-r) \sim 2.2 \). In the bottom
panel the dashed vertical line shows the actual value adopted
to split galaxies regarding concentration \( (C = 2.6) \). Fig. 2 is
analogous, but for faint galaxies \( (M_r^* + 1 < M_r \leq M^* + 3) \).
As we can see from these two figures, for the data used here,
\( C = 2.4 \) gives the median value of galaxies with \( (u-r) \sim 2.2 \).
We consider \( C = 2.6 \) for concordance with the literature (ac-
tually some authors even consider higher values of \( C \)). Note
also that we show only galaxies in cluster regions and not
from the whole sky; and concentration does not provide a
sharp cut as color or \( c_{\text{class}} \). Our choice \( C = 2.6 \) provides a
good compromise between completeness and concentration
of the two broad populations (early and late type galaxies).
A smaller value of \( C \) would increase the completeness
of early-type objects at the cost of a larger contamination
by late-types and vice-versa (see discussion in \( \text{Strateva et al.}
(2001)} \).

Note that this choice of \( C = 2.6 \) is good enough to
split galaxies in two broad populations (early and late type
galaxies), as is the goal of next section \( (\S 3) \). In \( \S 4 \) we investi-
gate the environmental dependence of the relations between
different galaxy properties. In that case, we analyze the re-
lations for different subsamples according to concentration.
There we decided to consider three ranges of concentration.
We call low concentration galaxies or \( \text{classical disc} \)s
objects with \( C \leq 2.4 \), while we consider \( \text{classical bulge} \)s
galaxies with \( C > 2.8 \). Objects with \( 2.4 < C \leq 2.8 \) are called
intermediate types. In that case we have purer samples of bulges and discs
(avoiding contamination from the other type) and consider
an intermediate population that can give clues to galaxy
transformation regarding environment and stellar mass.

In the next section we investigate the environmental
variation of the fractions of blue, high \( c_{\text{class}} \) (we call those
star-forming) and low concentration galaxies (we call those
disc-dominated), which we refer as \( F_B, F_L \) and \( F_D \), respec-
tively. Instead of separating galaxy populations using only
one parameter \( (e.g. \text{color}) \) we work with these three param-
eters as “red” does not necessarily imply “bulge” \( (\text{or high-
concentration}) \), due to differences in the relations between
color and morphology with density.
Figure 1. The correlation between \((u-r)\) color with the parameters \(e_{\text{class}}\) and \(C = R_{90}/R_{50}\) for bright galaxies \((M_r \leq M^* + 1)\) in group/clusters regions. The horizontal lines indicate the color separation, while the solid vertical lines indicate the median value of galaxies with \((u-r) \sim 2.2\). In the bottom panel the dashed vertical line shows the actual value adopted to split galaxies according to concentration \((C = 2.6)\).

Figure 2. The same as in the previous figure, but for faint galaxies \((M^* + 1 < M_r \leq M^* + 3)\). The horizontal and vertical lines are the same.

3 THE ENVIRONMENTAL VARIATION OF BLUE, HIGH \(E_{\text{CLASS}}\) AND LOW CONCENTRATION GALAXIES

In this section we investigate the variation of galaxy properties (given by fractions of populations) with the environment, characterized by the local galaxy density, normalized radial distance to the parent cluster, presence of substructure, as well as its X-ray luminosity and velocity dispersion. In §3.5 the environmental influence is also investigated in different ranges of galaxy stellar mass. When considering the local galaxy density we use cluster members and field galaxies. For the remaining tracers of environment we use only cluster members.

3.1 Dependence on Local Galaxy Density

In Fig. 3 we show how the fractions of blue \((F_B)\), high \(e_{\text{class}}\) (or star-forming, \(F_L\)), and low concentration (or disc-dominated, \(F_D\)) galaxies depend on local galaxy density \((\Sigma_5)\), for the bright regime \((M_r \leq M^* + 1)\). \(F_B\) is shown in the top panel, while \(F_L\) is in the middle panel and \(F_D\) in the bottom. Red open circles show cluster members, while blue filled circles indicate field galaxies. Fig. 4 is analogous, but showing faint galaxies \((M^* + 1 < M_r \leq M^* + 3)\).

From both figures we can see the results of the color- and morphology-density relations, with a small fraction of blue and late-type galaxies (characterized by \(e_{\text{class}}\) and \(C\)) in the most dense regions of the Universe. These fractions grow continuously to the lower density regime. However, the pace is reduced when we leave clusters and reach the field for bright galaxies, while for faint objects the fractions actually become approximately constant. For instance, for bright objects we have \(F_B \sim 5\%\) and \(\sim 27\%\) at the highest and lowest density bins, for cluster members, respectively. For field galaxies we go from \(F_B \sim 20\%\) to \(\sim 44\%\) from the highest to lowest density bins. For bright cluster members we still have \(F_L \sim 5\%\) and \(\sim 24\%\), and \(F_D \sim 20\%\) and \(\sim 40\%\), in the highest and lowest density bins, respectively. The equivalent fractions to field galaxies are \(F_L \sim 17\%\) and \(\sim 42\%\), and \(F_D \sim 33\%\) and \(\sim 53\%\). The fact that the variation with density still holds to the lowest density bins in the field, for bright galaxies, indicates that other factors not directly related to clusters may act to affect these galaxies (such as tidal effects from neighbour galaxies).

Note that in the transition between clusters and the field we might have some contamination on both sides; i.e., field galaxies that are erroneously classified as cluster members and possibly cluster galaxies that are wrongly called field objects (the former would belong to systems not listed in Gal et al. 2009). However, we do not expect these contaminations to be high as the “shifting gapper” technique (Fadda et al. 1996) was extensively tested elsewhere (with its member list being well compared to other methods; see Lopes et al. 2009a); and the cluster catalog of Gal et al. (2009) is complete for rich systems in the local Universe. So, the expected smooth transition from clusters to the field is not affected in our results.

For bright galaxies (Fig. 3) we can see that the highest density field galaxies show larger fractions \((F_B, F_L\) and \(F_D)\) than cluster galaxies at similar density, indicating that even the cluster low density environment plays a role on fur-
Figure 3. From top to bottom we show the variation of $F_B$, $F_L$ and $F_D$ with local galaxy density ($\Sigma_D$). Red open circles are for cluster members and blue filled circles for field galaxies. These results consider bright galaxies ($M_r \leq M^* + 1$).

Three other interesting features stand out in Fig. 3. First, there is nearly no environmental variation for faint field objects, except for the most dense bin. That indicates the factors acting on bright field galaxies are not equally effective for the faint objects. Second, the environmental variation is present in all bins for cluster members (red open circles); indicating the effectiveness of the cluster environment even in the outskirts. The third point is also seen in Fig. 4. $F_B$ and $F_L$ show very similar behavior to each other, while $F_D$ is generally higher, especially for cluster objects. That goes in line with other results in the literature suggesting that color and star-formation are affected much faster than structural parameters (Homeier et al. 2006; Goto et al. 2003; Bamford et al. 2009; Skibba et al. 2009; Bundy et al. 2010).

3.2 Dependence on Cluster Radius

Figures 4 and 5 are analogous to the ones shown in the section above, but now exhibiting the variations of $F_B$, $F_L$ and $F_D$ with the normalized distance to the parent cluster ($R/R_{200}$). The results are only shown to cluster members. Fig. 4 is for bright and Fig. 5 is for faint galaxies.

The color-morphology-radius imprint is clearly seen in both figures. Differently than what is seen for cluster galaxies as a function of $\Sigma_D$ (red open circles) the values of $F_B$, $F_L$ and $F_D$ stop growing (or grow much slower) after a given radius ($\sim R_{200}$). It is also possible to devise another abrupt change at another radius ($\sim 0.3 \times R_{200}$). From $\sim R_{200}$ to the central part of clusters the decline in $F_B$, $F_L$ and $F_D$ becomes steeper within $\sim 0.3 \times R_{200}$ (in agreement with Goto et al. 2003). For bright galaxies, in the most central bin we have almost no blue and high $e_{class} (\lesssim 2\%)$ galaxies, but the fraction of low $C$ objects is $\sim 17\%$. $F_B$ and $F_L$ grow to $\lesssim 16\%$ to roughly the virial radius (approximated by $R_{200}$). Outside the virial radius they grow to $\sim 20\%$, remaining nearly constant after that. $F_D$ grows to $\sim 30\%$ at $\lesssim R_{200}$, being $\lesssim 36\%$ for larger radii. In other words, the population of bright galaxies do not change significantly for objects falling into a cluster until they are within its virial radius. Within the cluster the population changes faster when in the core ($\sim 0.3 \times R_{200}$). That indicates the tidal effects (due to the cluster potential) and the interaction to the ICM (denser within $R_{200}$) are very effective on transforming the galaxy populations, which would also lead to the so called anemic spirals (van den Bergh 1979).

A similar trend is seen for faint galaxies, but different regimes may take place. From large to small radius it seems that $F_B$, $F_L$ and $F_D$ are roughly constant until $\sim 1.8 \times R_{200}$ ($\sim 70\%$ for $F_B$), falling to a lower plateau between $\sim 1.8 \times R_{200}$ and $\sim R_{200}$ ($\sim 55\%$ for $F_B$) and showing a steep decline until $\sim 0.4 \times R_{200}$ ($F_B$ decreases to $\sim 22\%$). In the very central region (within $\sim 0.4 \times R_{200}$) there is a slight rise in the values of $F_B$, $F_L$ and $F_D$ be-
before reaching the minimum value in the most central bin. If that rise in the central part is real it is probably associated to the formation of small galaxies in the core of clusters, from tidal debris or due to ram pressure stripping of larger galaxies (Mastropietro et al. 2005; Ribeiro et al. 2013). The variation in the four regimes mentioned above for $F_B$, $F_L$, and $F_D$ is similar to $F_B$, being slightly noisier for $F_D$.

Against local density $F_B$, $F_L$ have a minimum at $\sim 5\%$ and $\sim 20\%$ for bright and faint objects, respectively (the corresponding values are $\sim 20\%$ and $\sim 40\%$ for $F_D$). Regarding the physical radius the minimum values of $F_B$, $F_L$ are $\sim 2\%$ and $\sim 14\%$ for bright and faint objects, respectively (for $F_D$ those values are $\sim 17\%$ and $\sim 29\%$). Within $R \sim R_{200}$, for faint objects, and at all radius for bright galaxies, it can also be seen that $F_D$ is generally higher than $F_B$ and $F_L$, indicating that infalling galaxies have their color and spectral properties transformed quicker than their structure, corroborating the results from previous section.

One final result regarding radius deserves our attention. As seen in (Bahé et al. 2013), the variation of galaxy types reach far distances from the cluster centers. Here we show this variation to be real, for bright and faint galaxies, up to $\gtrsim 3 \times R_{200}$, suggesting that pre-processing by groups, overshooting and possibly ram pressure in the outskirts of those systems act to transform the galaxy population.

### 3.3 Dependence on Cluster Substructure

In Figures 7 and 8 we show the variations of $F_B$, $F_L$ and $F_D$ as a function of $\Sigma_5$ and $R/R_{200}$, as in the figures above. However, here we show the results for bright member galaxies coming from clusters with the presence or not of substructure (blue filled and red open circles, respectively). Substructure is estimated using the $\Delta$ (or Dressler and Schectman) test (details in paper I). It seems that in the most dense regions and within the virial radius there is no significant difference in the values of $F_B$ and $F_L$, but there might be more low concentration ($F_D$) galaxies in systems with substructure. For instance, at $R \sim 0.35 \times R_{200}$ $F_D \sim 29\%$ and $\sim 20\%$ for systems with and without substructure, respectively. For lower density regions and outside $R_{200}$ we have slightly higher fractions ($F_B$, $F_L$ and $F_D$) for clusters with substructure. These results agree to the findings of paper III, for which the systems are classified as Gaussian and non-Gaussian.

### 3.4 Dependence on Cluster Mass

In this section we investigate the possible dependence of the galaxy population on the parent cluster mass, which we indicate by X-ray Luminosity and velocity dispersion. On what follows we show the results obtained for systems at low and high mass ranges. In Figures 9 and 10 we show the variations of $F_B$, $F_L$ and $F_D$ as a function of $\Sigma_5$ and $R/R_{200}$. However, here we show the results for bright galaxies coming from clusters with low ($L_X < 0.3 \times 10^{44}$ ergs$^{-1}$) or high ($L_X \geq 1.0 \times 10^{44}$ ergs$^{-1}$) X-ray luminosity (used as a mass indicator), blue filled and red open circles, respectively. From these plots we do not find any significant difference between the results for low or high $L_X$ systems. The exception is $F_D$ showing different results (although the results are noisier than for $F_B$ and $F_L$), but only in the central (within $R_{200}$) and most dense bins (especially the most central and dense). For instance, at $R \sim 0.1 \times R_{200}$ $F_D \sim 23\%$ and $\sim 13\%$ for systems with low and high X-ray luminosity, respectively. At $R \sim 0.7 \times R_{200}$ we find $F_D \sim 34\%$ and $\sim 28\%$, for low and high $L_X$. 

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**Figure 5.** From top to bottom we show the variation of $F_B$, $F_L$ and $F_D$ with normalized distance to the cluster center ($R/R_{200}$). Only cluster members are shown. These results consider bright galaxies ($M_e \leq M^* + 1$).

**Figure 6.** Same as previous figure, but showing the variations for faint galaxies ($M^* + 1 < M_e \leq M^* + 3$).
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Figure 7. Same as in Fig. 3, but splitting the sample in galaxies from clusters with or without substructure.

Figure 8. Same as previous figure, but showing the variations with normalized distance to the cluster center ($R/R_{200}$).

Namely groups with velocity dispersion smaller than 400 km s$^{-1}$ (blue filled circles) and clusters with $\sigma_{cl} > 650$ km s$^{-1}$ (red open circles). According to this separation there are 84 low mass and 16 high mass systems from the original 152 in our sample. There is roughly the same number of galaxies in the two samples, namely 1,685 galaxies in the groups and 1,497 in the high mass clusters. The median value for $R_{200}$ of the groups is 0.99 Mpc, with a minimum of 0.51 Mpc and maximum value of 1.46 Mpc. The median mass is $1.19 \times 10^{14} M_{\odot}$, with minimum and maximum values of 0.16 and $3.84 \times 10^{14} M_{\odot}$, respectively. For the high mass sample the median, minimum and maximum values of $R_{200}$ are 2.00, 1.76 and 2.39 Mpc, respectively. In terms of mass the corresponding values are 9.82, 6.68 and $16.93 \times 10^{14} M_{\odot}$.

There is no large difference in the results for low and high mass systems, except for $F_D$ in the two most central bins and $F_L$ in the central bin. At $R \lesssim 0.3 \times R_{200}$ $F_D \sim 19\%$ for low mass systems and $\sim 12\%$ for high mass objects. Hence, we find no large differences regarding mass (using $L_X$ and $\sigma_{cl}$), except for $F_D$ and $F_L$ in the very central parts.

3.5 Dependence on Galaxy Stellar Mass

It is well known that galaxy stellar mass and environment are related, with massive galaxies preferentially residing in the densest regions of the Universe. Many galaxy properties also shown a correlation with stellar mass (Kauffmann et al. 2004), so that it is important to try disentangling the connection between galaxy properties to environment and stellar mass. In order to do that we investigate in this section the environmental dependence of the galaxy population at fixed stellar mass. To obtain galaxy stellar mass estimates we used the stellar population synthesis code STARLIGHT.
NoSOCS in SDSS. IV

This code fits an observed spectrum with a linear combination of a number of template spectra with known properties (see paper III for details). As shown in §4 most bright galaxies are massive, while most faint objects have small masses (the overlap for our sample occurs around $0.5 \times 10^{10} M_\odot$). Hence, the results shown next consider both bright and faint galaxies, with a combined sample having $M_r \leq M^* + 3$.

In Figures 12 and 13 we show the variations of $F_B$, $F_L$ and $F_D$ as a function of $\Sigma_3$ and $R/R_{200}$. However, the results are now displayed for four different stellar mass ranges: $M_\star \leq 0.3 \times 10^{10} M_\odot$ (circles), $0.3 < M_\star \leq 1.5 \times 10^{10} M_\odot$ (squares), $1.5 < M_\star \leq 3.0 \times 10^{10} M_\odot$ (triangles) and $M_\star > 3.0 \times 10^{10} M_\odot$ (hexagons). Cluster members are shown in red (filled symbols), while field galaxies are in blue (open symbols).

As expected, the largest fractions of blue, star-forming and discs are seen for the lower mass galaxies (the first two mass bins, $M_\star \leq 1.5 \times 10^{10} M_\odot$). The environmental variation for these objects is negligible for lower density regions, becoming relevant for galaxy populations (for these low mass objects) becomes stronger (in agreement with Presotto et al. 2012). However, the environmental dependence is steeper in terms of $F_B$ and $F_L$, being weaker (flatter) for $F_D$. On the contrary, the most massive galaxies have small values of $F_B$, $F_L$ and $F_D$ and also smaller variation with density and cluster radius. These results corroborate the idea that star formation is halted first in higher mass galaxies and that their environmental variation is small when compared to low mass galaxies. That is probably due to a combination of intrinsic galaxy evolution and the longer time these massive systems spend inside clusters.

4 RELATIONS OF PHYSICAL PROPERTIES OF GALAXIES AND THEIR ENVIRONMENTAL VARIATION

There are well known relations between different photometric and spectral parameters of galaxies, which can be used to understand their formation and evolution. So, as important as to see how those different parameters change with environment it is to investigate the environmental dependence of these relations. That is the goal of the current section, where we investigate relations involving spectral type, color, stellar mass and size, for subsamples obtained relative to concentration, density, cluster radial distance and mass.

In Fig. 14 we show the connection between the spectral type ($e_{\text{class}}$) and stellar mass in five local galaxy density bins and for different ranges of concentration. Density increases left-right and concentration from bottom-top. The $\Sigma_3$ bie-weight estimate of galaxies in each column is indicated in the top panels, ranging from $\Sigma_3 = 0.8$ to $\Sigma_3 = 20.1$ galaxies Mpc$^{-2}$. In the lower panels we show low concentration galaxies ($C \leq 2.4$), while intermediate types ($2.4 < C \leq 2.8$) are displayed in the middle panels and bulges ($C > 2.8$) are shown in the top panels. Red small points indicate bright galaxies ($M_r \leq M^* + 1$) and blue large crosses are for faint objects ($M^* + 1 < M_r \leq M^* + 3$). The results consider only group members. In §2.3 we call low concentration galaxies...
(C ≤ 2.4) as classical discs and the high concentration objects as classical bulges. From now on, for simplicity, we are calling these two populations just as discs and bulges, respectively.

From Fig. 14 we can see that bulge-dominated objects (C > 2.8) are mostly passive objects (e_class < −0.05). The exception is for a few star-forming galaxies found mainly in the lowest density bin. Those objects are mainly faint and with a small stellar mass content. However, a few bright star-forming objects (red points) are also found at higher local densities. For disc-dominated objects (C ≤ 2.4) most points are consistent with star-forming low mass galaxies (e_class > −0.05). We can also see that as density increases the median stellar mass too. The most dramatic environmental variation is seen for intermediate type galaxies, which become more massive and, most important, passive as we go from the left to right panels.

Investigating field galaxies (figure 15) we first notice the five density ranges are much different, ranging from \( \Sigma_5 = 0.03 \) to \( \Sigma_5 = 2.5 \) galaxies Mpc\(^{-2} \). Hence, the highest density bin is comparable to the second poorest for clusters (typical of their outskirts). Nonetheless, we can see the behavior for galaxies at similar densities (in groups or field, in figures 14 and 15) show similar relations. For field galaxies we notice that star-forming objects are dominant even for intermediate types (2.4 < C ≤ 2.8) and there is a steeper variation of e_class as a function of M* for intermediate types in the three lowest density bins.

Figure 14 is similar to the previous two, but we show the relation between the rest-frame color \((g − r)_0\) (a rough star formation indicator) and stellar mass in five local galaxy density bins and for different ranges of concentration. As before, density increases from left to right. Differently from previous two figures we only display the binned results (considering stellar mass) on each panel. We use different symbols for the three ranges of concentration. Blue triangles are for low concentration galaxies (C ≤ 2.4), red squares represent intermediate types (2.4 < C ≤ 2.8) and dark circles display bulges (C > 2.8). In the top panels we have the results for group members and in the bottom for field galaxies. The most striking variations are seen for intermediate concentration objects (2.4 < C ≤ 2.8), both for field and group galaxies. As density increases (left to right panels) these objects (shown by red squares) become progressively more massive and most important red. We can see the low mass intermediate type galaxies assume redder colors as density increases. That is true even for the field galaxies, which are restricted to lower density environments. We can see a similar behavior for low mass discs (blue triangles, C ≤ 2.4), but the effect is not as strong as for the red squares, especially for field galaxies. Bulges (dark circles, C > 2.8) are mostly massive and red objects. For groups that is true for all environments, even in the outskirts (low densities), while we see the lower mass field bulges are bluer in the low density environments (first three density bins).

We also investigate how the rest-frame color \((g − r)_0\) correlates with galaxy size (indicated by the petrosian radius in the r-band). That is shown for group members in Fig. 16 in the same five density bins and for the three concentration.
Figure 14. Relation between $e_{\text{class}}$ and stellar mass in five local galaxy density bins and for different ranges of concentration. Density increases from left to right and concentration from bottom to top panels. The $\Sigma_5$ bi-weight estimate of galaxies in each column is indicated in the top panels, ranging from $\Sigma_5 = 0.8$ to $\Sigma_5 = 20.1$ galaxies Mpc$^{-2}$. The lower panels have low concentration galaxies ($C \leq 2.4$), the middle panels have intermediate types ($2.4 < C \leq 2.8$), while the top panels display bulges, with $C > 2.8$. Red small points indicate bright galaxies ($M_r \leq M^* + 1$) and blue large crosses are for faint objects ($M^* + 1 < M_r \leq M^* + 3$). The results consider only group members.

From the group members, as we go bottom-up and left-right we can see galaxies forming a tight relation in the color-size space, with large and more concentrated galaxies becoming redder (see Cypriano et al. 2006). In other words, as galaxies get to denser environments and grow in size, their star formation decreases. Besides that we see that the fraction of blue galaxies is also larger for the middle and bottom panels. If we consider $(g-r)_0 = 0.75$ as a typical color for red galaxies (Lopes 2007; Fukugita, Shimasaku, & Ichikawa 1995) and call blue galaxies with $(g-r)_0 \leq 0.65$ (typical color minus 0.10) we see there is only a small number of blue
objects that are also bulges in the three most dense bins (upper right panels). In all the other panels the number of blue objects increases, even for bulges in the two lowest density bins (upper left panels). With a few exceptions, objects with $R_{petr} \gtrsim 20$ kpc are only seen in the two most dense bins, for intermediate types and bulges. An interest exception is a large disc ($R_{petr} \gtrsim 40$ kpc) seen in the lower right panel.

Considering the field galaxies (Fig. 15) we see the color-radius sequence is starting to form for bulges in high densities (upper right), but still with many blue galaxies and with a small proportion of large objects ($R_{petr} \gtrsim 20$ kpc). In all the remaining panels we see a large fraction of blue galaxies and nearly no galaxies with $R_{petr} \gtrsim 20$ kpc.

Fig. 15 is similar to the ones right above, but now we separate galaxies according to the distance to the center of their parent group. We show the relation between $(g - r)_0$ and $M_*$, also split according to $C$ and for bright (red) and faint (blue) objects. The red sequence is easily seen for bulges (upper panels) and it may be seen for intermediate types in the central parts of groups (middle right panels). It is interesting to see that for bulges in the outskirts (upper left) the red sequence has a much larger scatter and there

Figure 15. Same as previous figure, but showing the results for field galaxies.
is a non-negligible fraction of blue bulges. In the outskirts the discs (lower left) are mainly blue. In general, the results of this figure corroborate what was seen in Fig. 16 splitting galaxies according to local density.

4.1 Possible Variation With Cluster Mass

Besides the dependence on environment traced by local galaxy density or radial distance (to the parent cluster) we have also investigated if the relations between physical properties of galaxies depend on the parent cluster mass, traced by velocity dispersion ($\sigma_{cl}$). Fig. 20 is similar to Fig. 16 but now galaxies are separated accordingly to the velocity disp-

**Figure 16.** Relation between rest-frame color ($g - r)_0$ and stellar mass in five local galaxy density bins and for different ranges of concentration. Density increases from left to right. Differently from previous two figures we only display the binned results (considering stellar mass) on each panel. Low concentration galaxies ($C \leq 2.4$) are displayed as blue triangles, intermediate types ($2.4 < C \leq 2.8$) as red squares and bulges ($C > 2.8$) as dark circles. The top panels show the results for group members and the bottom panels are for field galaxies.
Figure 17. Relation between rest-frame color \((g - r)_0\) and petrosian radius in five local galaxy density bins and for different ranges of concentration. Density increases from left to right and concentration from bottom to top panels. The \(\Sigma_5\) bi-weight estimate of galaxies in each column is indicated in the top panels, ranging from \(\Sigma_5 = 0.8\) to \(\Sigma_5 = 20.1\) galaxies Mpc\(^{-2}\). The lower panels have low concentration galaxies (\(C \leq 2.4\)), the middle panels have intermediate types (\(2.4 < C \leq 2.8\)), while the top panels display bulges, with \(C > 2.8\). Red small points indicate bright galaxies (\(M_r \leq M^* + 1\)) and blue large crosses are for faint objects (\(M^* + 1 < M_r \leq M^* + 3\)). The results consider only group members.

Perspersion of the parent group/cluster. We consider five bins of \((\sigma_{cl})\). The \(\sigma_{cl}\) bi-weight estimate in each column is indicated in the top panels, ranging from \(\sigma_{cl} = 239\) to \(\sigma_{cl} = 656\) km s\(^{-1}\). The lower panels have low concentration galaxies (\(C \leq 2.4\)), the middle panels have intermediate types (\(2.4 < C \leq 2.8\)), while the top panels display bulges, with \(C > 2.8\). As before, red small points indicate bright galaxies (\(M_r \leq M^* + 1\)) and blue large crosses are for faint objects (\(M^* + 1 < M_r \leq M^* + 3\)). The results consider only group members. From this figure, the main difference regarding \(\sigma_{cl}\) may only be the scatter of the red sequence, which might be smaller for higher mass clusters. More massive clusters may also have more faint low mass bulges (blue crosses), as seen in the upper panels. Considering galaxies to first be
pre-processed in groups, their star formation and color transformation may be further reduced when their parent groups are accreted into larger clusters. Those results would contradict the ones from Valentinuzzi et al. (2011). They find no dependence of several different properties of the cluster RS (including the scatter) with parent halo mass. However, the comparison is not straightforward as their sample is restricted to clusters with $\sigma_p > 500 \text{ km s}^{-1}$ and for galaxies within $0.5 \times R_{200}$.

From this plot we conclude that there is no large difference (expect for the scatter in the red sequence and large number of low mass bulges) in the relations of galaxy properties for groups and massive clusters, corroborating the idea that galaxies are pre-processed in groups before those are assembled in larger systems. But no large modification occurs after that, except for the tightening of the relations involving luminosity (color-magnitude, for instance). That may be due to a gradual decrease in the star formation rate of galaxies as they reside in larger structures.

Figure 18. Same as previous figure, but showing the results for field galaxies.
**Figure 19.** Relation between $(g - r)_0$ and stellar mass in five bins of radial separation from the cluster center (in units of $R_{200}$) and for different ranges of concentration. Radial separation decreases from left to right and concentration increases from bottom to top panels. The radial offset bi-weight estimate of galaxies in each column is indicated in the top panels, ranging from $R = 2.1R_{200}$ to $R = 0.2R_{200}$. The lower panels have low concentration galaxies ($C \leq 2.4$), the middle panels have intermediate types ($2.4 < C \leq 2.8$), while the top panels display bulges, with $C > 2.8$. Red small points indicate bright galaxies ($M_r \leq M^* + 1$) and blue large crosses are for faint objects ($M^* + 1 < M_r \leq M^* + 3$). The results consider only group members.

## 5 SUMMARY & DISCUSSION

In this work we investigate the impact of environment on the abundance of galaxy populations and on the relations of their physical properties (such as color, stellar mass, size and spectral classification). Our sample consists of 6,415 cluster members split in two luminosity and redshift ranges, being 5,106 bright galaxies ($M_r \leq M^* + 1$; at $z \leq 0.100$) and 1,309 faint galaxies ($M^* + 1 < M_r \leq M^* + 3$; at $z \leq 0.045$). These galaxies are selected from a total of 152 clusters in the local Universe with velocity dispersion in the range $150 \lesssim \sigma_P \lesssim 950$ km s$^{-1}$ (in terms of mass being $10^{13} \lesssim M_{200} \lesssim 10^{15} M_\odot$). The local environment is traced by $\Sigma_5$ (a nearest neighbour method), while the global envi-
Figure 20. Relation between \((g-r)_0\) and stellar mass in five bins of cluster velocity dispersion (in units of km s\(^{-1}\)) and for different ranges of concentration. Velocity dispersion \((\sigma_{cl})\) increases from left to right and concentration from bottom to top panels. The \(\sigma_{cl}\) bi-weight estimate in each column is indicated in the top panels, ranging from \(\sigma_{cl} = 239\) to \(\sigma_{cl} = 656\) km s\(^{-1}\). The lower panels have low concentration galaxies \((C \leq 2.4)\), the middle panels have intermediate types \((2.4 < C \leq 2.8)\), while the top panels display bulges, with \(C > 2.8\). Red small points indicate bright galaxies \((M_r \leq M^* + 1)\) and blue large crosses are for faint objects \((M^* + 1 < M_r \leq M^* + 3)\). The results consider only group members.

The environment is related to cluster parameters, such as distance to the cluster center, substructure, X-ray luminosity and velocity dispersion. The analysis regarding the local environment also shows density estimates \((\Sigma_5)\) of field galaxies. Besides the influence of the environment we investigated the dependence of galaxy populations relative to galaxy stellar mass. Our main results are:

(i) The fractions of blue \((F_B)\), high \(e_{\text{class}}\) (or star-forming, \(F_L\)), and low concentration (or disc-dominated, \(F_D\)) galaxies show a strong variation with local galaxy density, from cluster cores to the field. For bright cluster members \(F_B\) ranges from \(\sim 5\%\) to \(\sim 27\%\), while for field galaxies the variation is from \(\sim 20\%\) to \(\sim 44\%). The results are similar for \(F_L\), but the typical values are higher for \(F_D\) (ranges...
from $\sim 20\%$ to $\sim 40\%$ for bright member galaxies and from $\sim 33\%$ to $\sim 53\%$ for field galaxies). There is a smooth transition between cluster and field galaxies, and at similar densities the fractions are higher for field galaxies.

(ii) For faint objects there is a strong variation with density in $F_B$, $F_L$ and $F_D$ for cluster members. However, for field galaxies these fractions are nearly constant. $F_B$ and $F_L$ range from $\gtrsim 20\%$ to $\lesssim 70\%$ for cluster members, increasing at most to $80\%$ for field objects. $F_D$ changes from $\sim 40\%$ to $\lesssim 70\%$ for cluster members, being that the field value. Note that for all the parameters there is a minimum fraction ($\sim 20\%$ for $F_B$ and $F_L$ and $\sim 40\%$ for $F_D$) in the most dense regions, indicating that the formation of dwarfs in the central parts of clusters might be effective.

(iii) For bright and faint galaxies $F_B$ and $F_L$ are similar and generally lower than $F_D$, especially for cluster objects. That corroborate other results in the literature indicating that color and star-formation are affected faster than structural properties (e.g., Homeier et al. 2006; Bundy et al. 2010).

(iv) Considering the distance to the cluster center, for bright galaxies, the populations do not change significantly until they fall within the virial radius. Another abrupt variation seems to happen at $0.3 \times R_{200}$ (in agreement with Goto et al. 2003). Within that radius the values of $F_B$, $F_L$, and $F_D$ decrease faster. We also find the clusters’ cores to be nearly devoided of bright, blue and star-forming objects ($F_B = F_L \lesssim 2\%$).

(v) For faint objects a similar behavior is seen, but with different regimes. From large to small radius $F_B$, $F_L$, and $F_D$ are approximately constant until $\sim 1.8 \times R_{200}$, then decreasing, but remaining roughly constant between $\sim 1.8 \times R_{200}$ and $\sim R_{200}$. Then there is a steep decline until $0.4 \times R_{200}$. Within that radius there is a slight rise in the values of $F_B$, $F_L$, and $F_D$ before reaching the minimum value in the most central bin. That rise might be associated to the formation of small galaxies in the core of clusters, from tidal debris or due to ram pressure stripping of larger galaxies (Mastropietro et al. 2003; Ribeiro et al. 2014).

(vi) As a function of radius $F_D$ is also generally higher than $F_B$ and $F_L$, corroborating the slower change in structural parameters. We also show that the dependence with radius goes to large radius ($\gtrsim 3 \times R_{200}$), although the variation is much stronger within the virial radius. That agrees with Bahé et al. (2013), suggesting that some processes like overshooting and ram pressure may be relevant in the outskirts.

(vii) Separating the clusters according to the presence of substructure we find that within the virial radius $F_B$ seems to be higher for systems with substructure. Outside $R_{200}$ and for lower density regions there are slightly higher fractions for objects with substructure.

(viii) Investigating the dependence to cluster mass, traced by $L_X$ or velocity dispersion we find no significant difference between the results for groups and massive clusters. The exceptions are $F_D$ and $F_L$ in the most central bins, which agrees with other results in the literature (e.g., Calvi et al. 2012).

(ix) Regarding galaxy stellar mass we find the largest fractions of blue, star-forming and discs are seen for the lower mass galaxies. The environmental variation for these objects is negligible for lower density regions, becoming relevant once galaxies reach regions typical of cluster outskirts, increasing further to higher densities. The variation of $F_D$ is not as steep as for $F_B$ and $F_L$.

(x) On the other hand, the most massive galaxies have small values of $F_B$, $F_L$ and $F_D$ and also smaller variation with density and cluster radius. These results corroborate the idea that star formation is halted first in higher mass galaxies and that their environmental variation is small when compared to low mass galaxies. That is probably due to a combination of intrinsic galaxy evolution and the longer time these massive systems spend inside clusters.

(xi) The relation between $c_{\text{class}}$ and stellar mass shows a tight connection for bulges, both at low and high densities. For discs the relation may be forming at high densities for cluster members. However, the most dramatic environmental variation is seen for intermediate type galaxies. They become more massive and, most important, passive as density increases. We also find that for the most dense regions (either in clusters or field) there is a non-negligible population of bulges that are classified as star-forming (those are mainly faint and low-mass galaxies). For field objects the fractions of star-forming are higher and the connection between $c_{\text{class}}$ and $M_*$ is steeper than for cluster galaxies.

(xii) The connection between rest-frame color $(g-r)_0$ and stellar mass also indicates the largest environmental variation is seen for intermediate type objects ($2.4 < C \leq 2.8$) when compared to classical discs $(C \leq 2.4)$ and bulges $(C > 2.8)$. Galaxies called intermediate type progressively become more massive and especially redder as density increases. That is true even for the field galaxies (restricted to lower density environments).

(xiii) The color-size relation also shows a tight connection as concentration and density increases. However, large galaxies ($R_{\text{petr}} \gtrsim 20$ kpc) are generally seen for intermediate types and cluster bulges in the two highest density bins. The fraction of blue galaxies is also larger for systems in low-density regions or discs in high densities (both for field and cluster galaxies).

(xiv) Separating the color-mass (galaxy stellar mass) relation according to the mass of the parent system we find no significant difference between the results for group or high mass cluster galaxies. The only exception being the scatter of the color-mass relation and an excess of low mass bulges in massive clusters. Those results also indicate that pre-processing in groups should be very effective.

A controversial issue in the literature regards the variation of galaxy populations with parent halo mass (see De Lucia et al. 2013; Valentini et al. 2011; Calvi et al. 2012; Hoyle et al. 2012). Although some works find no variation with halo mass, others indicate a significant dependence. Part of this discrepancy may be due to different mass and radial ranges sampled by each study. In the current work we have objects from small groups to large clusters ($10^{13} \lesssim M_{200} \lesssim 10^{15} M_\odot$), and spanning radial distances up to $\gtrsim 3 \times R_{200}$. We find that only in the very central parts there is a small difference in $F_B$ and $F_L$ for low and high mass clusters. That agrees with Calvi et al. (2012), but slightly disagrees with Valentini et al. (2011) and Hoyle et al. (2012) (although they find a small dependence of the spiral fraction on halo mass). For the first case the mass range sampled is very different (Valentini et al. 2011 only have large clusters), while in the second the mor-
phological indicator (as well as the member selection) used is different than ours. However, all these results reinforce the idea that galaxy transformation happens predominantly on group scales, with large clusters being the result of an hierarchical aggregation of smaller systems (with no significant further morphological transformation, [Hoyle et al. 2013]).

The results from [Lackner & Gunn 2013] are complementary to this idea, indicating that star formation is quenched in the group scale, but morphological transformation is a separate process, occurring in clusters. In other words, environmental galaxy transformations can be divided in two steps. First, star formation is halted in discs residing in relatively low density environments. Second, a morphological transformation from disc to bulge dominated systems occur at higher densities. The authors consider groups as low density and high mass clusters as high density environments. But groups can be as dense as clusters (especially compact groups, CG). For instance, [Coenda, Muriel & Martínez 2012] consider that pre-processing is even more effective in compact groups compared to loose groups (LG). That could be due to the high densities and low velocity dispersion typical of CGs. Note that [Lackner & Gunn 2013] are interested on classical bulge plus disc galaxies (sample with 12500 objects).

Our results add to the above conclusions, as we find no significant differences between the values of $F_B$, $F_L$ and $F_D$ for groups and clusters (except for $F_D$ in the most central regions). We also find that $F_D$ is larger than $F_B$ and $F_L$ for bright and faint galaxies. Hence, in agreement to [Valentinuzzi et al. 2011], our results point to a scenario on which local density is the main driver for galaxy evolution and not the parent halo mass. This evolution happens as pre-processing in the group scale with star formation quenching and, to a lesser extent, morphological transformation. However, the second effect takes longer for being effective ($F_D > F_B, F_L$) and shows a small segregation between groups and clusters in their central regions (most dense in the Universe); as $F_D$ is slightly higher for groups than for high mass clusters. That can be seen from Figures 6, 8 and 11 (so, both as a function of density and radius). What we see in the current work does not contradict [Lackner & Gunn 2013] or [Valentinuzzi et al. 2011]. The former consider a sample of classical bulge plus disc galaxies only, while we have galaxies of all morphologies. [Valentinuzzi et al. 2011] work with high mass clusters, consider the most central region ($0.5 \times R_{200}$) only and are restricted to red sequence galaxies, while we consider a broader mass range and a larger region around clusters.

The pre-processing in groups can be explained by different mechanisms, such as mergers, strangulation and ram pressure, that can accelerate star formation, remove the gas reservoir and destroy galactic discs [Kauffmann et al. 2004]. Internal processes associated to the stellar mass are also relevant to halt star formation. Within larger systems galaxy mergers are less probable, but galaxies may still be transformed due to the cumulative effects of successive weak encounters, tidal stripping by the cluster gravitational potential and interaction with the denser ICM.

The smooth transition between cluster and field, seen in Figures 3 and 1 indicate that although cluster edges are hard to define, density is indeed a key parameter for galaxy transformation. For bright galaxies (Figure 3) the larger fractions for the highest density bin of field galaxies (compared to cluster galaxies at similar densities) indicate the significance of cluster environment related effects even in their outskirts [Bahe et al. 2013]. For bright field galaxies density is a key parameter for their evolution (although we cannot discard or distinguish internal feedback process).

That is not true for faint field objects (Figure 4), as low luminosity field galaxies are almost independent of environment. For cluster members the dependence on local density is very strong, both for bright and faint galaxies. Considering galaxy stellar mass (Figures 12 and 13) we find the largest fractions of blue, star-forming and discs for lower mass galaxies. Environment is not relevant for these objects until they are in regions with local density typical of cluster outskirts. The environmental influence becomes stronger for higher densities for these low mass galaxies. On the contrary, the most massive galaxies show small values of $F_B$, $F_L$ and $F_D$, as well as a smaller variation with density and cluster radius.

Comparing Figures 3 and 5 we see that bright cluster galaxies outside $R_{200}$ have local densities of about 2 galaxies Mpc$^{-2}$. In other words, outside the virial radius the local density drops very fast, which explains in part the strong transition we see once galaxies are within this radius. Within the virial radius another transition is seen in the inner parts, indicating that cluster related processes (tidal effects and ram pressure) further influence the galaxy populations. For faint galaxies, another characteristic region is still seen at $> 1.8 \times R_{200}$. Using detailed simulations [Bahe et al. 2013] could investigate which processes are most common at these regions. They found that at $\sim 2 \sim 3 \times R_{200}$ overshooting and pre-processing by groups explain the cold gas and star formation radial trends. But to larger radius (reaching $5 \times R_{200}$) those two process can not fully explain the hot gas radial trends, so that ram pressure is also relevant. Their results indicate that at large radius the ram pressure due to the ICM can strip the hot gas haloes both for low and high mass galaxies. The cold gas can be stripped only within $\sim R_{200}$.

[Kauffmann et al. 2004] show that even in low density regions the division of galaxy populations in two broad families is valid. We corroborate these results here, inspecting galaxies at different densities, but we also split them in cluster members and field galaxies. Even for the latter this division is still valid. When moving to higher densities we can see the red, early-type sequence is well established with a few transition galaxies still being noticed, such as bulges classified as star-forming (or blue). That is also seen as function of cluster radius, with the red sequence becoming narrower from the outer to inner regions of clusters. In agreement to [Valentinuzzi et al. 2011] we find that cluster mass is not a key parameter for establishing the red sequence. But we find evidence that for high mass systems the red sequence show a reduced scatter compared to small groups. That result indicates that star formation is shut down and galaxies reach the red sequence already in the group scale, but the job is finished in higher mass systems, when the red sequence becomes tighter. Note again that [Valentinuzzi et al. 2011] is restricted to the central region and, most important, to higher mass clusters.

Hence, our main results point to the variation of galaxy populations from very low to the most dense regions of the
Universe, with a stronger variation after galaxies become part of groups/clusters (being found within $R_{200}$). The picture that comes out favors a pre-processing in the group scale, affecting first the star-formation and in a second stage galaxy structure. Our results indicate that local density is the main driver for galaxy evolution. The parent halo mass may be relevant only to the most central regions. However, that is a controversial issue in the literature, possibly due to selection effects of the samples considered. In agreement with Bahé et al. (2013) and Lu et al. (2012), we also find an environmental dependence out to very large radius, corroborating the idea that pre-processing by groups and overshooting act to transform galaxy properties. The possible effect of ram pressure at large radius can only be tested using high resolution numerical simulations, as seen in the work of Bahé et al. (2013). Nonetheless, our main findings are in good agreement to what is found in semi-analytic models.

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