DISENTANGLING THE ROLE OF ENVIRONMENTAL PROCESSES IN GALAXY CLUSTERS

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ABSTRACT

In this work, we present the results of a novel approach devoted to disentangling the role of the environmental processes affecting galaxies in clusters. This is based on the analysis of the near-UV (NUV) – r′ distributions of a large sample of star-forming galaxies in clusters spanning more than four absolute magnitudes. The galaxies inhabit three distinct environmental regions: virial regions, cluster infall regions, and field environment. We have applied rigorous statistical tests to analyze both the complete NUV – r′ distributions and their averages for three different bins of the r′-band galaxy luminosity down to M_r′ ~ −18, throughout the three environmental regions considered. We have identified the environmental processes that significantly affect the star-forming galaxies in a given luminosity bin by using criteria based on the characteristics of these processes: their typical timescales, the regions where they operate, and the galaxy luminosity range for which their effects are more intense. We have found that the high-luminosity (M_r′ ≤ −20) star-forming galaxies do not show significant signs in their star formation activity of being affected by: (1) the environment in the last ~108 yr, or (2) a sudden quenching in the last 1.5 Gyr. The intermediate-luminosity (−20 < M_r′ ≤ −19) star-forming galaxies appear to be affected by starvation in the virial regions and by the harassment in the virial and infall regions. Low-luminosity (−19 < M_r′ ≤ −18.2) star-forming galaxies seem to be affected by the same environmental processes as intermediate-luminosity star-forming galaxies in a stronger way, which would be expected for their lower luminosities.

Key words: galaxies: clusters: general – galaxies: dwarf – galaxies: evolution – galaxies: interactions – galaxies: star formation – ultraviolet: galaxies

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1. INTRODUCTION

The influence of the environment on galaxies involves a rich variety of processes that include the interactions of galaxies with other components of the universe: other galaxies, the intracluster medium (ICM), or the cluster/group dark matter halos (DMHs). As a result of the different studies devoted to shedding light on this key issue of extragalactic astronomy, a number of reviews have become available in the recent years (Treu et al. 2003; Poggianti 2006; Boselli & Gavazzi 2006; Mo et al. 2010). As a reference, Treu et al. (2003) split the environmental processes into three groups.

1. Galaxy–ICM interactions dominate the gas-stripping processes, where the interstellar medium of galaxies is stripped via various mechanisms, including viscous and turbulent stripping, thermal evaporation, and ram-pressure stripping (Boselli & Gavazzi 2006). Galaxy–ICM interactions can also trigger star formation through the compression of galactic gas clouds (Dressler & Gunn 1983; Evrard 1991; Fujita 1998). The ICM stripping of hot halo gas results in a subsequent quenching of star formation (Bekki et al. 2002).

2. Galaxy–cluster gravitational interactions can tidally compress the galaxy envelope of gas and increase the star formation rate (Byrd & Valtonen 1990; Henriksen & Byrd 1996; Fujita 1998). The galaxy starvation can be enhanced by the tidal interaction with the cluster DMH, which contributes to the removal of the hot gas halo of the galaxy (Bekki et al. 2002). Due to the action of the cluster potential, the tidal truncation of the external galaxy regions produces a late quenching of star formation along a few Gyr if the galaxy reservoir is removed. However, their effects are more clearly observed in the structural changes of the mass profile (Merritt 1984; Ghigna et al. 1998; Natarajan et al. 1998).

3. Tidal galaxy–galaxy interactions dominate the galaxy mergers or strong galaxy encounters (Icke 1985; Mihos 1995; Bekki 1998) and the galaxy harassment (Moore et al. 1996, 1999, 1998). These three groups of processes have associated different spatial/timescales and characteristics that we describe below.

1. Timescales. We can distinguish between long- and short-timescale processes. Following the scheme proposed by Poggianti (2006), the long-timescale processes embrace the gas-stripping processes and the galaxy mergers or strong galaxy interactions, and the long-timescale processes embrace the galaxy starvation (Larson et al. 1980; Bekki et al. 2002) and the galaxy harassment (Moore et al. 1996). The timescale for the suppression of star formation in gas stripping goes from ~107 yr (Abadi et al. 1999) to 108 yr (Quilis et al. 2000) for a Milky-Way-like galaxy. In galaxy mergers, both the encounter time and the duration of the starburst phase have a timescale of the order of 107 yr (Mihos & Hernquist 1994, 1996). Numerical simulations (Bekki et al. 2002) indicate that the starvation combining the interaction with the ICM and the cluster potential has a timescale of several Gyr. Galaxy harassment takes place along several cluster-crossing times, i.e., a few Gyr (Boselli & Gavazzi 2006; Moore et al. 1998; Appendix).

2. Spatial scales. We can also distinguish between long and short spatial-scale processes. The galaxy starvation and the galaxy harassment have spatial scales of the order of the virial radius or longer (Treu et al. 2003; Boselli & Gavazzi 2006). During gas stripping, the cold gas of the galaxies...
hydrodynamically interacts with the ICM from its vicinity, but this occurs along the pathway of the galaxy across the ICM of the virial region; thus, it is assumed to be a long spatial-scale process. The main small-scale environmental processes are the galaxy mergers or galaxy–galaxy tidal interactions that occur in a spatial scale that is of the order of the size of galaxies.

3. Environments. Certain environmental processes more efficiently operate or more frequently occur in certain types of environments or places. Starvation or gas stripping preferentially operates in the central regions of clusters, which are where the ICM drag force and the cluster tidal forces are enough to strip the gas components of the galaxy. The galaxy harassment rate $f_h$ scales with the luminous galaxy density $\rho_{\text{gal}}$ and mass $M_\ast$ as $f_h \propto \rho_{\text{gal}} M_\ast^{-2} \propto \rho_{\text{gal}} r^{-2}$. In the simple case where the local density scales smoothly as $r^{-2}$, the harassment rate should be independent of the cluster radius (Treu et al. 2003). The merging processes are the most efficient when the relative velocities between the galaxies are low; thus, they are expected to be more efficient in galaxy groups than in the inner regions of clusters. The galaxy groups infalling to clusters represent ideal places for an environmental-driven galaxy evolution in the frame of a “preprocessing” scenario (Cortese et al. 2006; Mihos 2004).

4. Galaxy luminosity range. In addition to this, it must be taken into account that the effect of the different processes depends on galaxy luminosities; some of them are more efficient when operating on bright/giant galaxies (gas stripping; Quilis et al. 2000) and other processes affect dwarf and low surface brightness galaxies more strongly (galaxy harassment; Moore et al. 1999).

These physical processes have been proposed/invoked to explain numerous observational facts that indicate that the environment in which a galaxy inhabits has a profound impact on its evolution in terms of defining both its structural properties and star formation histories. Perhaps the two most remarkable observational results are the morphology–density relation—the fraction of early-type galaxies increases toward high-density environments (Dressler 1980)—and the star formation–density relation—the fraction of star-forming galaxies and the intensity of the star formation per galaxy decrease toward high-density environments (Lewis et al. 2002; Gómez et al. 2003; Rines et al. 2005).

The ultraviolet (UV) luminosity is a good proxy of the recent star formation because it comes from the more short-lived stars $\tau < 10^8$ yr (Kennicutt 1998; Kauffmann et al. 2007; Martin et al. 2005). Hence, we can trace time variations of around 100 Myr in the star formation history of a galaxy using the UV luminosity (Leitherer et al. 1999), UV–optical colors, or both (Kaviraj et al. 2007a, 2007b). The UV luminosity is strongly linked to the far-IR (FIR) luminosity ($\sim$8–1000 $\mu$m); the UV radiation emitted by young stellar populations is strongly absorbed by dust in the star-forming molecular clouds and reemitted through IR photons. So, both the UV-to-FIR luminosity budget as a proxy of the attenuation suffered by the young stellar population (see Buat et al. 2005) or the bolometric luminosity from the young stellar populations $L_{\text{bol}} = L_{\text{UV}} + L_{\text{FIR}}$ as a proxy of the star formation rate (Wang & Heckman 1996; Iglesias-Páramo et al. 2006) also provide important insights into the star formation activity of galaxies.

By contrast, assuming that the field galaxies are the galaxies less affected by the influence of the environment, we can take a sample of field galaxies as a fiducial sample (approximated) free from interactions, i.e., in the absence of any environmental influence. Therefore, if the distribution of a UV–optical color of a star-forming galaxy sample (i.e., those with blue UV–optical colors, e.g., Haines et al. 2008; Chilingarian & Zolotukhin 2012) is statistically different from the corresponding distribution for a field star-forming galaxy sample (at the same cosmic time), then we can conclude that those galaxies are experiencing a significant change in their star formation level in a timescale of around $10^9$ yr or longer. Assuming this fact, we can develop an original approach that permits us to assign the intensity of those environmental processes affecting the galaxies, depending on their luminosity, through an analysis of the variations of the distributions of a UV–optical color of star-forming galaxies throughout different environmental regions. We choose the UV–optical color near-UV (NUV) $- r'$ because these two spectral bands trace two different timescales of the star formation history; the NUV band traces a $\tau \sim 10^3$ yr and the $r'$ band traces a longer timescale $\tau \sim 10^3$–$10^7$ yr (Kennicutt 1998; Martin et al. 2005). Because of this, NUV $- r'$ shows a tight correlation with the ratio of the recent star formation over the past-averaged star formation (Salim et al. 2005).

The remainder of the paper is organized as follows. In Section 2, we describe the photometric data and the sample of galaxies in clusters used in this work. In Section 3, we present the main results derived from the NUV $- r'$ distributions of our sample of galaxies. We discuss the implications resulting from our analysis in Section 4. In Section 5, we summarize the main results and conclusions of this work.

2. SAMPLE OF CLUSTER GALAXIES

This work is based on data compiled from the Sloan Digital Sky Survey Data Release 6 (SDSS DR6; Adelman-McCarthy et al. 2008) and Galaxy Evolution Explorer all-sky imaging survey (GALEX-AIS) (Martin et al. 2005) for a sample of cluster galaxies extensively described in Hernández-Fernández et al. (2012, hereafter Paper I). This sample consists of a total of ~5000 galaxies from 16 nearby clusters ($z < 0.05$) showing a rich variety in their characteristics, from poor to rich clusters with cluster-velocity dispersions between 200 $< \sigma_{v} < 800$. The basic properties of these clusters are listed in Table 1. The galaxies span a luminosity range containing the classical luminosity boundary between giant and dwarf galaxies $M_B \sim -18$. The selection of the clusters was constrained by the condition that they were covered by SDSS DR6 and GALEX-AIS throughout sky areas that corresponded to physical sizes of several virial radii, i.e., several Mpc. This condition ensures that our sample of galaxies probes different environments from the central regions of rich clusters to the low-density field, including the galaxy structures around clusters as groups, sheets, and filaments. The main galaxy sample (MGS) of SDSS (Strauss et al. 2002) consists of those galaxies with $r'$-band petrosian magnitudes $r' < 17.77$ and $r'$-band petrosian half-light surface brightnesses $\mu < 24.5$ mag arcsec$^{-2}$ retrieved from the imaging survey, which has a 95% completeness limit for stars of $r' = 22.2$ (Stoughton et al. 2002). GALEX has performed the first space UV imaging AIS in two bands (FUV: 1350–1750 Å and NUV: 1750–2750 Å) down to a Galactic-extincted magnitude of $M_{AB} = 20.5$. The broadband photometry from both SDSS DR6 and GALEX-AIS is carefully chosen to retrieve the total integrated flux for each galaxy in the selected band. For the SDSS photometry, we choose the composite-model magnitude, which is a weighted linear
combination of the fluxes extracted with a de Vaucouleurs profile and an exponential radial profile fit to the surface brightness profile of each galaxy (Abazajian et al. 2004). For the GALEX photometry, we choose the elliptical aperture photometry (MAG_AUTO option in SExtractor code; Bertin & Arnouts 1996) to include the total integrated UV flux for each galaxy source.

3. RESULTS: UV–OPTICAL COLOR DISTRIBUTION OF CLUSTER GALAXIES

The main goal of this work is to characterize the role of the environment in the star formation properties of a sample of cluster galaxies with active star formation. First, we select the star-forming galaxies from the total cluster galaxy sample previously described. For this we apply the UV–optical color cut proposed for the (NUV − r′) versus (u′ − r′) color–color diagram in Paper I. We assume that a galaxy is a star-forming galaxy if its colors fulfill the following prescription:

\[
\begin{align*}
\text{STAR-FORMING:} & \quad \begin{cases} 
\text{NUV} - r' < 4.9, \\
\text{for } u' - r' < 2.175 \\
\text{NUV} - r' < -2(u' - r') + 9.25, \\
\text{for } u' - r' > 2.175
\end{cases} 
\end{align*}
\]

As can be seen in Figure 1, this boundary appears more appropriate to segregate star-forming galaxies from passive galaxies than the optical cut in the u′ − r′ color proposed by Strateva et al. (2001).

Second, we define three regions (i.e., cluster virial regions, cluster infall regions, and the field environment) where different physical processes are expected to act in a different way and intensity due to the different environmental conditions. To select galaxies from each environment, we take advantage of their spatial ˜r and velocity ˜s variables through the phase diagram:

\[
(\tilde{s}, \tilde{r}) \equiv \left( \frac{c(\tilde{z} - \tilde{z}_{\text{med}})}{\sigma_c}, \frac{R_P}{r_{200}} \right),
\]

with c being light speed, z the galaxy redshift, ˜z_{\text{med}} the cluster redshift, \sigma_c the cluster velocity dispersion, R_P the physical projected radius from the cluster center, and r_{200} the virial radius.

In this phase diagram, galaxies in clusters are located inside the region delimited by a bivalued caustic \˜s = ±4(˜r) with a characteristic trumpet shape symmetrical with respect to the ˜r

![Figure 1](image-url)
axis (Kaiser 1987); outside the caustic limits, the density of the galaxies substantially drops. Galaxies outside of the caustics are background or foreground galaxies (e.g., den Hartog & Katgert 1996). Rines et al. (2003) numerically compute the caustic \( A(\tilde{r}) \) for a sample of galaxy clusters in the local universe (see their Figure 4) using the method proposed by Diaferio (1999). This caustic curve can be accurately approximated using the following terms:

\[
A(\tilde{r}) = \begin{cases} 
2.5 - \frac{5}{3} \tilde{r}, & \text{for } \tilde{r} \leq 2.30 \\
1.0 - \frac{1}{16} \tilde{r}, & \text{for } \tilde{r} > 2.30 
\end{cases}
\]

Following Rines et al. (2003), we define the three different environments studied here in the following way:

- **Virial regions:** \( -A(\tilde{r}) \leq \tilde{s} \leq +A(\tilde{r}) \) and \( \tilde{r} \leq 1 \)
- **Infall regions:** \( -A(\tilde{r}) \leq \tilde{s} \leq +A(\tilde{r}) \) and \( 1 < \tilde{r} \leq 5 \)
- **Field environment:** \( \tilde{s} < -A(\tilde{r}) \) or \( +A(\tilde{r}) < \tilde{s} \) where \( 5 < \tilde{r} \)

Two galaxy clusters from Paper I, A2199 and WBL 514, present two evident galaxy systems in their surroundings between \( \sim2r_{200} \) and \( \sim3r_{200} \) (see Figures 1 and 2 in Paper I). In the case of WBL 514, this galaxy system corresponds to the cluster WBL 518 located \( \sim2^\circ \) west on the sky with coordinates \((\alpha, \delta)_{J2000} = (14^h40^m43^s, +03^d27^m11^s)\) and a central redshift of \( z = 0.027 \). The cluster A2199 has the cluster A2197 in its surroundings; located \( \sim1.5\) of projected distance, its coordinates are \((\alpha, \delta)_{J2000} = (16^h38^m10^s, +40^d54^m26^s)\), and it has a redshift of \( z = 0.0308 \). These two galaxy systems, WBL 518 and A2197, are not included in the set of clusters from Paper I according to the constraint of being observed by SDSS DR6 and by GALEX-AIS throughout sky regions corresponding to several megaparsecs. The central regions of these galaxy systems can be only inhabited by the typical galaxy population of the central regions of galaxy clusters. To avoid the mix between galaxy population from virial regions and infall regions, we exclude the galaxy subsample of these two clusters from the galaxy sample corresponding with the infall regions. Specifically, we exclude those galaxies from the infall regions with the following coordinates:

\[
\text{A2197: } 40.4 < \alpha_{J2000} < 41.8 \quad \text{and} \quad 245.8 < \delta_{J2000} < 248.0
\]

\[
\text{WBL518: } 3.0 < \alpha_{J2000} < 4.2 \quad \text{and} \quad 219.8 < \delta_{J2000} < 220.75
\]

In the Appendix, we show the results of the same analysis performed here, but we include the central regions of these clusters as part of the galaxy sample in the infall regions.

Figure 2 shows the distribution and the average trend of the NUV – \( r' \) color for our sample of star-forming galaxies along their \( r' \)-band absolute magnitude \( M_{r'} \) in the three different environments. For each luminosity bin to be complete, we select only those star-forming galaxies that fulfill the two following conditions: (i) galaxies whose \( r' \)-band composite-model absolute magnitude, \( M_{r'}^\text{clim} \), is within the limits (lower limit—\( M_{r'}^\text{lim} \), upper limit—\( M_{r'}^\text{ubin} \)) of each luminosity bin,

\[
M_{r'}^\text{lim} < M_{r'} < M_{r'}^\text{ubin}
\]

and (ii) galaxies from those clusters for which their completeness limit of the \( r' \)-band composite-model absolute magnitude \( M_{r'}^\text{clim} \) is fainter than the upper limit of each luminosity bin \( M_{r'}^\text{ubin} \),

\[
M_{r'}^\text{ubin} < M_{r'}^\text{clim}
\]

To compute \( M_{r'}^\text{clim} \), we assume the completeness limit of the Main Galaxy Sample \( r' = 17.77 \) and a conservative cut of \( r' - r_{\text{em}} = 0.21 \) in the difference between the \( r' \)-band composite-model magnitude, \( r_{\text{em}} \), and the \( r' \)-band petrosian magnitude \( r' \). This cut embraces \( 90\% \) of the overall sample of cluster galaxies and \( \sim92.5\% \) of galaxies from the faintest bin, \( 17 < r' < 17.77 \), or the optical-selected blue galaxies \( u' - r' < 2.22 \), as can be seen in Figure 3.

Those galaxies for which an NUV detection is not available are discarded from our analysis. Those galaxies are not observed because they occupy the gaps between the circular GALEX fields or they are fainter than the completeness limit of GALEX-AIS. The first case does not introduce any bias since a correlation between the star formation properties of those galaxies and their celestial coordinates is not expected. In the second case, those galaxies are outside the color–magnitude locus dedicated to this study (Figure 4), assuming the AB-magnitude limit of an SDSS-GALEX matched catalog NUV \( \sim 22.5 \) (Bianchi et al. 2007) and the completeness limit of the SDSS MGS in the \( r' \)-band composite-model magnitude \( r_{\text{em}} = 17.56 \).

Figure 2 shows two clearly different behaviors in the (NUV – \( r' \))–(\( M_{r'} \)) plane for star-forming galaxies that depend on the environment they inhabit. The average of NUV – \( r' \) for the field star-forming galaxy sample follows a monotonic trend from NUV – \( r' \) \( \sim 3.5 \) at \( M_{r'} \) \( \sim -22.25 \) to NUV – \( r' \) \( \sim 2.35 \) at \( M_{r'} \) \( \sim -18 \). In the case of star-forming galaxies that inhabit the infall regions of clusters, they show a very similar trend to field star-forming galaxies, with a systematic bias of \( \sim 0.1 \) mag toward redder values of the NUV – \( r' \) average. The trend of the NUV – \( r' \) average for star-forming galaxies from the virial regions shows a distinct behavior: their NUV – \( r' \) averages in the \( M_{r'} < -20 \) range are consistent with the NUV – \( r' \) trend for infalling and field star-forming galaxies, within the uncertainties of NUV – \( r' \) averages. By contrast, star-forming galaxies from virial regions in the \( -20 < M_{r'} < -18 \) range are systematically biased toward redder values of NUV – \( r' \) in \( \sim 0.5 \) mag.

To accomplish an in-depth analysis of the NUV – \( r' \) distribution along the \( M_{r'} \) range throughout the defined cluster regions,
we split the star-forming galaxy sample into three luminosity intervals: the high-luminosity (HL) bin with \( M_r \leq -20 \), the intermediate-luminosity (IL) bin with \(-20 < M_r \leq -19 \), and the low-luminosity (LL) bin with \(-19 < M_r \leq -18.2 \). We choose the lowest luminosity cut, \( M_r = -18.2 \), to maximize the size of the sample of the star-forming galaxies in this bin, according to Equations (2) and (3). Figure 5 shows the NUV \(- r'\) distributions of star-forming galaxies for these three luminosity bins in the three environmental regions defined above. In Table 2, we show the averages and their bootstrap uncertainties for the distributions of each subsample.

As shown in Figure 5 and Table 2, two monotonic trends arise from these results: (1) at all luminosities, the average NUV \(- r'\) reddens from the field environment to the virial regions, and (2) for a given environment, the average NUV \(- r'\) reddens as we move from LL to HL star-forming galaxies. The first trend follows the general trend shown in the color–magnitude diagrams by the “blue cloud” (e.g., Baldry et al. 2004; Haines et al. 2008). Despite the small differences, the average NUV \(- r'\) measured for HL galaxies in the three environments are consistent within 1\( \sigma \). This does not seem to be the case for IL and LL galaxies, where the average NUV \(- r'\) of infall and field galaxies is clearly bluer than that of the virial galaxies, and this behavior is more pronounced for LL than for IL galaxies.
Table 2

Averages and Average Uncertainties of NUV − r′ Distributions for Each Luminosity Bin in Each Environmental Region

| Environment (M_r′ < −20) | ⟨NUV − r′⟩ ± σ_{bootstrap} (NUV − r′) | (2) | (3) |
|--------------------------|----------------------------------------|------|-----|
| Virial                   | 3.169 ± 0.080                          | 0.052|     |
| Infall                   | 3.067 ± 0.052                          | 0.048|     |
| Field                    | 2.940 ± 0.048                          |      |     |
| IL (−20 < M_r′ < −19)    | 3.128 ± 0.073                          | 0.050|     |
| Virial                   | 2.707 ± 0.050                          | 0.038|     |
| Infall                   | 2.630 ± 0.038                          |      |     |
| LL (−19 < M_r′ < −18.2)  | 3.035 ± 0.095                          | 0.055|     |
| Virial                   | 2.483 ± 0.055                          | 0.039|     |
| Infall                   | 2.395 ± 0.039                          |      |     |

Notes. (1) Environmental region. (2) Mean of NUV − r′ distribution in the corresponding environmental region. (3) Bootstrap uncertainty of the corresponding NUV − r′ mean.

Table 3

Results from the K-S Test

| Subsamples (M_r′ < −20) | D_{x1,x2} (1) | P(x_{11},x_{22}) (2) | (3) |
|--------------------------|---------------|---------------------|-----|
| Virial−Infall            | 0.100         | 0.429               |     |
| Infall−Field             | 0.117         | 0.057               |     |
| Virial−Field             | 0.162         | 0.0256              |     |
| IL (−20 < M_r′ < −19)    | 0.245         | 4.75 \times 10^{-6} |     |
| Virial−Infall            | 0.076         | 0.268               |     |
| Virial−Field             | 0.295         | 1.56 \times 10^{-9} |     |
| LL (−19 < M_r′ < −18.2)  | 0.285         | 3.96 \times 10^{-7} |     |
| Virial−Infall            | 0.081         | 0.214               |     |
| Virial−Field             | 0.334         | 3.38 \times 10^{-11} |     |

Notes. (1) Environmental regions where the K-S test is applied to the NUV − r′ distributions of their galaxy subsamples. (2) Maximum difference between the two cumulative distribution functions of the NUV − r′ distributions. (3) Probability that the two NUV − r′ distributions came from the same parent population.

In addition, the NUV − r′ distributions for IL and LL galaxies present a maximum around NUV − r′ = 2 in the infall and field environments. This maximum is clearly absent in the virial environment, where the NUV − r′ distributions present a top-hat shape at all luminosity ranges.

4. DISCUSSION

In the previous section, we have shown that the NUV − r′ distributions of galaxies in different environments present significant differences depending on the considered r′-band luminosity. To accomplish a rigorous analysis based on the NUV − r′ distributions, we apply a Kolmogorov–Smirnov (K-S) test. Table 3 shows the results from the K-S test when comparing the samples that correspond to the three environments for each luminosity bin. Figure 6 illustrates the results of the K-S test by showing a simplified scheme of the probability that the star-forming galaxy subsamples of same luminosity bin in different environments come from the same population. In what follows, we discuss the implications of these results for each of the different luminosity bins.

4.1. HL Star-Forming Galaxies

In the case of HL (M_r′ < −20) star-forming galaxies, the probability P(x_{11}, x_{22}) that the NUV − r′ distribution of the virial regions and the infall regions came from the same parent population is P ≈ 43%, so they show a high similarity in their NUV − r′ distributions. When comparing the infall regions and the field environment, this probability lowers to P(x_{21}, x_{22}) ≈ 6%, so we cannot reject the null hypothesis that the distributions came from the same parent population. The comparison between the virial regions and the field environment yields a probability P(x_{11}, x_{22}) ≈ 3%, which is still low but does not allow us to reject the null hypothesis. All these results suggest that the HL star-forming galaxies, from the point of view of the environmental influence on their NUV − r′ distributions, form a unique family of galaxies only subtly affected by the environment they inhabit. They only show a very mild gradient of reddening toward the inner parts of the galaxy clusters. Assuming that the NUV − r′ distributions of the HL star-forming galaxies are our unique observable, we propose two scenarios about the environmental influence on the star formation activity of these galaxies: (1) there is not a strong environmental influence on the star formation activity of these galaxies in the last ∼10^8 yr or (2) the environmental processes that would affect these galaxies act on short timescales, referring to the timescale of UV luminosity, τ_{UV} ∼ 10^8 yr.

A sudden truncation of a previously significant star formation in the last 1.5 Gyr leaves (at least) two observables imprints on the galaxy spectrum: strong Balmer lines in absorption (EW_{Hβ} > 3 Å) and negligible emission lines (e.g., [O II]) (Poggianti et al. 2004); this kind of galaxies has been named k+a galaxies (in the modern designation, Dressler et al. 1999) or E+A galaxies (as they were first identified by Dressler &
Figure 7. (NUV − r′) vs. (g′ − r′) for the M_r < −20 galaxy sample. Yellow isocontours represent the isodensity contours of the HL galaxies. Blue and red points represent star-forming and passive galaxies, respectively, under the prescription shown in Section 3. The square box represents the locus of the k+a galaxies in this color–color diagram (Kaviraj et al. 2007a, Figure 1). (A color version of this figure is available in the online journal.)

Gunn 1983). Because of this, the k+a spectra are often linked with poststarburst galaxies. Those galaxies have a specific locus in a UV–optical color–color diagram (e.g., GALEX-SDSS color diagram). Their optical colors are as blue as the optical colors of the blue-cloud galaxies and their UV–optical colors are as red as the UV–optical colors of the red-sequence galaxies (Kaviraj et al. 2007a). As you can see in Figure 7, the appearance of our sample of HL galaxies in such a color–color diagram shows that these kinds of galaxies are clearly absent in the observed locus for k+a galaxies found by Kaviraj et al. (2007a, see their Figure 1). This is in agreement with other results found for local galaxy clusters (e.g., Fabricant et al. 1991). By contrast, the luminous k+a galaxies are abundant in the field (e.g., Goto 2005), and they also represent a significant fraction of the cluster dwarf galaxy population in the Coma cluster (Poggianti et al. 2004). In summary, a short timescale mechanism quenching star formation (i.e., gas stripping) in HL star-forming galaxies is not expected to have significantly affected those galaxies in the last ∼1.5 Gyr.

4.2. IL Star-Forming Galaxies

In the case of IL (−20 < M_r ≤ −19) star-forming galaxies, there is a high similarity between the NUV − r′ distribution of this subsample of galaxies inhabiting the infall regions and the corresponding one inhabiting the field environment, P(x1i, x2i) ≈ 27%. On the contrary, the comparison of virial and infall galaxies yields a probability of P(x1i, x2i) ∼ 10^{-4}%, similar to the one arising from the comparison of virial and field galaxies (P(x1i, x2i) ∼ 10^{-1}%). These results imply that the infall and field distributions do not come from the same parent population as the virial one, suggesting that there is an environmental mechanism strongly affecting the star formation activity of the galaxies inside the virial regions on timescales of 10^8 yr. Following the scheme proposed by Treu et al. (2003) for the radial range, which is where each environmental process predominantly operates, we propose starvation through interaction with the ICM and the DMH as the main environmental process that affects those galaxies in the virial regions. In addition, a systematic reddening is observed for star-forming galaxies in this luminosity bin, −20 < M_r ≤ −19, with respect to the field star-forming galaxies. This is not just observed in the virial region; it is also observed in the infall region. This result suggests that there is some environmental process acting in the virial region as well as the infall region. Again, following the scheme proposed by Treu et al. (2003) for the radial range for each environmental process, we propose galaxy harassment as the environmental process that quenches the star formation activity of IL star-forming galaxies in the virial and infall regions.

4.3. LL Star-Forming Galaxies

The results from the K-S test applied to the LL (−19 < M_r ≤ −18.2) star-forming galaxies show a similar scheme to those shown in the IL star-forming galaxies. The LL star-forming galaxies from the virial regions present an NUV − r′ distribution that is clearly different from those in the infall regions and the field environment. The probability of coming from the same parent population between the virial and infall regions is P(x1i, x2i) ∼ 10^{-5}, while this probability decreases to P(x1i, x2i) ∼ 10^{-9} for virial regions versus field environment. However, there is a significant similarity between the NUV − r′ distributions, the infall regions, and the field environment with a probability of P(x1i, x2i) ≈ 21%. These galaxies seem to experience a stronger quenching in their star formation activity than the IL star-forming galaxies. The reddening of the NUV−r′ averages toward the inner parts of the clusters is larger for the LL star-forming galaxies than it is for the IL star-forming galaxies, assuming the galaxies from the virial regions as the reference, the gross differences, and those normalized to the sum of the uncertainties (Table 2). The comparison of the virial regions with the field environment produces a difference normalized to the sum of uncertainties ∆/σ of 4.449 and 4.767 for the IL and the LL star-forming galaxies, respectively. The comparison of the virial regions with the infall regions produces a ∆/σ of 3.42190 and 3.67115 for the IL and LL star-forming galaxies, respectively.

The proposed environmental mechanisms that can more strongly affect the LL star-forming galaxies seem to be (in the same way as the IL star-forming galaxies) the galaxy harassment—to explain the reddening in the infall regions with respect to the field environment—and the starvation, through the interaction with the ICM and through interaction with the DMH, which would explain the evident difference in the NUV − r′ distributions between the virial regions and other environmental regions.

As mentioned above, the effects of the environment on the quenching of star formation activity seem to be more pronounced in the LL star-forming galaxies than in the IL star-forming galaxies. This suggests that the intensity of the above-cited environmental processes may have some dependence on the galaxy luminosity or on the galaxy (stellar or gravitational) mass. In the case of galaxy harassment, Moore et al. (1999) found that, through an equilibrium high-resolution model of spirals embedded in an N-body simulation, the response of a spiral galaxy to tidal encounters primarily depends on the central depth of its gravitational potential and its disk scale length, which is mainly determined by the stellar component of
galaxies. Low-surface brightness galaxies dramatically evolve under the influence of rapid encounters with cluster galaxies and strong tidal shocks from the global cluster potential (i.e., galaxy harassment), while high surface brightness galaxies are more stable to the galaxy stirring in clusters and the tidal encounters. In the case of starvation, Bekki et al. (2002) performed numerical simulations to evaluate the stripping that hot halo gas undergoes when it is subjected to both the ram pressure of the ICM and the global tidal field of the cluster. According to this work, the less massive a galaxy is, the more efficient those mechanisms are (ICM stripping, Bekki et al. 2002, and tidal halo stripping, Byrd & Valtonen 1990, 2001; Henriksen & Byrd 1996). In conclusion, the proposed environmental processes acting on IL and LL star-forming galaxies match the fact that they produce stronger effects on star formation activity in LL star-forming galaxies.

5. SUMMARY AND CONCLUSIONS

In this paper, we expose an original approach that analyzes the NUV $- r'$ distributions of a large sample of star-forming galaxies in clusters that cover a range of more than four $r'$-band magnitudes down to $M_r \sim -18$ and are distributed in three distinct environmental regions: the virial regions, the cluster infall regions, and the field environment. According to the characteristics of each environmental process, we discuss and propose which environmental processes affect the star-forming galaxies depending on their luminosity. In the following summary, we present the main results and conclusions of this work.

1. The similarity of the NUV $- r'$ distributions of HL ($M_r \leq -20$) star-forming galaxies in the different environmental regions together with the absence of luminous $k+a$ galaxies in our cluster galaxy sample suggest that there is neither a strong environmental influence on the star formation activity of these galaxies in the last $\sim 10^8$ yr nor a sudden truncation of star formation in the last 1.5 Gyr.

2. The NUV $- r'$ distributions of IL ($-20 < M_r < -19$) star-forming galaxies from the infall regions and the field environment show a remarkable similarity. By contrast, the NUV $- r'$ distributions of IL star-forming galaxies in virial regions are clearly distinct from the corresponding ones in infall regions and in the field environment. This behavior of the NUV $- r'$ distributions of IL star-forming galaxies points out the starvation through the combined interaction with the ICM and the DMH as the environmental process, significantly quenching the star formation activity of IL star-forming galaxies in the virial regions of clusters. The reddening of NUV $- r'$ distributions of these galaxies was observed not just in the virial regions, but also in the infall regions, and with respect to the field environment is an indication that there is some type of environmental process acting on these galaxies (at least) in the infall region. The galaxy harassment as a long timescale process $\tau \gtrsim 10^8$ yr is a suitable candidate responsible for the observed differences in the NUV $- r'$ distributions.

3. The LL ($-19 < M_r \leq -18.2$) star-forming galaxies present the same trends of the IL star-forming galaxies in their NUV $- r'$ distributions. Consequently, we propose that the same environmental processes in the same environmental regions are affecting the star formation activity of these galaxies. Moreover, the NUV $- r'$ averages of the LL star-forming galaxies in the virial regions show a stronger reddening with respect to the infall regions and the field environment than the IL star-forming galaxies. Indeed, the observed effect of these environmental processes (starvation, harassment) is stronger for LL galaxies.

To conclude, we suggest that our results highlight the added value of a sample of cluster galaxies that map a broad variety of environmental conditions with a large range in galaxy luminosity and with multiwavelength (from UV to FIR) available data.

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APPENDIX

In this appendix, we show results from the same analysis developed in this work and include the central regions of the clusters A2197 and WBL 518 as part of the galaxy sample in the infall regions.
clusters is a good approach. The probabilities of the NUV − r′ distributions of star-forming galaxy subsamples from the virial region and from the infall regions were derived from the same parent population increase with respect to the previous analysis, while the probabilities of the NUV − r′ distributions of star-forming galaxy subsamples from the infall regions and the field environment systematically decrease in the all luminosity bins. These issues suggest that the inclusion of A2197 and WBL 518 in the infall regions makes the NUV − r′ distributions more similar between the infall regions and the virial regions; in the same way, it makes the NUV − r′ distributions of the infall regions more different from those derived from the field environment. Therefore, the central regions of these clusters have a higher similarity in the NUV − r′ distributions of their star-forming galaxy population with the virial regions than the infall regions, which is what we supposed in our approach.

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Table 4
Averages and Average Uncertainties of NUV − r′ Distributions for Each Luminosity Bin in Each Environmental Region

| Environments | ⟨NUV − r′⟩ | ±σ_{bootstrap} |
|---------------|-----------------|-----------------|
| Virial (M_r ≤ −20) | 3.169 ± 0.080 | 3.097 ± 0.049 |
| Infall (M_r ≤ −20) | 2.940 ± 0.048 | 3.128 ± 0.073 |
| Field (M_r ≤ −20) | 2.630 ± 0.038 | 2.723 ± 0.051 |
| Virial (M_r ≤ −19) | 3.035 ± 0.095 | 2.601 ± 0.052 |
| Infall (M_r ≤ −19) | 2.953 ± 0.039 | 2.395 ± 0.102 |
| Field (M_r ≤ −19) | 3.083 ± 0.172 | 2.955 ± 0.156 |

Note. The central regions of A2197 and WBL 518 are included as part of the galaxy sample in the infall regions.

Table 5
Results from the K-S Test

| Subsamples | D_{11,2} (1) | P_{11,2} (2) | P_{11,2} (3) |
|-------------|---------------|---------------|---------------|
| Virial–Infall | 0.086 ± 0.601 | 0.137 ± 0.0106 | 0.162 ± 0.0260 |
| Infall–Field | 0.241 ± 5.13 × 10^{-6} | 0.083 ± 0.172 | 0.295 ± 1.56 × 10^{-9} |
| Field–Infall | 0.232 ± 4.28 × 10^{-5} | 0.130 ± 0.00377 | 0.334 ± 3.38 × 10^{-11} |

Notes. The central regions of A2197 and WBL 518 are included as part of the galaxy sample in the infall regions. (1) Environments where the K-S test is applied to the NUV − r′ distributions of their galaxy subsamples. (2) Maximum difference between the two cumulative distribution functions of the NUV − r′ distributions. (3) Probability that the two NUV − r′ distributions came from the same parent population.

Table 4 shows the averages (and uncertainties) of NUV − r′ distributions for each luminosity bin of star-forming galaxies in each environmental region. Table 5 shows the results of the K-S test applied to these galaxy subsamples.

As you can see, the data corresponding to infall regions (the only line modified in this section) systematically show redder NUV − r′ averages than the averages in the previous analysis in the three luminosity bins. This is in agreement with the motivation of the extraction of the central regions of these clusters from the cluster infall regions of their companions; the typical “red” galaxy population from the central cluster regions inhabit these excluded regions. The differences are lower than the associated uncertainties, except for the case of the LL star-forming galaxies, whose difference is ≈ 2σ.

In regard to the results from the K-S test, the changes in the probabilities for each case suggest that the extraction of clusters A2197 and WBL 518 from the infall regions of their neighbor
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