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The effect of the environment on the structure, morphology and star formation history of intermediate-redshift galaxies

Kshitija Kelkar, Meghan E. Gray, Alfonso Aragón-Salamanca, Gregory Rudnick, Bo Milvang-Jensen, Pascale Jablonka and Tim Schrabback

School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, UK
Department of Physics and Astronomy, University of Kansas, KS 66045-7582, USA
Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark
Laboratoire d’Astrophysique, Ecole Polytechnique Fédérale de Lausanne (EPFL), Observatoire de Sauverny, CH-1290 Versoix, Switzerland
GEPI, Observatoire de Paris, CNRS UMR 8111, Université Paris Diderot, F-92125 Meudon Cedex, France
Argelander Institut fuer Astronomie, Auf dem Huegel 71, D-53121 Bonn, Germany

ABSTRACT

With the aim of understanding the effect of the environment on the star formation history and morphological transformation of galaxies, we present a detailed analysis of the colour, morphology and internal structure of cluster and field galaxies at $0.4 \leq z \leq 0.8$. We use the Hubble Space Telescope data for over 500 galaxies from the ESO Distant Cluster Survey to quantify how the galaxies’ light distribution deviate from symmetric smooth profiles. We visually inspect the galaxies’ images to identify the likely causes for such deviations. We find that the residual flux fraction (RFF), which measures the fractional contribution to the galaxy light of the residuals left after subtracting a symmetric and smooth model, is very sensitive to the degree of structural disturbance but not the causes of such disturbance. On the other hand, the asymmetry of these residuals ($A_{res}$) is more sensitive to the causes of the disturbance, with merging galaxies having the highest values of $A_{res}$. Using these quantitative parameters, we find that, at a fixed morphology, cluster and field galaxies show statistically similar degrees of disturbance. However, there is a higher fraction of symmetric and passive spirals in the cluster than in the field. These galaxies have smoother light distributions than their star-forming counterparts. We also find that while almost all field and cluster S0s appear undisturbed, there is a relatively small population of star-forming S0s in clusters but not in the field. These findings are consistent with relatively gentle environmental processes acting on galaxies infalling on to clusters.

Key words: galaxies: clusters: general – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: interactions – galaxies: spiral.

1 INTRODUCTION

Galaxy clusters represent an excellent agglomeration of galaxy populations undergoing changes in several observable galaxy properties, some of which are attributed to the diversity of environments that the galaxies experience. One of the earliest suggestions that environment may play a role in transforming galaxy properties is the well-established morphology–density relation (Dressler 1980, 1984): high-density environments are observed to contain higher fractions of galaxies with early-type morphologies than the field. The question of precisely to what extent, and by what physical processes, the environment leaves an imprint on morphology as well as other observable properties (e.g. colour, star formation, internal structure) is still largely undetermined.

Evidence of global transformations happening over look-back time is given by the increasing fraction of spiral galaxies in clusters till $z \sim 0.5$ (Dressler et al. 1997; Fasano et al. 2000; Desai et al. 2007) and the fact that high-$z$ clusters are found to contain more star-forming galaxies as compared to present-day clusters (Butcher & Oemler 1984; Poggianti et al. 2006). In addition to the morphology–density relation, it is widely observed that the specific star formation rate declines towards dense local environments (Hashimoto et al. 1998; Lewis et al. 2002; Gray et al. 2004; Kauffmann et al. 2004; Balogh et al. 2007). Higher fractions of passive or quiescent galaxies are found in dense environments, both in the local Universe (Baldry et al. 2006; van den Bosch et al. 2008; Gavazzi et al. 2010; Haines et al. 2013) and out to $z \sim 2$ (Poggianti et al. 1999; Sobral et al. 2013).
Some environmental segregation in the galaxies’ properties is naturally expected: hierarchical models of structure formation predict that the densest regions will collapse at earlier times, forming the cores of clusters. The cluster galaxies at a given epoch will, therefore, be more evolved than the average field galaxy (De Lucia, Kauffmann & White 2004). Further, the decline in global star formation rate with redshift (Madau 1997; Ferguson, Dickinson & Williams 2000) will result in fewer star-forming field galaxies being accreted on to clusters at later times. However, as the clusters assemble and evolve, the accreting galaxies are also subjected to various interactions with other galaxies and the wider group or cluster environment.

These physical processes will impact the galaxies in different ways, affecting both star formation rates and stellar distributions. Strong gravitational interactions such as mergers and strong tidal interactions (Barnes & Hernquist 1992, 1996) are efficient in altering galaxy structure as well as triggering star formation. Indeed, it has been observed that most starbursts or galaxies with very high star formation display merger signatures, irrespective of redshift (Duc et al. 1997; Elbaz & Cesarsky 2003). Recent studies like Kartaltepe et al. (2012), however, show that extreme star-forming galaxies since $z \sim 2$ are comprised of a mix regular morphology galaxies and galaxies showing early stages of interaction/ongoing mergers. Tidal interactions or harassment lead to stripping of outer material from the galaxy under the impact of high-speed encounters, resulting in temporary enhancement of star formation (Moore et al. 1996; Boquien et al. 2009).

While gravitational interactions may redistribute the stellar content of the galaxy or trigger bursts of star formation, gaseous processes also influence the star formation rate. With $\sim 10$ percent of the total mass of the cluster consisting of hot intracluster medium (ICM), infalling galaxies may undergo loss of their cold disc gas through ram-pressure stripping (Gunn & Gott 1972) or hot gaseous halo through starvation (Larson, Tinsley & Caldwell 1980). Low-redshift observational studies have shown evidence of stripping of the material from galaxies in cluster environments in the form of ‘jellyfish’ galaxies (Kenney, van Gorkom & Vollmer 2004; Merluzzi et al. 2013; Fumagalli et al. 2014; Jaffe et al. 2015).

Several types of transition objects have been identified that represent populations of galaxies in the process of having their star formation shut down. For example, ‘post-starburst’ or ‘k+a’, galaxies make up a significant fraction of intermediate to high-z clusters, while being rare at $z = 0$. Further, the strong correlation between cluster velocity dispersion and ‘k+a’ fraction suggests a possibility of interactions with the ICM being responsible for the eventually turning them passive (Poggianti et al. 2009), though it may not be the dominant process for the transformation (De Lucia et al. 2009). Structurally, this could be related to the transformation of star-forming spiral galaxies into lenticular galaxies, as discussed by Dressler et al. (1997) and Poggianti et al. (1999), further corroborated by the lack of blue lenticulars in clusters (Jaffe et al. 2011). Indeed, Gallazzi et al. (2009) and Wolf et al. (2009) found a cluster-specific population of smooth spiral galaxies with suppressed star formation in the STAGES multiple-cluster system (Gray et al. 2009).

Analysis of rotation curves by Bosch et al. (2013) confirmed that these same objects contain kinematically disturbed gas while remaining optically symmetric. It is clear that for these smooth passive spirals, gas processes such as starvation and ram-pressure stripping (Haines et al. 2013) are shutting down star formation without simultaneous wide-scale redistribution of their stellar material.
0.4 < z < 1. Optical imaging in the V, R and I bands was obtained with FORS2 on the ESO Very Large Telescope (VLT; White et al. 2005). Near-IR J and Ks photometry from SOFI at the 3.5 m New Technology Telescope is also available (Rudnick et al. 2009). Spectroscopy with FORS2/VLT was obtained for an effectively I-band-selected sample of galaxies with redshifts at or near the cluster redshifts (Halliday et al. 2004; Milvang-Jensen et al. 2008).

In addition, the cluster fields studied here also have the Hubble Space Telescope (HST) I-band (F814W) imaging obtained with the ACS camera (Desai et al. 2007). A total of five pointings were taken in each field, four adjacent one-orbit pointings covering 6.5 arcmin × 6.5 arcmin (approximately the field of the VLT optical images) and an additional four-orbit pointing covering the central 3.3 arcmin × 3.3 arcmin region of each cluster. Mosaic stacks that encompass all ACS tiles for a given cluster were created employing MultiDrizzle (Koekemoer et al. 2003), and scripts for optimized image registration and weighting as detailed in Schrabback et al. (2010). The work presented in this paper exploits the HST imaging to carry out the structural analysis of the galaxies. Table 1 gives a summary of the properties of the cluster sample.

Other follow-up data for these clusters include Spitzer IRAC (3–8µm) and MIPS (24µm) imaging, H or narrow-band imaging for three of the fields (Finn et al. 2005) and XMM–Newton/EPIC X-ray observations for a subset of the clusters (Johnson et al. 2006). The HST-based visual galaxy morphologies were published by Desai et al. (2007). For the purposes of this study, we have collapsed the fine morphological classes given by the original catalogue into four broad bins: ellipticals, lenticulars, spirals and irregulars.

### 2.1 Environment definition

We separate the sample by global environment based on spectroscopic cluster membership. A galaxy is considered a member of a cluster if its spectroscopic redshift lies within ±3σcl from the average cluster redshift zcl (Halliday et al. 2004; Milvang-Jensen et al. 2008). All the galaxies that do not satisfy this criterion are considered to be in the field sample. Although the redshift distribution of cluster and field galaxies are very similar, to avoid potential biases we only consider field galaxies whose redshifts are contained within the redshift range spanned by the clusters (with a z tolerance of ±0.05 at each end, i.e. from the lowest and the highest cluster redshift in our sample).

Some of the EDisCS fields contain secondary clusters in addition to the main ones (White et al. 2005; Milvang-Jensen et al. 2008). Members of these secondary clusters are, for consistency, also included in the cluster sample. These secondary clusters are denoted in Table 1 with ‘a’ or ‘b’ following the main cluster ID. Poggianti et al. (2009) classified these secondary structures into clusters and groups. Structures with σcl > 400 km s⁻¹ were classed as ‘clusters’, while structures with 160 km s⁻¹ < σcl < 400 km s⁻¹ and at least eight spectroscopic members were classed as ‘groups’. In this paper, the global environment of the galaxies is defined based on their cluster membership irrespective of the host cluster/group identification.

### 2.2 Sample selection

In what follows, we will use both the whole spectroscopic sample defined in Section 2.1 (to maximize the number of galaxies) and a mass-complete subsample containing 265 galaxies with a stellar mass-completeness of log M* / M⊙ = 10.6 (Vulcani et al. 2010). The mass-complete subsample will be used to ensure that no mass-related biases affect our conclusions.

Note that both samples contain only galaxies whose spectra have an S/N ratio in the continuum that is larger than 2. This ensures not only the reliability of the redshifts, but also a reasonable quality in the measurements of spectral features such as the 4000 Å break, the [O ii] λ3727 emission line and several strong Balmer absorption lines. These spectral features are analysed in Kelkar et al. (in preparation) and Rudnick et al. (submitted) using similarly defined samples for direct comparison. Table 2 provides some information on these samples.

### 3 VISUAL CLASSIFICATION OF STRUCTURAL DISTURBANCES

To complement the information provided by the galaxies’ morphological Hubble types (Desai et al. 2007), in this paper, we qualitatively analyse galaxy ‘structure’ by studying the detailed distribution of galaxy light. For this purpose, we use the terms ‘asymmetry’ to refer to visible departures from a symmetric light profile, and ‘disturbance’ to indicate our assessment of whether the cause of that deviation is internal or external in origin. Therefore, a galaxy may have a combination of ‘asymmetry’ and ‘disturbance’ properties. For instance, a galaxy may be symmetric and undisturbed; another may be internally asymmetric but undisturbed (e.g. an otherwise
symmetric spiral galaxy with a prominent H II region); a third one may be asymmetric due to an external distortion (e.g. gravitational interaction). To clarify all these possible categories, Fig. 1 gives a graphical representation of the classification scheme, described below.

This classification was carried out by visually inspecting the HST images of all the galaxies in our sample taken in the I band (corresponding, approximately, to the rest-frame B band). Three of the authors (KK, AAS, MEG) performed independent classifications of every galaxy. Note that these classifications were carried out blindly, without knowledge of the cluster membership of the galaxies, their redshifts or their morphology type.

3.1 Visual asymmetry class

As a first step in the classification, we separate galaxies into two distinct classes, ‘symmetric’ and ‘asymmetric’. This is done by visually identifying asymmetric features in the galaxies’ images as possible indicators of structural disturbances. Explicitly, we classified galaxies as ‘asymmetric’ if they possess asymmetric features, and ‘symmetric’ in the absence of them.

3.2 Visual disturbance class

For those galaxies with visual asymmetry, we further designed a classification scheme, independent of morphological type, to identify the probable cause of the disturbance. Fig. 1 gives a graphical representation of the classification scheme, described below.

(i) Internal asymmetry (iA). The galaxies classified under this category showed distinct visual asymmetry due to features like prominent star-forming regions/knots in the galaxy. Further, these asymmetries showed no clear evidence of any form of external processes that may be acting on the target galaxy. These galaxies are assigned a non-zero asymmetry but no disturbance index and constitute only \(\sim 7\) per cent of the total sample. However, note that such internal asymmetries may well still be the result of external causes like mergers (Bournaud, Duc & Emsellem 2008) or ram-pressure stripping events (Poggianti et al. 2016), even though these may not be apparent.

(ii) Galaxy interaction (i/I). Galaxies in this class showed features indicating interactions with a companion galaxy. Lowercase ‘i’ denotes ‘weak interaction’, while uppercase ‘I’ indicates ‘strong interaction’, as judged by the classifier.

(iii) Tidal interaction (t/T). Galaxies in this class displayed tidal features (e.g. a tail of stripped material extending outside the galaxy) but with no obvious sign of an interacting neighbour. As before, lowercase/uppercase letters are used to indicate the strength of the features.

(iv) Mergers (m/M). We identified ongoing galaxy mergers based on distinct asymmetric merging signatures. Minor or major mergers were identified through a visual assessment of the stellar mass ratios involved. Galaxies appearing as a single distorted merger remnant
or possessing clear galaxy cores of similar brightness were classified as major mergers (M). Galaxies seen merging with a smaller galaxy were identified as minor mergers (m). Our classifications are informed by the visual appearance of merging galaxies in simulations, and experience of classifying mergers in STAGES (Gray et al. 2009) and EDisCS.

(i) Chaotic/undefined systems (C/X). The final class contained a small number of galaxies (less than 1 percent of the total sample) displaying structures that were chaotic or could not be associated with any of the categories above.

3.3 Final classifications

Symmetric galaxies were assigned an index of ‘0’, whereas asymmetric galaxies were indexed as ‘a’/‘A’, with the lower/upper case of the index denoting an assessment of the strength (weak/strong) of the asymmetric features. Asymmetric galaxies were then assigned a disturbance class label according to the schema described above, with the lower/upper case of the index denoting the mild/strong nature of the external features. To determine the strength of the visual classification (i.e. weak/strong), individual indices of ‘0’ were given a weight of 0 while lower/upper case indices were given a weight of ‘1’ and ‘2’, respectively.

Since three independent classifiers classified each galaxy, the final combined classification for asymmetry and disturbance was determined by majority vote (independent of the index case). The final classification was then associated with the summed weights of the contributing indices. If all the three classifiers disagreed, the final classification was selected at random from the three votes. The strength of classification in this case would be the weight of the randomly selected classification index. In a small number of cases where a classifier was not confident in the assessment, the individual contribution was downweighted to 0.5.

Also note one further subtlety in our classification scheme. A subset of galaxies with smooth early-type morphologies (asymmetry = ‘0’) nevertheless were identified on the balance of probability as having a disturbance class (minor interaction, ‘i’) based on the presence of a very close neighbour. These ‘0&i’ galaxies represent possible dry merger candidates, where a merger may be ongoing but the visual signatures are short lived due to an absence of gas in the galaxies (Bell et al. 2006).

Table 3 gives the fractions of galaxies in each disturbance class in the cluster and field environment with respect to the entire sample.

| Morphology | Environment | Undisturbed (O) | Internally asymmetric (IA) | Interacting (I/I) | Tidal (t/T) | Merger (m/M) |
|------------|-------------|-----------------|---------------------------|-----------------|------------|-------------|
| Ellipticals (E) | Cluster | 0.79 ± 0.04 | 0.01 ± 0.01 | 0.17 ± 0.04 | 0.02 ± 0.01 | 0.02 ± 0.01 |
| Lenticulars (S0) | Field | 0.64 ± 0.08 | 0.08 ± 0.05 | 0.14 ± 0.06 | 0.11 ± 0.05 | 0.08 ± 0.05 |
| Spirals (Sp) | Cluster | 0.93 ± 0.04 | 0.01 ± 0.01 | 0.07 ± 0.04 | 0.01 ± 0.01 | 0.01 ± 0.01 |
| Irregulars (Irr) | Field | 0.85 ± 0.11 | 0.05 ± 0.05 | 0.15 ± 0.11 | 0.05 ± 0.05 | 0.05 ± 0.05 |

We use the Wilson (1927) binomial confidence interval to compute the 1σ uncertainty in the fractions $\hat{f}$:

$$\hat{f} \pm \delta \hat{f} = \frac{N_i + k^2/2}{N_{tot} + k^2} \pm \frac{k \sqrt{N_{tot}}}{N_{tot} + k^2} \sqrt{f_i(1-f_i) + \frac{k^2}{4N_{tot}}},$$

(1)

where $f_i = N_i/N_{tot}$, and $k$ is the 100$(1 - \alpha)/2$th percentile of a standard normal distribution, $\alpha$ being the error percentile corresponding to the 1σ level (refer also to Brown, Cai & DasGupta 2001). These fractions will be discussed in Section 6. Note that even if $N_i = 0$, the estimated value of $\hat{f}$ is not necessarily 0.

4 QUANTITATIVE STRUCTURE

In addition to our qualitative assessment of galaxy asymmetry and disturbance, we also further explore quantitative measurements of galaxy structure. Specifically, we extract structural information from the galaxy residuals after a smooth surface brightness profile is removed. Although originally intending to identify minor mergers, Hoyos et al. (2012) show that measuring structural parameters of residuals of galaxies is a good way of determining disturbances in galaxy structure that are otherwise faint to detect visually but are observable over a longer time-scale.

4.1 Constructing galaxy residual images

The galaxy residual images required for this analysis were obtained using the data pipeline GALAPAGOS (Galaxy Analysis over Large Area: Parameter Assessment by GALFITing Objects from SEXTRACTOR; Barden et al. 2012). All galaxies from the 10 HST I-band mosaics were detected using SEXTRACTOR, and corresponding image stamps were created by GALAPAGOS. These image stamps were fitted with a 2D Sérsic light profile (Sérsic & de Córdoba Observatorio Astronómico 1968) using GALFIT (Peng et al. 2002, 2010a), which resulted in generation of galaxy residual stamp images after the Sérsic model was subtracted. Kelkar et al. (2015) contains further details of the fitting method. These residual images were used to compute quantitative ‘Asymmetry’ ($A_{as}$) and a measurement of the signal remaining after subtracting the Sérsic model (residual flux fraction, ‘RFF”).

4.2 Asymmetry in residual images ($A_{as}$)

Using the CAS (Concentration, Asymmetry, ClumpineSs;ershady, Jangren & Conselice 2000) system, we define the asymmetry
Image whereas Ii represents the flux at pixel (i, j) in the galaxy residual image whereas \( I_{i,j}^{180} \) represents the same image rotated through 180°.

The second term in the equation accounts for the background contribution. We construct a background noise image to compute the second term using the EDISCS noise images for the HST ACS mosaics. As with the construction of the residual images, associated noise images were cut out for individuals galaxies with the same dimensions as the residual images.

As a first step, these noise stamp images were multiplied with the exposure time corresponding to the region in the mosaic (refer to Section 2). This modified image was then multiplied by a white noise image with \( \sigma = 1 \). The resultant image is a good representation of the background noise. Both the terms in the above equation are computed over an aperture defined by constructing an ellipse whose semimajor axis is the radius of Kron aperture\(^2\) and are minimized independently. We implement a slightly modified method for minimizing these terms, deviating from the original recipe described in Conselice, Bershady & Jangren (2000). We allow the centre of rotation to lie at a maximum of 3 pixels in radius from the SEXTRACTOR defined centre over a grid of predefined points 1 pixel apart. The main advantage of this new method is that the pixel values are not interpolated under 180° rotation due to the choice of integral rotation centres. Moreover, one could think of this method computing global rotational asymmetry, and hence reducing the computation time as compared to the original method. The possible values that \( A_{res} \) can take ranges from 0 to 2.

### 4.3 Residual flux fraction

The second quantitative diagnostic we use is the RFF (Hoyos et al. 2011, 2012), which gives the fraction of signal contained in the residual image of the galaxy that cannot be explained by the background fluctuations. It is defined as

\[
\text{RFF} = \frac{\sum_{i,j} |I_{i,j} - I_{i,j}^{\text{GALFIT}}| - 0.8 \times \sum_{i,j} \sigma_{i,j}^{\text{bg}}}{\sum_{i,j} I_{i,j}^{\text{GALFIT}}},
\]

where \( I_{i,j} \) represents the flux at pixel (i, j) in the galaxy image, while \( I_{i,j}^{\text{GALFIT}} \) is the model created by GALFIT. \( \sigma_{i,j}^{\text{bg}} \) is the background rms. As discussed previously, we use the same galaxy residual images for computation of RFF over the Kron aperture. The factor of 0.8 enables the expectation value of RFF for purely Gaussian noise error image of constant variance to be 0.0.

### 4.4 Defining galaxy structure

Hoyos et al. (2012) show that \( A_{res} \) and RFF are capable of automatically detecting structural disturbances in galaxies when used together. Using a training sample of visually identified galaxy mergers from the low redshift STAGES field (Gray et al. 2009), Hoyos et al. (2012) show that these mergers occupy a specific region on the \( \text{RFF} - A_{res} \) plane. This enables a statistical division of the parent sample into two sub-populations: one containing mergers with some contamination by non-merging galaxies, and the other almost devoid of any merging galaxies (a powerful null test).

We use the same technique on our mass-complete sample to identify a subsample of structurally disturbed galaxies that we can compare with our qualitative identifications. We examine the RFF versus \( A_{res} \) distribution for the entire population of galaxies in our sample of morphologically classified galaxies with spectroscopic information. We divide our sample by defining a separating border as a second order polynomial of RFF in terms of \( A_{res} \) and separates visually identified mergers from non-mergers.

The statistical quality of the two populations is determined by the F-score, \( F_{\beta} \) (Rijsbergen 1979) given by

\[
F_{\beta} = \frac{(1 + \beta^2) \times p \times r}{\beta^2 \times p + r},
\]

where ‘\( r \)’ denotes the sensitivity or completeness of the method, and ‘\( p \)’ denotes specificity or the true negative rate. The factor \( \beta \) is a control parameter that determines the relative importance of \( r \) and \( p \). In this work, we have used \( \beta = 1.25 \), to be consistent with Hoyos et al. (2012). This border is then optimized such that it maximizes the F-score.

In order to apply the F-score maximization for detection of galaxy structure, we use a training sample of galaxies classified visually as mergers from our parent sample to calculate \( r \) and \( p \). Fig. 2 shows both populations for the mass-complete sample, with the separating border represented by the green solid line. The galaxies above the solid green line denote the positive detections of galaxies being mergers, with the merger training sample retrieved with a high

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\(^2\) In this paper, we use the definition of radius of the ‘Kron aperture’: 2.2\( r_1 \), where \( r_1 \) is the first moment of the light distribution (Bertin & Arnouts 1996). This corresponds to the semimajor axis for an elliptical light distribution.
tidal and interacting galaxies on the RFF versus $A_{\text{res}}$ plane. The $F$-score, $r$ and $p$ values for each class of galaxies are computed using this border. The open triangles in the right-hand panel denote the subclass of interacting galaxies nevertheless classified as ‘symmetric’ according to our classification scheme (discussed in Section 4.4).

We next connect the quantitative measures of galaxy structure with morphology. Using the CAS system, Conselice (2003) evaluate the morphologies of galaxies not classified as mergers. Refer to Hoyos et al. (2012), for the detailed method.

We note that including low-mass galaxies ($\log M_*/M_\odot < 10.6$) does not change the border significantly. We are able to separate the merger subsample from the parent sample, albeit with lower completeness. For comparison, the galaxies with masses below the mass completeness are overplotted in light blue in Fig. 2. It is clear that this method gives a clean sample of non-merging galaxies. Comparing to Hoyos et al. (2012), we see a significant flattening of the border separating the mergers. This can be attributed to the lower S/N of galaxies at intermediate redshifts, as compared to the local sample of STAGES galaxies used in Hoyos et al. (2012). This is also reflected in the range of RFF and $A_{\text{res}}$ values. However, the important outcome of this analysis is that while it is possible to separate regular galaxies from the disturbed galaxies using these two non-parametric measures, it is the RFF that is the most significant discriminator of galaxy structure in our sample. Thus, RFF gives a measure of ‘roughness’ in galaxy structure.

Comparing the border determined using the visually classified mergers to the distribution of galaxies showing disturbances due to other external causes, we see that this technique is consistent in separating structurally disturbed galaxies. Fig. 3 shows the merging, tidal and interacting galaxies on the RFF versus $A_{\text{res}}$ plane. The $F$-score, $r$ and $p$ for the tidal and interacting galaxies is computed using the border determined for the merger training subset. Although the location is comparable for merging and tidal galaxies on this plane, we find interacting galaxies extend below the separating line in RFF. Therefore, in accordance with the classification scheme, we separate the ‘true’ interacting galaxies from the visually symmetric interacting galaxies (open yellow triangles), despite the presence of a companion. We note that, as expected, the symmetric interacting galaxies (dry merger candidates, or ‘0&i’) are the objects populating the region below the separating border in the RFF versus $A_{\text{res}}$ plane.

5 LINK BETWEEN THE QUALITATIVE AND QUANTITATIVE STRUCTURE

We next consider the variation of quantitative measures of structure with the visually determined causes of disruption. Fig. 5 shows the distribution of RFF and $A_{\text{res}}$ for galaxies disrupted due to different mechanisms. If we consider only the RFF of galaxies, we find that RFF alone is not able to distinguish the tidal, merging and internally asymmetric galaxies, indicating that RFF is sensitive to the degree of disturbance rather than the cause of the disturbance. This result is also graphically demonstrated when comparing the best border for galaxies in different disturbance classes in Fig. 3. Additionally, the subclass of symmetric interacting galaxies (‘0&I’) seem to have RFF distributions similar to galaxies with regular morphologies, although the distribution for the true interacting galaxies lies in between.

The lower panel of Fig. 5 shows the distribution of $A_{\text{res}}$ for different disturbance classes. Interestingly, a significant stratification is seen in the distribution of $A_{\text{res}}$ for different disturbance classes, with undisturbed galaxies having a low $A_{\text{res}}$ and mergers showing extreme values of $A_{\text{res}}$.

We conclude that RFF is able to separate galaxies with disturbed structure from those with regular undisturbed structure, but has little discriminatory power to differentiate between the different types (or causes) of such disturbances. On the other hand, $A_{\text{res}}$ is more sensitive to the different types (or causes) of structural disturbance in the galaxies. In simple terms, RFF can be used as a measure of the degree of structural disturbance, while $A_{\text{res}}$ provides information on the cause of it. Or, more precisely, a combination of both parameters can be used to provide information on both the degree and the cause of galaxy deviations from symmetry.
Figure 4. Separating quantitative measurements of structure by visual asymmetry. The histograms show the distributions of RFF and \( A_{\text{res}} \) for visually symmetric (0), mild (a) and strongly asymmetric (A) galaxies at fixed morphology. Early-type galaxies (E+S0) show little quantitative or qualitative evidence for asymmetry or disturbance. Both top and bottom panels for spiral galaxies (middle) clearly show a separation in RFF and \( A_{\text{res}} \), with higher values corresponding to the strongest visual asymmetries.

6 STRUCTURE AND STAR FORMATION VERSUS GLOBAL ENVIRONMENT

6.1 Effect of global environment on galaxy disturbances

This analysis uses the spectroscopic sample with visual classifications to compare the properties of galaxies as a function of global environment (e.g. cluster versus field) rather than a more continuous measure of local environment. That will be the object of a subsequent paper (Kelkar et al., in preparation).

In Section 2.1, we described a full redshift-controlled field sample together with a mass-complete subsample. The full sample has the advantage of being significantly larger, but it suffers from incompleteness for galaxies with \( \log M_*/M_\odot < 10.6 \). Nevertheless, because the selection and the observation of cluster and field galaxies over the relevant redshift range is identical, the incompleteness should affect field and cluster galaxies equally. With this in mind, when carrying out comparisons between the properties of cluster and field galaxies it should be safe to use the full redshift-controlled sample. Nevertheless, we will carry out a parallel analysis using the smaller mass-complete subsample to test whether our conclusions depend on the exact sample that we use. In general, we find that the conclusions described below for the full sample are consistent with the ones we obtain for the mass-complete sample within the statistical uncertainties. Further, to remove additional effects brought in by the fact that galaxy morphology depends strongly on environment (Dressler 1984; Treu et al. 2003; Desai et al. 2007), we look at the disturbance content of galaxies in clusters and field at fixed morphology (Table 3). We find that the fractions of galaxies classified visually as interacting, tidal and merging do not seem to depend on the environment.

6.2 Distribution of galaxy disturbances and star formation as a function of global environment

As discussed in the introduction, the internal and external physical mechanisms in various galaxy environments are responsible for the transformation of galaxy structure as well as star formation. Although disentangling the relative importance of these processes is difficult, quenching in the star formation of galaxies is observed in dense environments (Balogh et al. 2007; Haines et al. 2013; Kovác et al. 2014). With the aim of studying the possible links between the quenching of star formation and the morphological change in galaxies, we next look at the star formation properties of structurally disturbed galaxies.

It was found by Wuyts et al. (2007) and Williams et al. (2009) that galaxies show a strong bimodality on the rest-frame \( (U - V) \) versus \( (V - J) \) colour–colour space, with the actively star-forming galaxies following a diagonal path and the quiescent galaxies populating the upper-left region on this space (see also Labbé et al. 2005; Wolf, Gray & Meisenheimer 2005). Moreover, the \( (U - V) \) versus \( (V - J) \) plane is more robust to separate the dusty star-forming galaxies from the passive galaxies, as compared to the single colour selection. Therefore, we construct a rest-frame \( (U - V) \) versus \( (V - J) \) colour plot (\( UVJ \) hereafter) to distinguish the passive and star-forming population (Fig. 6; see also Patel et al. 2012). The \( UVJ \) plot shows that the low-mass galaxies (\( \log M_*/M_\odot \leq 10.6 \)) are bluer in colour,
as expected from the existing correlations between mass, metallicity, star formation rate and dust extinction (Lara-López et al. 2010).

The empirical selection criteria for passive galaxies, as introduced by Williams et al. (2009), highlights the observed bimodal distribution of galaxies on the $UVJ$ plane at low-$z$, and the subsequent weakening at high-$z$. Fig. 6 shows such a distribution for galaxies in our sample with different morphologies. The boundary separating star-forming and passive galaxies in the $UVJ$ plane is somewhat arbitrary, and Williams et al. (2009) found that this boundary is weakly redshift dependent. It will also depend on the exact photometric bands used in the observations. In Fig. 6 we show the boundaries selected by Williams et al. (2009) for two redshift ranges, $0.5 < z < 1$ and $z > 1$. Given the redshift of our galaxies, the $0.5 < z < 1$ boundary should be, in principle, more appropriate. However, we notice that the $z > 1$ boundary seems to do a much better job at separating the bimodal colour distribution than the lower redshift one, in particular if we take into account the location of galaxies with different morphologies. A density-mapping analysis corroborates this visual impression, revealing that galaxies with early-type morphology are visually smoother as expected from the existing correlations between mass, metallicity, star formation rate and dust extinction (Lara-López et al. 2010).

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smoother and symmetric. This correlation, however, seems to be independent of the global environment.

6.3 A population of smooth passive spirals in clusters

We make particular note of those spiral galaxies that are simultaneously classified as visually smooth/undisturbed and passive. Fig. 7 shows that most are found to reside in clusters, with the majority (>70 per cent) of these having stellar masses greater than the mass completeness limit, both in cluster and field environment. This observation agrees with the findings from works such Poggianti et al. (1999), Wolf et al. (2009), Cantale et al. (2016) and Rodríguez del Piño et al. (2017), who both find a significant fraction of passive spirals in the cluster environment that may represent a key transition population undergoing slow environmental quenching (see also Bamford et al. 2009; Masters et al. 2010). Most recently, Hoyos et al. (2016) reported that optically passive spiral galaxies in clusters, at a given mass, tend to have lower star formation rates and smoother structure as compared to the galaxies in field. This result is particularly relevant here because these authors used quantitative structural measurements similar to the ones we present in this paper.

To test whether quantitative measurements of galaxy disturbance support the findings based on our visual diagnostics, we present in Figs 8 and 9 the rest-frame $UVJ$ diagram colour-coded with respect to RFF and $A_{res}$, for cluster and field galaxies. Complementing Fig. 7, both panels in Fig. 8 show that these passive undisturbed spirals have lower RFF, indicating a smoother structure. This is further enhanced in Fig. 9, where we see that passive spirals in clusters are much more symmetric with low $A_{res}$. This observation combines the result from Figs 5 and 7 demonstrating the external nature of structural disturbances for the majority of the asymmetric spirals, and the different behaviour of $A_{res}$ in the different disturbance classes.

We use two-sample Kolmogorov–Smirnov (K–S) tests to check whether the RFF and $A_{res}$ distributions for these passive spirals, and the regular undisturbed spirals are statistically similar. Fig. 10 compares the RFF and $A_{res}$ distributions for passive spirals and regular undisturbed spirals, both in cluster and field environments. The KS tests yields probabilities of $5.3 \times 10^{-4}$ and 0.02 for these distributions to be the same for cluster and field galaxies, respectively. This emphasizes the fact that passive spirals tend to show statistically smaller RFF values -and are therefore smoother than star-forming ones irrespective of their global environment. However, the distributions of $A_{res}$ for passive and star-forming spirals appear to be only marginally different in clusters (K–S test probability of 0.03), while the small number statistics prevent a robust comparison for field spirals.

These results reinforce out findings from Fig. 7, implying that the effect of the cluster environment on the spiral galaxy population is to increase the fraction of passive smooth spiral galaxies without destroying their spiral morphology. This would signify that spirals on entering clusters become structurally smooth due to the quenching of their star formation followed later by morphological transformation, perhaps into S0s. This implies that that the mechanisms ultimately responsible for the quenching of these galaxies’ star formation in clusters must be reasonably gentle, affecting primarily the gas while leaving the galaxies’ stellar structure largely unchanged. These galaxies become smoother due to the suppression of the star formation itself, since ‘rough’ structures such as H II regions would disappear (see e.g. Hoyos et al. 2016). Gas-driven mechanisms such as ram-pressure striping are therefore strongly favoured. These conclusions are in good agreement with the
findings of Bösch et al. (2013) based on observation of the lower redshift STAGES field (Gray et al. 2009), which show that red spirals display distinct asymmetries in their gas rotation curves, and are therefore preferentially experiencing ram-pressure stripping, as compared to normal spiral galaxies.

Complementary conclusions were obtained by Cantale et al. (2016, see their fig. 10) using the UVJ colours of discs in the EDiSCS data set. These authors find that \sim 50\% of cluster spirals have redder discs than their field counterparts at fixed morphology, but they also find evidence that spiral galaxies must
Aragón-Salamanca & Merrifield (2014), suggesting that in the pu-
If that is not the case, this result supports the findings of Johnston,
that these galaxies may have been missed preferentially in the field.
completeness limit. It is therefore not impossible, albeit unlikely,
ter lenticulars have relatively low stellar masses that are below the
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in (and/or is channelled to) the bulge, where this final gasp of star
formation takes place. This process probably requires an external
cause and it may therefore be cluster-specific. That could explain
why this final episode of star formation is not observed in undis-
turbed field S0s, where other formation mechanisms may need to
be invoked.

7 CONCLUSIONS

In this paper, we present a detailed analysis of the structure of
a sample of field and cluster galaxies at intermediate redshift
(0.4 < z < 0.8) using HST images from the EDisCS that approx-
imately sample the B-band in the rest-frame of the galaxies. We
combine this structural information with extensive photometric and
spectroscopic data to study the links between galaxy structure and
other internal properties such as mass, morphology and star forma-
tion history, and how these are affected by the global environment
where the galaxies live.

We have analysed the galaxies’ structure following two paral-
lel methods. In the first one, we visually inspected the galaxies’
HST images and classified them into symmetric and asymmetric;
the asymmetric class was further divided into subclasses that try
to identify the likely cause of the asymmetry (internal asymme-
gy, galaxy–galaxy interactions, tidal interactions and mergers). The
second method uses quantitative non-parametric measurements of
the galaxies’ deviation from a smooth symmetric light distribution.
An elliptical Sérsic model is first fitted to the galaxies’ HST images,
and the residuals are then quantified using the RFF (measuring the
fractional contribution of the residuals to the total galaxy light, tak-
ing into account the noise), and $A_{res}$ (the asymmetry of the residual
light distribution). The main conclusions of this structural analysis
are as following.

(i) The qualitative (visual classification) and quantitative (RFF
and $A_{res}$) assessments of galaxy structure provide consistent and
complementary information.

(ii) RFF is able to separate galaxies with disturbed structure from
those with regular undisturbed structure, but has little discriminatory
power to differentiate between the different types (or causes) of
such disturbances. On the other hand, $A_{res}$ is more sensitive to the
different types (or causes) of structural disturbance in the galaxies.
A combination of both parameters can therefore be used to provide
information on both the degree and the cause of galaxy deviations
from symmetry.

We then link this structural information with the galaxies’
masses, morphologies and star formation histories, and conclude the
following.

(i) As expected, the vast majority of elliptical and S0 galaxies are
smooth and symmetric, while all irregular galaxies are ‘rough’ and
asymmetric. Statistically, spiral galaxies tend to have higher values
of RFF and $A_{res}$ than early-type galaxies.

(ii) Over 60 per cent of all spiral galaxies are visually classified
as showing some degree of asymmetry. Of these, about one third
exhibit asymmetry of internal origin (due, e.g. to the presence of
large star-forming regions), while the rest show signs of galaxy–
galaxy interactions, tidal interactions or mergers in comparable
proportions.

(iii) In agreement with the results of Hoyos et al. (2016), we
find that RFF correlates strongly with the star formation activity
of the galaxies: star-forming galaxies tend to have much ‘rougher’
structures.

Figure 10. The RFF and $A_{res}$ distributions for spiral galaxies in cluster (left-
hand panel) and field (right-hand panel) environments. The filled purple
histograms show the subset of passive symmetric spirals, as discussed in
Section 6.3. The inset ‘$p$-values’ give the probability from two sample K–S
test, showing that in addition to being visually symmetric, the cluster passive
spirals are quantitatively ‘smoother’.

6.4 A small population of star-forming cluster S0s

Turning our attention to lenticular (S0) galaxies, Fig. 7 indicates
that, as expected, the vast majority of these galaxies are symmetric
and passive both in clusters and in the field. However, although
the numbers are small and the statistical uncertainties very large,
there seems to be some marginal evidence suggesting the presence
of an excess of star-forming S0 galaxies in clusters with respect to
the field. Some of these star-forming S0s are asymmetric, showing
signs of perturbation (interactions, mergers and tidal features),
but there seems to be also a population of symmetric star-forming
S0s in clusters that is absent in the field. Specifically, we do not
find a single asymmetric undisturbed star-forming S0 in the field,
although the expectation value of their fraction shown in Fig. 7 is
not 0 (cf. equation 1). Although the undisturbed lenticulars have a
wide spectrum of stellar masses in all environments, we note that
the majority (>80 per cent) of the symmetric star-forming cluster
lenticulars have relatively low stellar masses that are below the
completeness limit. It is therefore not impossible, albeit unlikely,
that these galaxies may have been missed preferentially in the field.
If that is not the case, this result supports the findings of Johnston,
Aragón-Salamanca & Merrifield (2014), suggesting that in the pu-
tative transformation of spirals into S0s in clusters, a final episode
of star formation takes place in the central regions (bulges) of these
galaxies after the disc star formation has ceased. In this scenario, the
gas is removed from the disc of the spirals, while some gas remains
in (and/or is channelled to) the bulge, where this final gasp of star
formation takes place. This process probably requires an external
cause and it may therefore be cluster-specific. That could explain
why this final episode of star formation is not observed in undis-
turbed field S0s, where other formation mechanisms may need to
be invoked.

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are as following.

(i) The qualitative (visual classification) and quantitative (RFF
and $A_{res}$) assessments of galaxy structure provide consistent and
complementary information.

(ii) RFF is able to separate galaxies with disturbed structure from
those with regular undisturbed structure, but has little discriminatory
power to differentiate between the different types (or causes) of
such disturbances. On the other hand, $A_{res}$ is more sensitive to the
different types (or causes) of structural disturbance in the galaxies.
A combination of both parameters can therefore be used to provide
information on both the degree and the cause of galaxy deviations
from symmetry.

We then link this structural information with the galaxies’
masses, morphologies and star formation histories, and conclude the
following.

(i) As expected, the vast majority of elliptical and S0 galaxies are
smooth and symmetric, while all irregular galaxies are ‘rough’ and
asymmetric. Statistically, spiral galaxies tend to have higher values
of RFF and $A_{res}$ than early-type galaxies.

(ii) Over 60 per cent of all spiral galaxies are visually classified
as showing some degree of asymmetry. Of these, about one third
exhibit asymmetry of internal origin (due, e.g. to the presence of
large star-forming regions), while the rest show signs of galaxy–
galaxy interactions, tidal interactions or mergers in comparable
proportions.

(iii) In agreement with the results of Hoyos et al. (2016), we
find that RFF correlates strongly with the star formation activity
of the galaxies: star-forming galaxies tend to have much ‘rougher’
structures.
Finally, the global environment (cluster versus field) of the galaxies is taken into consideration, and we find the following.

(i) At fixed morphology, there are no significant differences in the distribution of the disturbance classes of cluster and field galaxies.

(ii) About 40 per cent of all the spiral galaxies are classified as symmetric and undisturbed both in clusters and in the field. However, the fraction of these that are passive (i.e. non-star-forming) is twice as large in clusters than in the field: about half of the cluster symmetric spirals are passive, versus only one quarter in the field (with a significance of 2.3σ). These passive spirals are not only visually symmetric, but also quantitatively smoother (i.e. have smaller RFF values) than star-forming ones.

(iii) While nearly all lenticular galaxies are visually symmetric and undisturbed both in clusters and in the field, all the field ones are passive, while nearly ~20 per cent in the clusters are star-forming.

These results have significant implications for the evolution of spiral galaxies falling on to clusters and their subsequent transformation. Spirals entering clusters become structurally smooth (and red) due to the quenching of their star formation, but retain their spiral morphology for a while. The morphological evolution follows later, transforming them, probably, into S0s. The mechanism(s) ultimately responsible for the quenching of these galaxies’ star formation in clusters must primarily affect the gas while leaving the galaxies’ stellar structure largely unchanged. Gas-driven mechanisms such as ram-pressure stripping (where the disc gas is partially or totally stripped) and/or starvation/strangulation (where the gas supply is truncated) are therefore favoured. These conclusions are in good agreement with the findings of Bösch et al. (2013) based on observation of the lower redshift STAGES field (Gray et al. 2009), which show that red spirals display distinct asymmetries in their gas rotation curves, and are therefore preferentially experiencing ram-pressure stripping, as compared to normal spiral galaxies. Similar conclusions were obtained by Jaffé et al. (2011) for the EDisCS galaxies. This general scenario also agrees with observations indicating a rapid buildup of red-sequence galaxies earlier than the buildup of early-type galaxies as seen in clusters (Desai et al. 2007; De Lucia et al. 2007; Rudnick et al. 2009, 2012; Wolf et al. 2009; Cerulo et al. 2016).

At a more speculative level, our analysis also provides some clues on the putative transformation of spirals into S0s. The star-forming S0s we find in the clusters (but not the field) could be the descendants of the spiral galaxies experiencing a last episode of star formation before becoming S0s, supporting the findings of Johnston et al. (2014). These authors suggest that when spirals transform into S0s in clusters, a final episode of star formation takes place in the central regions (bulges) of these galaxies after the disc star formation has ceased. In this scenario, the gas is removed from the disc of the spirals, while some gas remains in (and/or is channelled to) the bulge, where this final gasp of star formation takes place. This process probably requires an external cause (e.g. ram pressure) and it may not work in the field. This could explain why this final episode of star formation is not observed in undisturbed field S0s, where other formation mechanisms may need to be invoked.

Focusing on the general question of ‘nature’ versus ‘nurture’ in galaxy evolution, it is now clear that the processes leading to the cessation of star formation depend both on internal properties (e.g. stellar mass) and environment, with the dominant quenching mechanisms being environmentally driven or mass-driven for different mass ranges, cosmic epochs and environments (Peng et al. 2010b; Thomas et al. 2010). Studies at lower (Baldry et al. 2006; Wetzel, Tinker & Conroy 2012) and higher redshifts (Muzzin et al. 2012) show that the quiescent fraction is correlated with both stellar mass and environment, and this relationship is maintained even at z > 1 (Quadri et al. 2012; Cooke et al. 2016; Hatch et al. 2016). With the importance of environmental quenching increasing with cosmic time and decreasing with stellar mass, our analysis is particularly relevant because we explore the intermediate-mass and redshift regimes, where both stellar mass and environment probably play significant roles in shutting down the star formation. In addition, focusing on differences in the internal galaxy structure at fixed morphology has allowed us to uncover subtle environmental effects that broader-brush studies had missed.

However, the work published here does not provide sufficient details on the possible environmental mechanisms at play because we have only considered global environments such as clusters and the field, disregarding more localized effects. This will be the focus of Kelkar et al. (in preparation) where we use tools like the projected phase-space diagram to constrain the detailed environmental history of the cluster galaxies. Moreover, studying directly the time-scales associated with the quenching of star formation will provide very valuable complementary information (Wolf et al., in preparation).

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