
Structure, Star formation history and Environment of galaxies

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“It is our choices, Harry, that show what we truly are, far more than our abilities.”

– Prof. A. P. W. B. Dumbledore
The Order of Merlin (First Class)
Headmaster of Hogwarts School of
Witchcraft and Wizardry
(pre 1955-1997)

Abstract

This thesis probes the role of environment in galaxy evolution, focussing particularly on understanding the links between the truncation of star formation, the transformation of galaxy structure, and environment. This study utilises deep *HST* imaging, photometric and spectroscopic data for galaxies within ten high- z cluster fields, which form part of the ESO Distant Cluster Survey (EDisCS). I first compare the mass–size relations of cluster and field galaxies, to address the dependence of galaxy size on environment observed from $z \sim 2.5$, and which seemingly disappear at lower redshifts. I find no significant difference in the size distributions of cluster and field galaxies of a given morphology, or with similar rest-frame $B - V$ colours. I rule out average size differences larger than 10–20% in both cases. Thus, I conclude that if the size difference at higher- z reported in the literature is real, the growth of field galaxies seem to have caught up with that of cluster galaxies by $z \sim 1$. Any putative mechanism responsible for galaxy growth has to account for the existence of environmental differences at high redshift and their absence (or weakening) at lower redshifts.

I then move on to analyse the effects of the global cluster/field environment on the internal structure of galaxies and their colours. I introduce quantitative non-parametric measures like the residual flux fraction ($RF\!F$) and the asymmetry in galaxy residuals (A_{res}) which measure deviations from symmetric light distributions using *HST* images, to explore the internal structure of galaxies. I also obtain complementary information on the probable causes of structural disturbances, both internal and external in nature, by performing visual classifications of cluster and field galaxies. Combining these two approaches of measuring galaxy structure, it is found that the $RF\!F$ is a good proxy for ‘roughness’ in the surface brightness distribution, while A_{res} is more sensitive to the *causes* of the structural disruption. Incorporating visual morphology and environment,

it was found that the external causes of disturbances were most often associated with star formation in spiral galaxies. When adding information on the star formation activity of galaxies, I discover two complementary subpopulations of galaxies abundant in clusters: visually undisturbed passive spirals, and undisturbed star-forming lenticulars. In addition to being visually symmetric, these passive cluster spirals are also consistently smoother than their star-forming counterparts. These observations, therefore, strongly advocate gentle physical processes acting on the gas content to modify the star formation properties of galaxies accreted into clusters, without large-scale disturbances in their stellar structure.

Considering the variations of quantitative galaxy structure with the star formation history of galaxies, I find that the young, star-forming galaxies are consistently rougher and more asymmetric than the galaxies with older passive stellar populations. Further, the galaxies with different average stellar ages seem to have similar distributions of RFF and A_{res} over cluster/field environments, thereby emphasising that the star formation history of galaxies is strongly linked to their intrinsic structure alone. Finally, complementing the global cluster/field environment, I explore the projected phase-space as a tool to investigate possible variations in galaxy structure and their stellar ages over the internal cluster environment. The analysis with the projected phase-space shows a decrease in the fraction of galaxies with younger stellar populations in the cluster core when separated by morphology, especially for spirals. This trend, however, is less pronounced in the observed distributions of RFF and A_{res} across the projected phase-space and the field.

All these observations, when put together, signify that the star formation in galaxies is shut down as they get accreted into clusters, while the internal structure of galaxies remains more or less unaffected. The actual morphological change in galaxies, therefore, will follow later after the star formation has already been truncated. Furthermore, the physical mechanisms driving these transformations would, therefore, be gas extinguishing ICM processes like ram-pressure stripping and starvation, which leave the galaxy structure undisturbed.

Published work

The vast majority of the work presented in this thesis is carried out by the author, and is contained in the following papers:

- I **Kelkar K.**, Aragón-Salamanca A., Gray M. E., Maltby D., Vulcani B., De Lucia G., Poggianti B. M., Zaritsky D., 2015, ‘*Galaxy sizes as a function of environment at intermediate redshift from the ESO Distant Cluster Survey*’, MNRAS, 250, 1246
- II **Kelkar K.**, Aragón-Salamanca A., Gray M. E., Rudnick G., & the EDisCS collaboration, 2016, ‘*Galaxy structure and environment at intermediate redshift-I: Links with star formation*’, MNRAS, in prep
- III **Kelkar K.**, Aragón-Salamanca A., Gray M. E., Rudnick G., Jaffé Y. L., Poggianti B. M., & the EDisCS collaboration, 2016, ‘*Galaxy structure and environment at intermediate redshift-II: A phase-space view*’, MNRAS, in prep

All the papers exploit the observations and data products, as discussed in Chapter 2, taken by many of my collaborators listed above. Paper I entirely contains Chapter 3, while Paper II and III are based on Chapters 4 and 5 respectively. Both these papers are currently in preparation, with Paper II ready to be submitted.

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My PhD. experience at the University of Nottingham has been truly enriching. I would, therefore, like to thank the University for giving me this opportunity and the financial support which enabled me to successfully finish the PhD.

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Structure, Star formation history and Environment of galaxies

Chapter 1

Introduction

Astronomy is the oldest science, with origins in prehistory through mythology, metaphysics and observational time-keeping. Since ancient times, the night sky has always baffled humans, inspiring them to question the periodic behaviour of celestial objects like stars, the Moon, and the Sun; the oldest records of astronomical phenomena were kept by the Sumerian civilisation¹ in ~ 3300 BC. From there, a momentous time in the history of astronomy that really established it as a science to the modern world, came when Galileo Galilei decided to point his telescope towards the night sky. Galileo's explorations thus expanded the frontiers of observational astronomy beyond the Solar system in the early 16th century. Further in the 17th century, it was William Herschel who gave the first understanding of the Milky Way being actually a disk-like system of stars around the Sun. The idea of 'island universes', coined by Immanuel Kant, further sowed seeds of possibilities for such systems existing outside the Milky Way, which we now know as galaxies. Very significant progress has been made on the data quality available for these systems, and hence our understanding of their properties (See, for example, 1.1).

Years of observing such 'nebulae', as the galaxies were thought of at the time, led to the first ever classification scheme, which is prevalent even today. Hubble (1926) gave the first systematic classification of structural characteristics of galaxies, or 'morphology' as we now term it. Using the 100-inch telescope at Mount Wilson, he cat-

¹Generally considered as 'cradle of civilisation', the Sumerians are also credited for developing the earliest writing system.



Figure 1.1: A view of Whirlpool galaxy (M51): evolution of observational astronomy over 160 years. *Left:* a sketch (with notes) made in 1845 by W. Parsons, 3rd Earl of Rosse, revealing the spiral structure of M51 for the first time as observed through his telescope ‘*The Leviathan*’. This discovery laid the foundation of characteristic stellar distribution of galaxies, different from the gaseous ‘nebulae’ observed at the time. *Right:* The current technologically advanced telescopes like the *Hubble Space Telescope (HST)* offer a detailed view of M51 and its morphology. This composite image was taken in 2005 with the ACS camera onboard *HST*.

alogued galaxies into four major classes: Ellipticals (galaxies with spheroidal shape), Lenticulars (‘lens’ like galaxies), Spirals (galaxies having distinct spiral arms) and peculiar/irregular galaxies (Figure 1.2). Various studies to date have confirmed that galaxies with early-type morphologies are primarily old passive and contain little gas while the spiral galaxies have bluer colours, star-forming and hence are gas-rich (for example, Holmberg, 1958). Hubble merely identified ‘early-type’ galaxies as those having least complex morphology as opposed to the ‘late-type’ galaxies², without implying any evolutionary connection. Nevertheless, this classification is still a very useful tool when trying to understand how the galaxies’ shape, colour and stellar content are linked and evolve over cosmic time and environments.

1.1 Our Universe: then and now

As it turns out, density is destiny – in a hierarchical universe - A. Dressler³

In order to understand the formation of galaxies and how they transform over cosmic time, we need to start from the roots of the universe. The origin of universe is thought to have been through the Big Bang, the current favoured theory, which occurred some 13.8 Gyr ago. Although this theory is not perfect, it is able to explain

²However, modern astronomers still use the terms for consistency.

³Proceedings of Symposium 2 of JENAM 2010 Ferreras & Pasquali (2013)

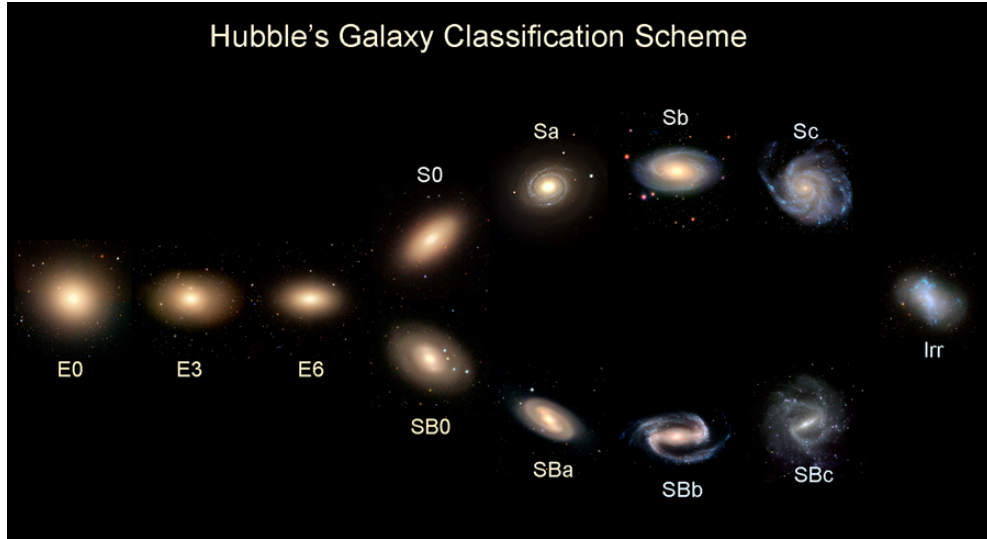


Figure 1.2: The Hubble classification scheme using the classic ‘fork’ diagram established by Hubble (1936). This figure illustrates the complexity of the galaxy morphology given by the presence of spiral arms and stellar disk, ranging from spheroidal ellipticals (E), lenticulars (S0), disk spirals (S) and irregular galaxies (Irr). In addition, the spirals are also classified into sub-categories based on the presence of central bars (denominated by ‘SB’). It is evident that the lenticular galaxies (S0) indeed represent a transition population, with prominent bulges and smooth stellar disk. Image credits: Galaxy Zoo Project

the observed Cosmic Microwave Background (CMB) radiation, primordial synthesis of light elements, the expansion of the universe and the observed large-scale structure in the Λ CDM universe. However, this theory fails to explain the flatness of universe, and the homogeneity in the observable universe (also known ‘horizon’ problem), leading to the theoretical concept of ‘inflation’- in simple terms, accelerated exponential expansion of the primordial universe.

The CMB, being a relic radiation from the Big Bang, gives us a picture of the early universe at a time when it was homogenous and dominated by dark matter. As the universe expanded, tiny fluctuations in the density of early universe resulted in the dark matter ‘halos’ clumping together, which then began to grow in mass through continuous accretion. These fluctuations are seen as temperature anisotropies on the CMB map. As the universe further cooled through expansion, the primordial baryonic raw material (consisting of H and He) began to condense in these dark matter halos to form the first stars⁴, leading eventually to the formation of proto-galaxies. Thereupon, these dark matter halos grew hierarchically to create larger halos through subsequent mergers. This phenomenon is widely known as the ‘hierarchical assembly’ of the large-scale structure, and is traced by the visible baryonic matter in the form of galaxies. On a lo-

⁴These stars are also called Population III stars

cal scale, however, the individual halos will have different baryonic distribution due to the underlying hydrodynamics. A direct consequence of this mode of structure formation is that the large-scale collapsed haloes which result in galaxy clusters, therefore, have an evolved population of galaxies (De Lucia, Kauffmann & White, 2004).

There are however some discrepancies in the present observable universe which are not very well explained by the hierarchical assembly. One such problem is the ‘downsizing’ of galaxies observed across cosmic time (Cowie *et al.*, 1997; Thomas *et al.*, 2005) which implies that the main epoch of star formation was earlier for more massive galaxies (See also, Pérez-González *et al.*, 2008). This means that the star formation in less massive galaxies is somehow delayed, possibly due to a feedback mechanism through powerful supernovae from the first stars. Supporting evidence is given by early-type galaxies in local clusters which are observed to have the majority of their stars formed at $z > 2$ (Bower, Lucey & Ellis, 1992; Aragón-Salamanca *et al.*, 1993; Thomas *et al.*, 2010).

With the advancement in computing technology, a great deal of simulation work is now being developed to understand structure formation on a cosmological scale. While these numerical simulations agree with the observational results to a large degree, the simulations enable us to track individual halos through the cosmic time: thus providing a crucial information which the real space-time cannot. N-body simulations like the Millennium simulation (Springel *et al.*, 2005) are especially noteworthy for simulating the dark matter distribution in the universe. Recently, several numerical simulations like EAGLE (Schaye *et al.*, 2015) and Illustris (Vogelsberger *et al.*, 2014) have been developed not only to trace the dark matter through N-body simulations but also to track the evolution of gas through hydrodynamical prescriptions and subgrid physics. Figure 1.3 illustrates the information we can obtain through these hydrodynamical simulations.

With this picture of structure formation, there is still considerable progress to be made regarding detailed aspects galaxy formation and evolution. Nonetheless, it constitutes an excellent platform to study galaxy evolution in the Λ CDM universe.

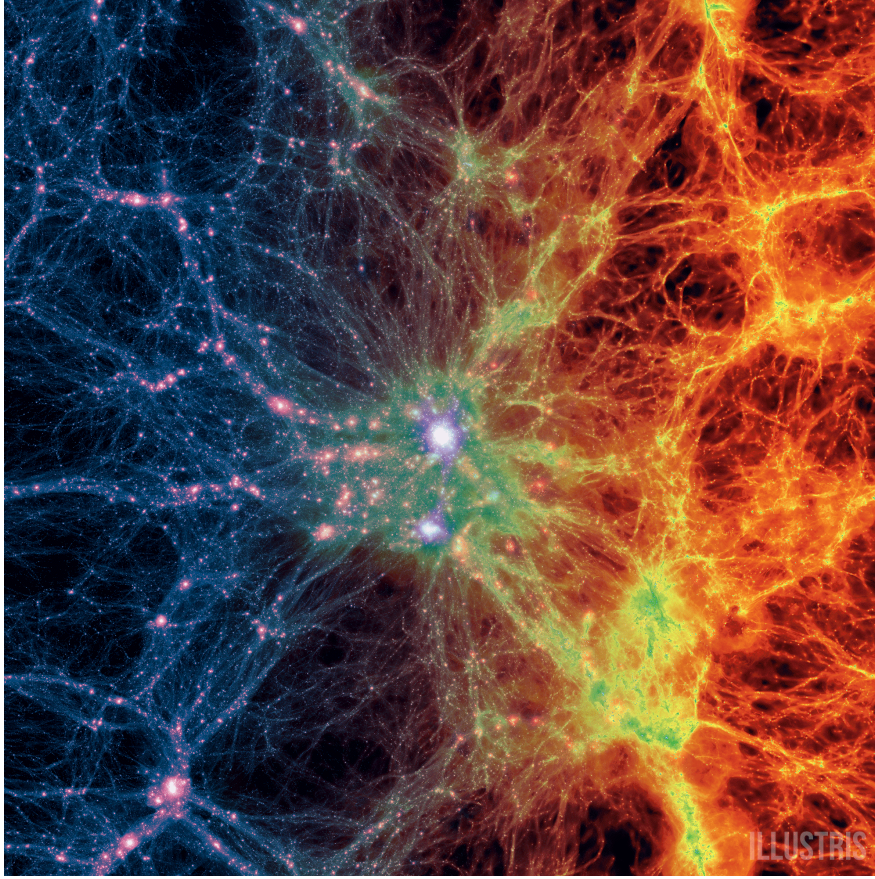


Figure 1.3: The view of the most massive cluster at $z = 0$ through the Illustris volume, covering a depth of $15Mpc/h$. The dark matter density is shown in left, transitioning to the gas density (right).

1.2 Evolving nature of galaxies

The observation of the universe at high redshift essentially gives us a snapshot of the universe in the past. This gives us the power to observe and study galaxies when they are in different stages of evolution over cosmic time.

Galaxy formation is believed to happen in several ways like galaxy merging, gas accretion from the intergalactic medium and in situ star formation in collapsed gas. The structure of galaxies is therefore a useful tracer to understand the physical drivers behind the formation and subsequent evolution of galaxies. One of the structural galaxy properties we observe changing with redshifts is the galaxy morphology, which is a qualitative assessment of the stellar distribution in galaxies. Using a broad bulge/disk dichotomy to represent Hubble-type morphologies, it is found that bulge+disk systems are predominant within $1 < z < 2$, while the galaxies in the local universe are mainly bulge dominated (Bruce *et al.*, 2012; Buitrago *et al.*, 2013; Margalef-Bentabol *et al.*,

2016). Moreover, galaxies at high redshift more often show peculiar/disturbed structure in contrast to the traditional morphologies (Abraham *et al.*, 1996; Papovich *et al.*, 2005; Conselice *et al.*, 2011; Mortlock *et al.*, 2013), suggesting that galaxies have undergone remarkable structural transformation over cosmic time (See also Conselice, 2014).

On the other hand, the optical colours of galaxies are obtained from the integrated light of the stellar populations, and hence reflect the stellar composition of galaxies. Thus, bluer colours imply young stellar populations, and/or ongoing star formation in galaxies due to the presence of the hot young massive OB stars. The redder colours of galaxies, on the other hand, are associated with passive stellar populations, although dust in star-forming galaxies may also lead to redder colours. This correlation can further be traced to higher redshifts (Figure 1.4), with these populations commonly referred to as ‘blue cloud’ and the ‘red sequence’ (for example, Pozzetti *et al.* 2010).

Additionally, it has long been established that the morphology of galaxies is tightly correlated with their optical colours (de Vaucouleurs, 1961). These correlations show that E/S0 essentially have redder optical colours as compared to spirals. Moreover, better photometric studies of galaxies at low redshifts have revealed an elemental colour bimodality existing in galaxy populations (Strateva *et al.*, 2001; Kauffmann *et al.*, 2003b; Baldry *et al.*, 2004). Further, the correlation of star formation with morphology is directly indicated by the deficit of cold gas (the necessary raw material for star formation) in early-type galaxies as compared to late-type galaxies (Roberts & Haynes, 1994).

Thus, assembling the overall picture with respect to star formation and morphology of galaxies, there exist two recognisable galaxy populations in the universe: the younger blue star-forming galaxies with late-type (spiral) morphologies, and the older red passively evolving galaxies with early-type (E/S0) morphologies. However, several sub-populations of galaxies exist which do not necessarily follow these correlations (red late-type and blue early-type galaxies). Typically known as ‘green valley’ galaxies in the context of colour bimodality, such transition galaxies hint towards the evolution of star formation and transformation of the morphology happening over different timescales. Moreover, varied processes may be causing such transitional properties, some of which may be environmentally driven (See, for example, Vulcani *et al.*, 2015).

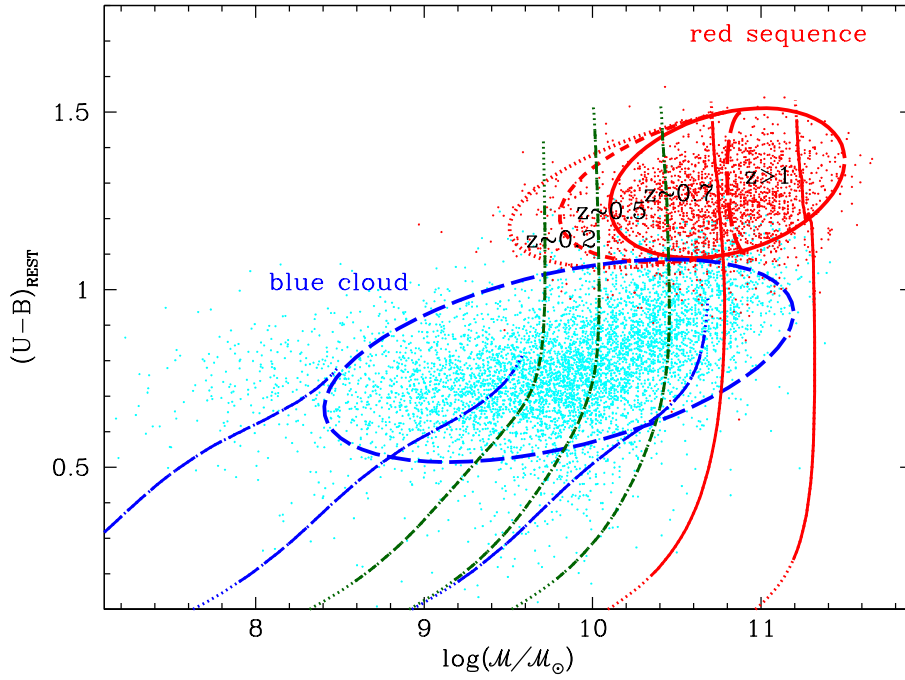


Figure 1.4: Schematic representation of the evolving bimodal galaxy population, as explored with zCOSMOS sample (Pozzetti *et al.*, 2010). The ‘blue cloud’ and the ‘red sequence’ are denoted with ellipses corresponding to different redshifts. Further, the lines denote the evolutionary tracks which galaxies follow with different star formation histories, ranging from a timescale of 0.1 Gyr (solid red curve) to 10 Gyr (dashed blue curve).

The physical drivers behind this observed bimodality in galaxies however are not very well understood, especially why the transition from star-forming blue galaxies to passive red galaxies is associated with transformation in galaxies’ morphology and structure. Several mechanisms are thought to be at play in ceasing star formation in galaxies- either by heating the cold gas which forms the reservoir for star formation, or expulsion/truncation of external supply of gas into galaxies.

The mechanisms responsible for heating the cold gas often work in combination resulting in global shutdown of star formation in galaxies. These could either be feedback processes from supernovae (Dekel & Silk, 1986), AGN (Croton *et al.*, 2006) and/or cutting down the supply of external gas into galaxies (Rees & Ostriker, 1977; Feldmann & Mayer, 2015). Central galaxies residing in massive halos can experience a continued suppression of external supply gas through virial shock heating, resulting from the infall of intergalactic gas into the galactic dark matter halo (Birnboim & Dekel, 2003). Furthermore, gravitational interactions between galaxies, like major mergers, are also thought to be efficient in quenching star formation in galaxies along with transforming

galaxy morphology.

What remains as the outstanding question, therefore, is:

What evolutionary paths render the blue star-forming late-type galaxies to become passive early-type galaxies? Further, what precise role does galaxy environment play in bringing about such transformations?

1.3 Galaxy evolution in clusters

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. Evidence of global transformations happening over look-back time are given by the increasing fraction of spiral galaxies and decreasing fraction of lenticulars in clusters till $z \sim 0.5$, with fraction of elliptical galaxies remaining constant (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).

However, an unassailable observation, highlighting the role of the environment in shaping present galaxy population is the higher likelihood of encountering early-type E/S0 galaxies in high-density environment, although mass dependence of these populations could also play a vital role in the observed trends (Bolzonella *et al.*, 2010). This was first explored by Dressler (1980) and later by works like Treu *et al.* (2003); Houghton (2015); Fasano *et al.* (2015) (Figure 1.5). Moreover, the tight ‘red-sequence’ (Visvanathan & Sandage, 1977) evident on the colour-magnitude diagram of cluster galaxies, indicate that these red early-type cluster galaxies have evolved passively since their formation at $z > 2$ (Bower, Lucey & Ellis, 1992; Aragón-Salamanca *et al.*, 1993; Jaffé *et al.*, 2011a).

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); Kauffmann *et al.* (2004); Balogh *et al.* (2007), see also Gray *et al.* (2004)).

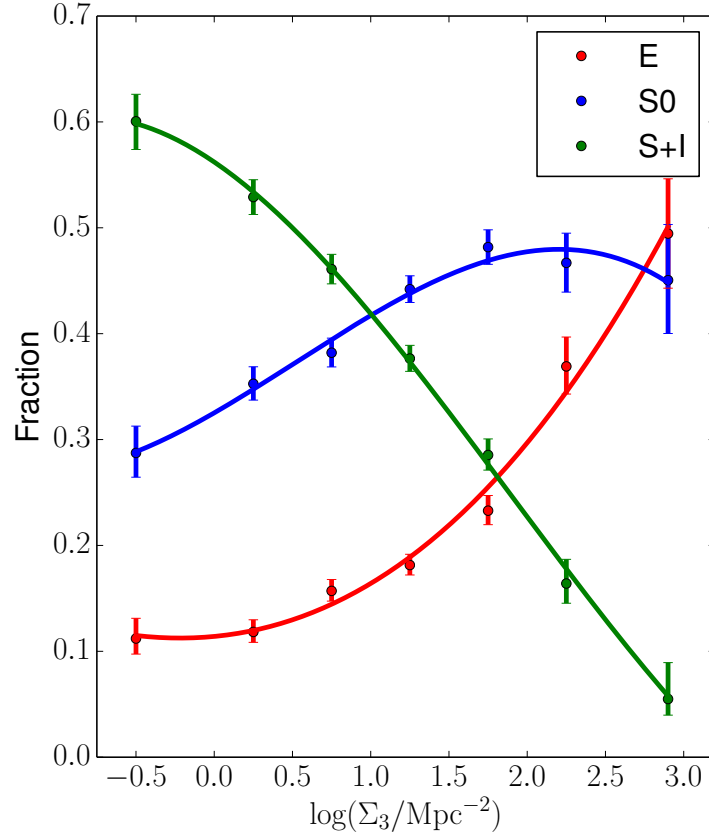


Figure 1.5: Reproduction of the morphology–density relation from Dressler (1980). This figure uses updated data in terms of cluster redshifts, projected densities and completeness corrections (Houghton, 2015).

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; Cooper *et al.*, 2012; Sobral *et al.*, 2011; Quadri *et al.*, 2012; Woo *et al.*, 2013; Kovač *et al.*, 2014). However,

What are the main drivers behind morphology–density relation? And how do they interlink with the observed quenching of star formation in cluster galaxies?

Some environmental segregation in galaxies’ properties is naturally expected: hierarchical models of structure formation predict that 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

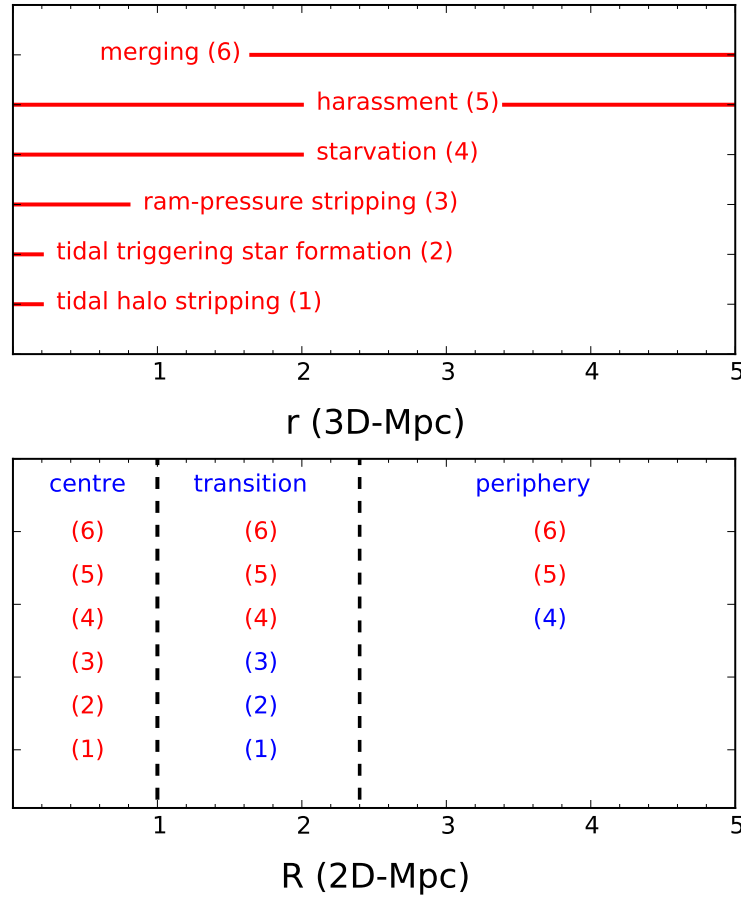


Figure 1.6: Graphical illustration of various physical mechanisms affecting galaxies in cluster environment, as discussed in Section 1.3 (adapted from Treu *et al.*, 2003). *Top:* The horizontal lines indicate the radial range over which the mechanisms act. *Bottom:* Translating this on 2-D space, the dashed lines separate various regions in a typical cluster with virial radius $r_v \sim 1.7$ Mpc. The numbers indicate the processes described in the top panel. The blue colour of the numbers indicate mechanisms which are less effective at that projected radius.

galaxies being accreted onto 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 of the starburst or galaxies with very high star formation display merger signatures, irrespective of redshift (Duc *et al.*, 1997; Elbaz & Cesarsky, 2003). 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 (Boquien *et al.*, 2009; Moore *et al.*, 1996).

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 $\sim 10\%$ of the total mass of the cluster consisting of hot intracluster medium (ICM), infalling galaxies may undergo loss of their cold disk 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; Jaffé *et al.*, 2015). Figure 1.6 gives a summary of these processes and the regions where they are likely to affect galaxies in cluster environment.

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 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 (Jaffé *et al.*, 2011b). 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 Bösch *et al.* (2013) confirmed that these same objects are kinematically disturbed while remaining optically symmetric. It is clear that for these smooth passive spirals, slow gas processes (such as starvation and ram-pressure stripping) are shutting down star formation without simultaneous wide-scale redistribution of their stellar material.

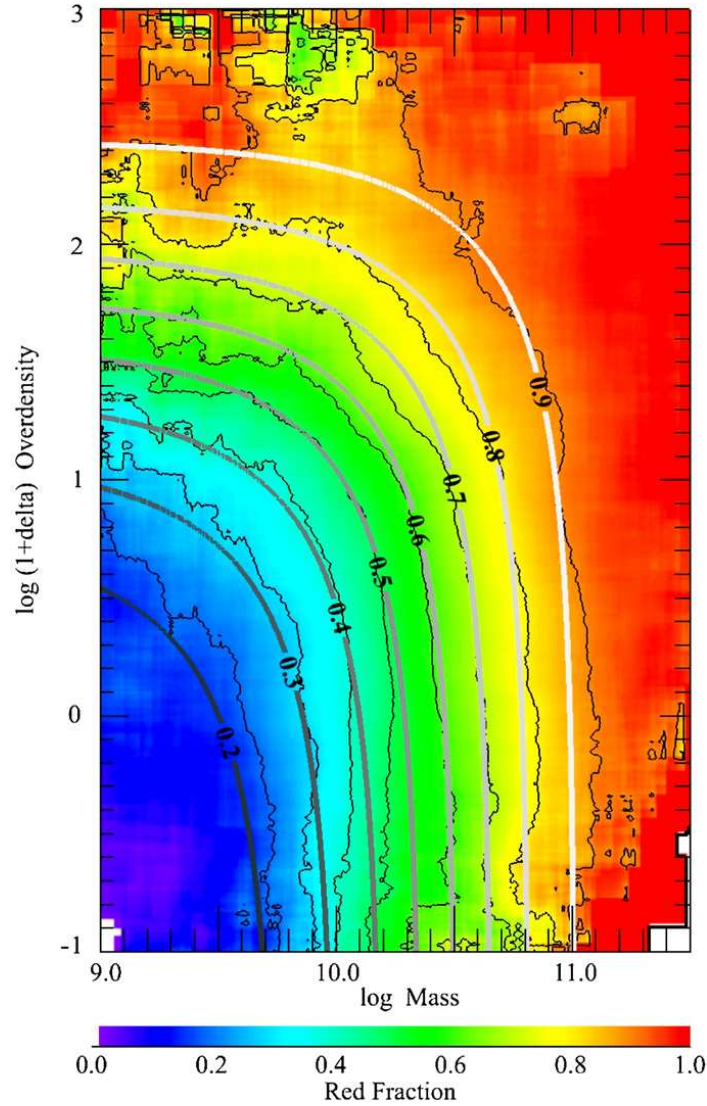


Figure 1.7: Red fraction as a function of environment and stellar mass at $z = 0$ (Peng *et al.*, 2010b). The grey contours indicate the fraction of red galaxies at a given stellar mass and overdensity.

Importance of galaxy stellar mass

The puzzle of galaxy evolution discussed so far remains incomplete without the final piece of information: galaxy stellar mass. Studies like Bundy *et al.* (2006) proposed a threshold stellar mass above which star formation in galaxies gets quenched. Further, galaxy downsizing, as discussed in Section 1.1, also accentuates the importance of galaxy mass in determining the extent of star-formation activity in galaxies (Bundy, Ellis & Conselice, 2005). With the stellar mass of galaxies being dependent on environment (for example, Bolzonella *et al.*, 2010), one cannot ignore the perception that galaxy stellar mass and its environment are intertwined, making it arduous to study

galaxy evolution within the global framework. Indeed, recent works like Peng *et al.* (2010b) and Kovač *et al.* (2014) present analysis wherein the star formation of star-forming galaxies is found to depend on mass, and not environment. Thus, the effects of stellar mass and environment on quenching are separable to $z \sim 0.7$ (Figure 1.7), and hence different processes may be at play for galaxies of different stellar masses (Haines *et al.*, 2007)(See also, Thomas *et al.*, 2010).

1.4 *Summary and outstanding questions*

In summary, galaxies are known to have undergone remarkable evolution in their structural, stellar distributions and stellar content throughout cosmic time: transforming from star-forming late-type galaxies into passive early-type galaxies. The coeval evolution of the large-scale structures like galaxy clusters manifests into the observed dependence of galaxy properties like morphology and star formation on the environment. Although disentangling the relative importance of intrinsic and extrinsic influences on galaxy evolution is difficult, it is nonetheless unequivocal that the environment plays a crucial role in shaping the galaxies we see today. Presently, several questions still remain unresolved:

- *What truncates the star formation in cluster galaxies and keeps them passive?:* Although clusters are known to harbour evolved galaxies as compared to the general field, the environment-specific processes affecting the star formation in galaxies are largely unknown. Gas-extinguishing ICM processes like starvation (for example, McGee, Bower & Balogh, 2014) and ram-pressure stripping (for example, Bösch *et al.*, 2013) are believed to be the prime candidates for the processes resulting in the quenching of star formation. A variety of observations have brought forth the tension between the timescales inferred from these processes and the very long timescales required to build up the passive fractions observed in clusters (McGee *et al.*, 2011; De Lucia *et al.*, 2012; Peng *et al.*, 2010b; Haines *et al.*, 2013, 2015). Moreover, clusters are found to grow over cosmic time through the accretion of galaxy groups (Dressler *et al.*, 2013). Hence, accounting for the accretion history of clusters is crucial since galaxies

might already be ‘preprocessed’ in the infalling groups (for example, Jaffé *et al.*, 2015).

- *Towards the origins of morphology–density relation:* The apparent suppression of star formation has not yet been reconciled with the observed morphological transformations which the cluster galaxies undergo. As discussed earlier, extensive studies of transition populations like S0 and ‘k+a’ galaxies have substantiated that the star formation is truncated without commensurate changes in the galaxy morphology. Whether these observations direct towards different timescales over which star-forming activity and morphology transform, or whether observing the structural changes associated with the above mechanisms are challenging, still remains a topic of study.

This thesis will try to make a significant contribution towards understanding these questions through the analysis of structure and the star formation history of galaxies within clusters.

1.5 Motivation and outline of the thesis

This thesis focusses on the effect of galaxy environment on the structure and star formation of galaxies since $z \sim 1$. This work strives to address the main question of whether galaxy environment leaves a distinct signature on the structural and stellar distribution of galaxies, and whether it is possible to interpret these effects in evaluating the plausible external mechanisms resulting in galaxy transformation.

For this purpose, I use *HST* imaging data, and the corresponding spectroscopic and photometric information from the ESO Distant Cluster Survey, which is described in Chapter 2.

Chapter 3 investigates the effect of global environment on the physical sizes of galaxies. I do this by first extracting structural information from the *HST* *I*–band images, and then comparing galaxy sizes across the global cluster-field environment for spectroscopic and photometric samples.

Chapter 4 introduces a unique method of quantifying galaxy structure based on devi-

ations from a symmetric galaxy surface brightness profile. I then investigate how this measurable structure compares with a visual assessment of galaxy structure based on structural disturbances. The effects of global environment on the visual structure and star formation are then analysed.

In Chapter 5, I discuss the interlink between the star formation history of galaxies and their quantitative structure. I specifically use the projected phase-space analysis to study the dynamical environment within the clusters, and how it influences the observed metamorphosis of cluster galaxy population.

Finally, the conclusions of this thesis are presented in Chapter 6 along with a brief discussion on the future prospects of this work.

Throughout this thesis, I use the standard Λ CDM Cosmology with $h_0 = 0.7$, $\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$, Vega magnitudes (Chapter 3), and AB magnitudes (Chapters 4 and 5).

Chapter 2

The Data

The ESO Distant Cluster Survey (EDisCS) serves as the main dataset for the studies presented in this thesis. EDisCS provides an excellent laboratory to study the evolution of galaxy populations in cluster environment over last half of the Hubble time. This Chapter describes the relevant data and the derived samples used in the subsequent analysis presented in the forthcoming chapters.

2.1 EDisCS: Overview

EDisCS is a multiwavelength survey comprising 20 fields containing galaxy clusters in the redshift range $0.4 < z < 1$ (White *et al.*, 2005), with ten optically selected rich clusters among each of the $0.45 < z < 0.55$ and $0.75 < z < 0.85$ redshift bins. These fields were originally drawn from the parent catalogue derived from the Las Campanas Distant Cluster Survey (LCDCS; Gonzalez *et al.*, 2001), consisting of a strip of sky 90 degrees long and 1.5 degrees wide centred at $\alpha = 12.5$ hours and $\delta = -12$ degrees. The EDisCS dataset is unique in that it is larger than all previous (similar) studies at these redshifts, with the advantage of covering a broad range of cluster properties and a significant field sample to match the cluster galaxies. Moreover, the EDisCS clusters span a wide range of cluster velocity dispersions such that the majority of EDisCS clusters can be progenitors of typical clusters observed at low redshift (Figure 2.1).

Primarily, the EDisCS programme is designed to enable detailed spectroscopic and

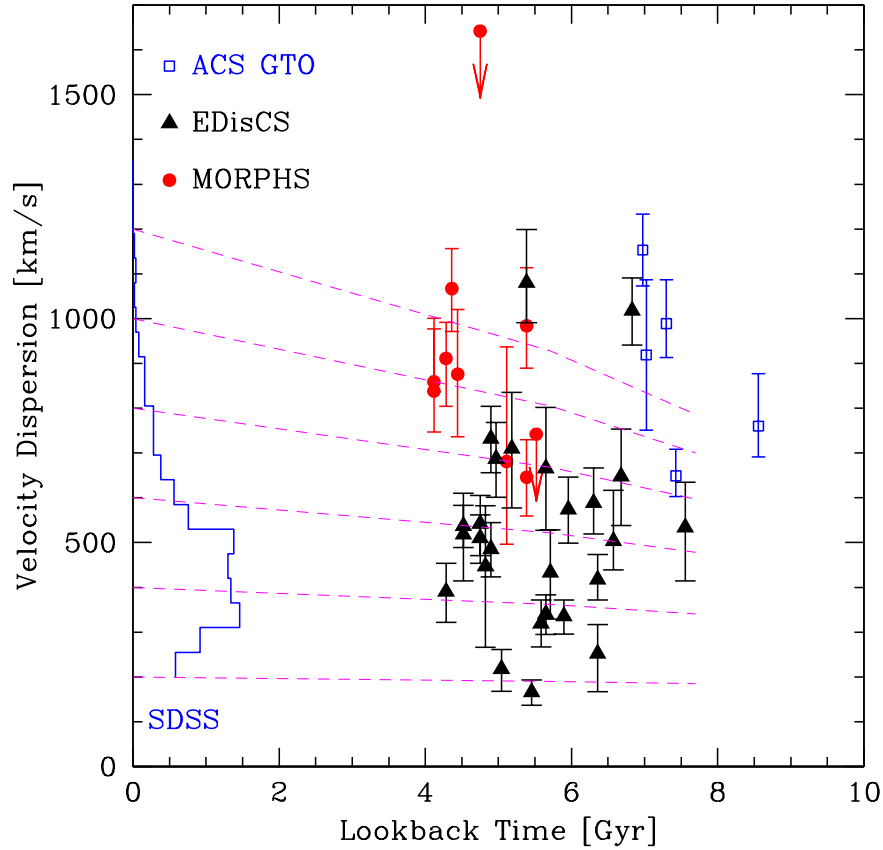


Figure 2.1: The distribution of velocity dispersion vs. look-back time for EDisCS (black triangles) and for two other cluster samples at similar redshifts (red and blue points). The histogram represents the velocity dispersion distribution for a well-studied local sample (von der Linden *et al.*, 2007). The dashed lines show the expected evolution of velocity dispersion with time (Milvang-Jensen *et al.*, 2008).

photometric studies of cluster structure and galaxy populations within at intermediate redshifts. Optical photometry for all fields was obtained using FORS2 on the *ESO Very Large Telescope (VLT)* (White *et al.*, 2005). This ground-based photometry included *B*-, *V*-, and *I*-band imaging for the ten intermediate-*z* ($0.4 < z < 0.5$) clusters and *V*-, *R*- and *I*-band imaging for the remaining ten high-*z* ($0.5 < z < 1$) clusters. Spectroscopy with FORS2/VLT was carried out on galaxies selected using the *I*-band magnitude and the best-fit photometric redshift (z_{phot}) from the photometric sample, as described in Halliday *et al.* (2004) and Milvang-Jensen *et al.* (2008). The typical accuracy of z_{phot} is $\sim 0.05 \pm 0.01$ depending on target field, the filters utilised and the spectral type of galaxies. This z_{phot} accuracy was computed using simulations, direct comparison with the spectroscopic redshifts (z_{spec}) of galaxies, and the expected accuracy of z_{phot} for galaxies fainter than the spectroscopic sample (Pelló *et al.*, 2009). Additionally, near-IR *J*- and *K*-band photometry were obtained for most of the clus-

ters using SOFI at the 3.5 m *New Technology Telescope (NTT)* (Aragón-Salamanca et al., in prep). The selection criteria applied ensure that the spectroscopic sample is, essentially, an *I*-band selected sample, with a target completeness of $\sim 95\%$ and redshift success rate of $\sim 50\%$ for all the fields. A detailed discussion regarding the redshift biases and magnitude dependence of these quantities is presented in Milvang-Jensen et al. (2008).

In addition, the ten high- z cluster fields also have *HST I*-band imaging data taken using the *F814* filter on the ACS Wide Field Camera in a total of five pointings per field: four adjacent one-orbit pointings covering $6.5' \times 6.5'$ (which approximately matches the field of the ground-based VLT optical images) and an additional four-orbit pointing covering the central $3.5' \times 3.5'$ region of each cluster, centred at the location of the BCG (Desai et al., 2007). The resulting exposure time for the cluster centres was therefore 10200 seconds, whereas the surrounding area had an effective exposure of 2040 seconds. Figure 2.2 shows a section of the *HST I*-band mosaic for cl1216, the highest redshift cluster in EDisCS with $z \sim 0.79$. The work presented in this thesis exploits the data for the ten high- z clusters (including secondary clusters and groups, cf. Section 2.2.1) covered by *HST* imaging for the structural analysis. Table 2.1 gives a summary of the properties of these clusters used in this analysis.

The follow-up data include *Spitzer* IRAC ($3 - 8\mu m$) and MIPS ($24\mu m$) imaging, $H\alpha$ narrow-band imaging for three of the high- z fields (Finn et al., 2005), and *XMM-Newton/EPIC* X-ray observations (Johnson et al., 2006).

2.2 Derived galaxy properties

Galaxies with spectroscopic redshifts form a subset of the EDisCS photometric sample (White et al., 2005). These spectroscopic target galaxies were selected using their *I*-band magnitudes measured in a $1''$ -radius circular aperture, with the mid- z and high- z fields having apparent magnitude limits of 18.6 and 19.5 respectively (Milvang-Jensen et al., 2008). The resultant spectroscopic sample contains relatively bright galaxies, and therefore surface-brightness selection effects are negligible because the FORS2 images reach much deeper than the spectroscopic limits (by 3-4 magnitudes). As dis-

Table 2.1: Summary of the cluster sample properties (including secondary clusters, cf. Section 2.2.1). Columns 1–5 contain the cluster ID, cluster redshift, cluster velocity dispersion, cluster mass, and the number of spectroscopically confirmed cluster members (Halliday *et al.*, 2004; Milvang-Jensen *et al.*, 2008). The cluster masses and R_{200} have been estimated from the velocity dispersions following Finn *et al.* (2005).

Cluster	z_{cl}	σ_{cl} (km s ^{−1})	$\log M_{\text{cl}}$ ($M_{\odot}$)	No. of spec. members	R_{200} (Mpc)
<i>Clusters</i>					
cl1232–1250	0.5414	1080 ⁺¹¹⁹ _{−89}	15.21	54	1.99
cl1216–1201 [†]	0.7943	1018 ⁺⁷³ _{−77}	15.06	67	1.64
cl1138–1133	0.4796	732 ⁺⁷² _{−76}	14.72	49	1.4
cl1354–1230 [†]	0.7620	648 ⁺¹⁰⁵ _{−110}	14.48	22	1.05
cl1054–1146 [†]	0.6972	589 ⁺⁷⁸ _{−70}	14.38	49	0.99
cl1227–1138 [†]	0.6357	574 ⁺⁷² _{−75}	14.36	22	1.0
cl1138–1133a [†]	0.4548	542 ⁺⁶³ _{−71}	14.33	14	1.05
cl1037–1243a [†]	0.4252	537 ⁺⁴⁶ _{−48}	14.33	43	1.05
cl1054–1245 [†]	0.7498	504 ⁺¹¹³ _{−65}	14.16	36	0.82
cl1227–1138a	0.5826	432 ⁺²²⁵ _{−81}	13.69	11	0.61
cl1040–1155 [†]	0.7043	418 ⁺⁵⁵ _{−46}	13.93	30	0.7
<i>Groups</i>					
cl1037–1243	0.5783	319 ⁺⁵³ _{−52}	13.61	16	0.58
cl1103–1245a	0.6261	336 ⁺³⁶ _{−40}	13.66	15	0.59
cl1103–1245b	0.7031	252 ⁺⁶⁵ _{−85}	13.27	11	0.42

[†] Clusters used for projected phase-space analysis in Chapter 5

cussed in Milvang-Jensen *et al.* (2008), the spectroscopic sample is effectively an *I*-band limited sample.

2.2.1 Cluster membership: global environment and substructure

In this thesis, the global environment of the galaxies is defined based on their cluster membership. Originally, galaxies were allocated to individual clusters and the general field using both spectroscopic and photometric redshifts. The method used to determine cluster membership is different for the spectroscopic and photometric samples. As discussed in Milvang-Jensen *et al.* (2008), for the spectroscopic sample a galaxy is considered to belong to a cluster if its spectroscopic redshift lies within $\pm 3\sigma_{\text{cl}}$ from the average redshift of the cluster (z_{cl}). The spectroscopically-defined cluster membership is therefore expected to be very robust.

For the photometric sample, cluster membership was determined by assigning them

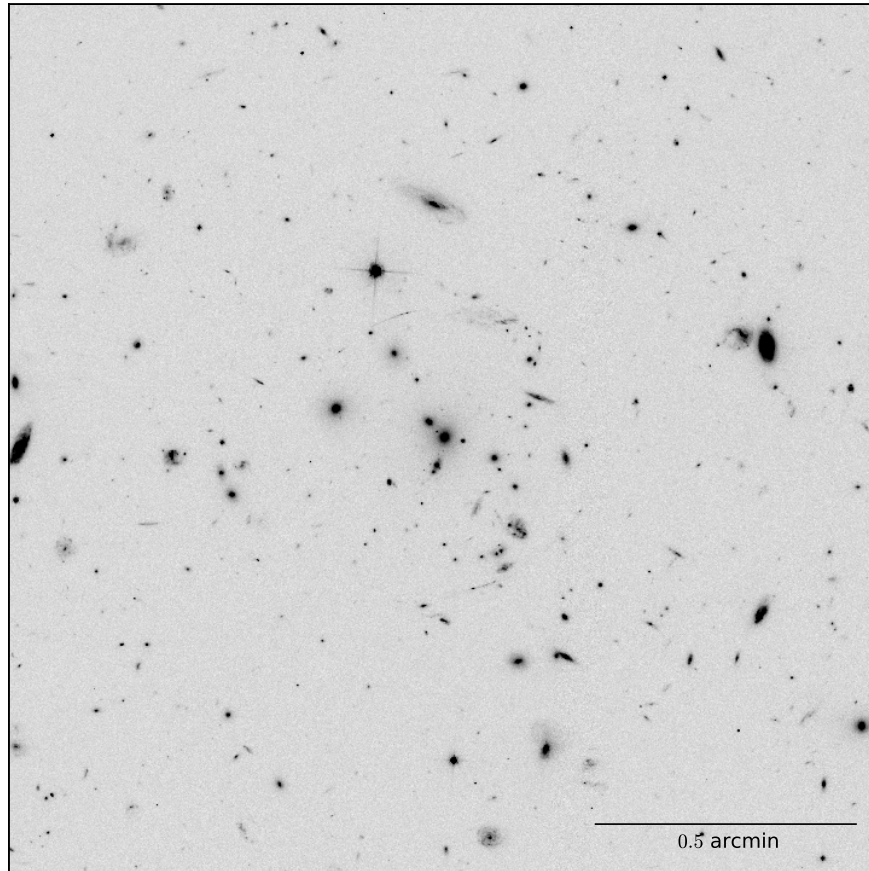


Figure 2.2: *HST* *I*-band view of c11216-12 centred on the brightest cluster galaxy, the richest and highest redshift cluster in EDisCS with $z \sim 0.79$. The scale bar indicates the size of 0.5 arcminutes, which at this cluster redshift is equivalent to ~ 210 kpc.

a probability of belonging to the cluster that had to be greater than a given threshold (Pelló *et al.*, 2009). This threshold was calibrated using the spectroscopic sample in order to minimise contamination and maximise completeness. Explicitly, the probability distribution function of each galaxy's photometric redshift is integrated within a ± 0.1 redshift slice about the cluster redshift z_{cl} , and the value of this integral has to be higher than the empirically-determined threshold in order to consider a galaxy as cluster member. This threshold is determined such that $> 90\%$ confirmed cluster members are recovered with little dependence on colours (rest-framed or observed). This rejection threshold is defined in Pelló *et al.* (2009) for specific photo- z codes, and corresponding filter set. Extensive tests carried out by Pelló *et al.* (2009) using the large number of available spectroscopic redshifts indicate that the method retains $\sim 90\%$ of

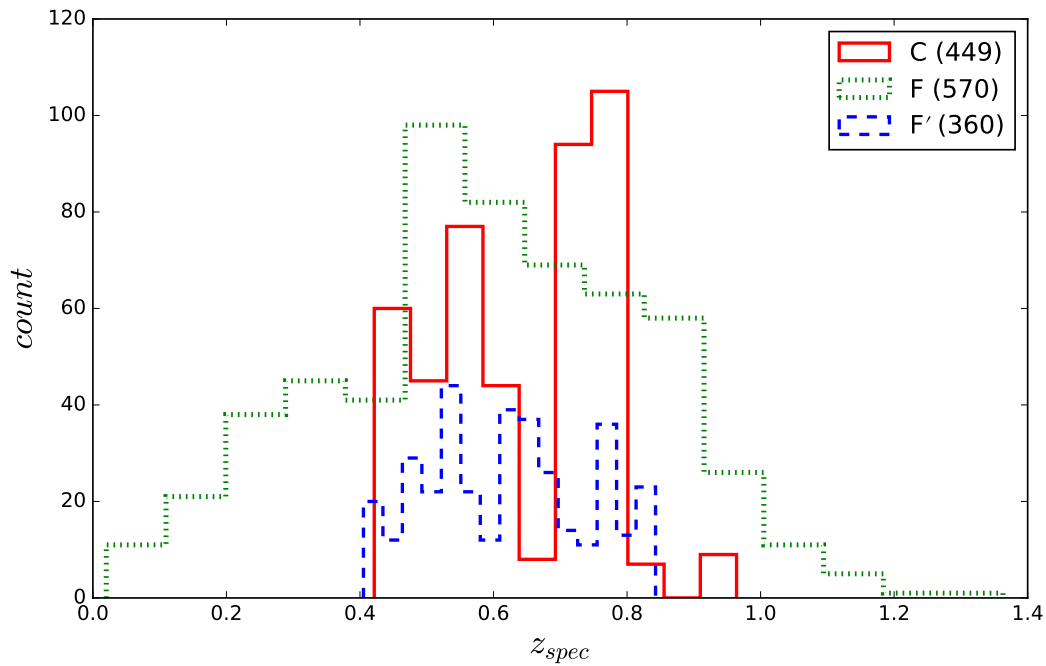


Figure 2.3: The redshift distribution of field and cluster galaxies from the spectroscopic sample. The solid red histogram corresponds to the cluster sample. The dotted green line corresponds to the complete field sample, and the dashed blue line corresponds to the field sample used for comparison with the cluster galaxies (Chapter 4).

the cluster members while rejecting $\sim 88\%$ of non-members for the clusters studied here. However, it is important to point out that these tests are based on the brighter spectroscopic sample. For the photometric sample these numbers are, strictly speaking, upper limits. All the galaxies not identified as cluster members are considered to be in the field sample.

Note also that some of the EDisCS fields contain secondary clusters in addition to the main ones. These were discovered when analysing the spatial distributions and spectroscopic redshifts of the galaxies in each field (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 2.1 with ‘a’ or ‘b’ following the main cluster ID. According to the analysis presented in Poggianti *et al.* (2009), these structures were further identified as cluster and group systems based on the σ_{cl} and the number of spectroscopic members. All the structures with $\sigma_{\text{cl}} > 400 \text{ km s}^{-1}$ were defined as ‘clusters’, while the structures with $160 < \sigma_{\text{cl}} < 400 \text{ km s}^{-1}$ with at least 8 spectroscopic members were defined as ‘groups’. In this thesis, the global environment of the galaxies is defined based on their cluster membership

irrespective of the host cluster/group identification.

The field galaxies I use in the comparison have a similar redshift distribution to the cluster galaxies studied here (Figure 2.3). This ensures that a direct comparison can be made, avoiding redshift-dependent evolutionary effects and biases. Although the full EDisCS field sample has a broader redshift distribution than the cluster sample, for the analysis presented in Chapter 4, I consider field galaxies within ± 0.05 from the minimum and maximum cluster redshift from the spectroscopic sample.

2.2.2 Galaxy stellar masses

The stellar masses for the spectroscopic sample and photo- z cluster members were computed by Benedetta Vulcani (2013, private communication). Distances to the galaxies were calculated using the individual spectroscopic redshifts for field galaxies and the mean spectroscopic cluster redshift (Halliday *et al.*, 2004; Milvang-Jensen *et al.*, 2008) for cluster members. The stellar masses for the spectroscopic sample and photo- z cluster members were computed using the Kroupa (2001) IMF following the method proposed by Bell & de Jong (2001), which utilises the stellar mass-to-light (M/L_B) ratios and $(B - V)$ colour of galaxies for solar metallicity using the relation

$$\log M/L_B = 0.51 + 1.45(B - V) \quad (2.1)$$

However, this method suffers from uncertainties arising due to dust, and bursty star-formation. The mass-completeness limit for the spectroscopic sample is $\log M_*/M_\odot = 10.6$ (Vulcani *et al.*, 2010) and for the photometric sample $\log M_*/M_\odot = 10.2$ (Vulcani *et al.*, 2011). These mass-completeness limits were obtained from the most distant cluster in our sample, cl1216.8–1201, by determining the mass of a galaxy with an absolute B -magnitude corresponding to $I = 24(23)$ for the photometric(spectroscopic) sample and a colour $B - V \sim 0.9$, which is the reddest colour of the galaxies in this cluster. The stellar masses for the photometric field galaxies were not computed as the photometric redshifts are not accurate enough to estimate reliable distances and thus the rest-frame luminosities and colours required to calculate stellar masses. In all the samples used throughout this thesis, the BCGs were removed from each of the ten clusters, as identified by Whiley *et al.* (2008), since they do not follow the mass–size

relation of normal galaxies (Maltby *et al.*, 2010).

When building the field sample for comparison with the photometric cluster sample, we used the spectroscopic field sample but with a stellar-mass limit of $\log M_*/M_\odot = 10.2$, the same limit used for the photometric cluster sample. The resultant field sample will, therefore, be mass-incomplete but contain broader range of masses. As mentioned in Section 2.2.1, the photo- z uncertainties prevent us from obtaining reliable distances (and thus stellar masses and intrinsic sizes) for field galaxies without spectroscopic redshifts.

2.2.3 Visual morphologies

Visual morphologies for the galaxies were obtained from the *HST* morphology catalogue published by Desai *et al.* (2007). The morphological classifications were carried out by 5 classifiers, and the final morphology for each galaxy was assigned using a weighted combination of the individual classifications. This process is designed to minimise uncertainties and individual biases (Desai *et al.*, 2007). For the spectroscopic morphology-selected sample, only galaxies with spectroscopic redshifts that were covered by the *HST* images were used. Furthermore, the fine morphological classes given by the original catalogue are collapsed into four broad bins for the purpose of this analysis: Ellipticals, Lenticulars, Spirals and Irregulars. Given the qualitative nature of the classification process, formal uncertainties are very difficult to assign to the morphologies, but since the morphological classes used here are much coarser than those given in the original paper, the broad classes that used are expected to be reasonably robust. The spectroscopic morphology-selected sample contains 213 cluster galaxies and 167 field galaxies. The photometric morphology-selected sample was constructed using galaxies with known morphologies found in the photo- z catalogues (White *et al.*, 2005; Pelló *et al.*, 2009), and contains 1167 cluster galaxies and 278 field galaxies (Table 2.2).

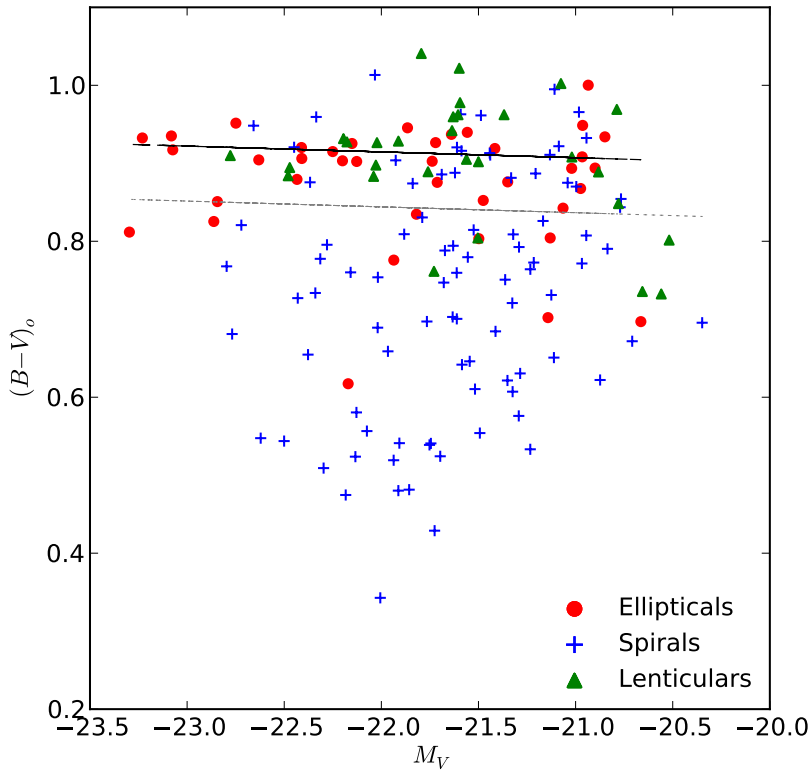


Figure 2.4: The rest-frame $B - V$ colour–magnitude relation for the combined spectroscopic cluster sample with morphology information. The solid line shows a linear fit to the red sequence, while the dotted grey line indicates the boundary separating the red and blue galaxy samples. This boundary has the same slope as the red sequence but is located 3σ below, where σ is the scatter of the elliptical galaxy colours around the red sequence.

2.2.4 Galaxy colours: defining passive galaxies

The red galaxies in clusters are known to form a tight sequence on the colour–magnitude diagram (Visvanathan & Sandage, 1977; Bell *et al.*, 2004), indicating a passively evolving galaxy population. I, therefore, use the rest-frame $B - V$ colour to distinguish the red sequence galaxies in the sample. These colours were computed using a $1''$ radius aperture for galaxies in crowded fields and the SExtractor ISO aperture (Bertin & Arnouts, 1996) for other galaxies (Rudnick *et al.*, 2003). In general, the typical ISO apertures chosen by sextractor were $1''$, $2''$, and $3''$ (White *et al.*, 2005). Rest-frame colours were interpolated from the observed Vega magnitudes using spectral energy distributions fitted using the observed spectroscopic redshifts (Pelló *et al.*, 2009). Complementing previous studies with EDisCS dataset (De Lucia *et al.*, 2007; Jaffé *et al.*, 2011a), a linear fit to the colour–magnitude relation of the elliptical galaxies

Table 2.2: Properties and sizes of the photometric and the spectroscopic samples and sub-samples analysed in this thesis. Note that the field parent sample is drawn from the spectroscopic sample.

	Spectroscopic	Photometric
Parent Sample	1019	3299
Cluster	449	2729
Field	570	570
Mass range	$10.6 \leq \log \left(\frac{M_*}{M_\odot} \right) \leq 11.8$	$10.2 \leq \log \left(\frac{M_*}{M_\odot} \right) \leq 12.0$
Total	380	1445
Cluster	213	1167
Field	167	278

was used to determine the location and slope of the red sequence in the spectroscopic sample (Figure 2.4). The form of this fit is

$$(B - V)_0 = (0.728 \pm 0.119) - (0.008 \pm 0.005)M_V \quad (2.2)$$

consistent with studies like van Dokkum *et al.* (1998). The boundary separating the red and blue galaxy samples was defined as a line with the same slope as the red sequence but located 3σ below, where σ is the scatter of the elliptical galaxy colours around the red sequence. All the galaxies above this line are considered red and all below blue. The same boundary was used for the spectroscopic and photometric samples. These subsamples of red and blue galaxies are utilised in Chapter 3 for analysing the mass–size relation for red and blue galaxies. Table 2.2 summarises the photometric/spectroscopic samples with the subsamples with morphology and colour based selection.

It was found by Labbé *et al.* (2005) that galaxies show a strong bimodality on the rest-frame $(U - V)$ vs $(V - J)$ colour-colour space, with the actively star-forming galaxies following a diagonal path and the quiescent galaxies populating upper-left region on this space. Moreover, the $(U - V)$ vs $(V - J)$ plane is more robust to separate the dusty star-forming galaxies from the passive galaxies, as compared to the single colour selection discussed before. Therefore, the colour information from the photometric data of the spectroscopic sample is further used to construct a rest-frame $(U - V)$ vs $(V - J)$ colour plot (UVJ hereafter) to distinguish the passive and star-forming

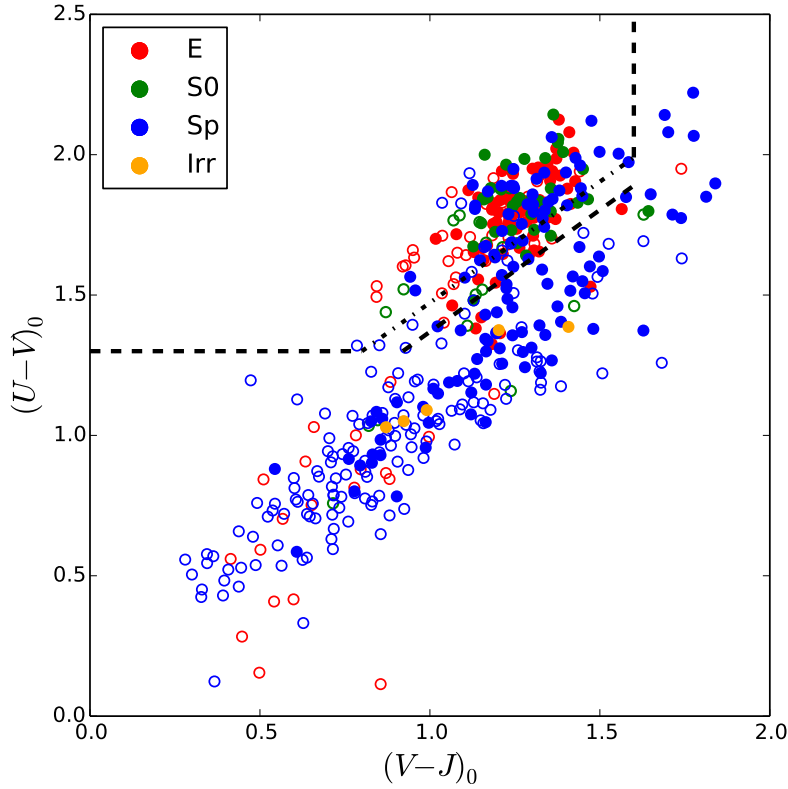


Figure 2.5: The rest-frame UVJ colour for the ellipticals (red), lenticulars (green), spirals (blue), and irregulars (yellow). The galaxies are defined as passive and star-forming according to the boundaries of Williams *et al.* (2009) for the two redshift bins: $0.5 < z < 1$ (dashdot) and $z > 1$ (dashed). The empty symbols denote galaxies with masses below the mass completeness limit for the spectroscopic sample (cf. Section 2.2.2).

population (Figure 2.5; 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 by the established mass-metallicity relation (Tremonti *et al.*, 2004; Gallazzi *et al.*, 2005), with low-mass galaxies having low metallicities and hence bluer colours.

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 . Figure 2.5 shows such a distribution for galaxies in the galaxy 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 Figure 2.5 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 galaxies in the spectroscopic sample,

the $0.5 < z < 1$ boundary should be, in principle, more appropriate. However, I 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 morphologies populate the upper left region of the UVJ plot, as defined by the $z > 1$ boundary, while the late-type spiral and irregular galaxies occupy the diagonal sequence, and the separation is significantly better with this boundary than with the $0.5 < z < 1$ one. I, therefore, conclude that for the spectroscopic sample, the $z > 1$ is better at separating star-forming from non-star-forming galaxies. Explicitly, I use the boundary defined by:

$$\left\{ \begin{array}{l} (U - V) \geq 1.3 \end{array} \right. \quad (2.3)$$

$$\left\{ \begin{array}{l} (U - V) \geq 0.88 * (V - J) + 0.49 \end{array} \right. \quad (2.4)$$

$$\left\{ \begin{array}{l} (V - J) \leq 1.6 \end{array} \right. \quad (2.5)$$

This boundary will be used in Chapter 4 to separate star-forming and passive galaxies.

Chapter 3

Dependence of galaxy sizes on global environment

Many high redshift ($z > 1$) studies report differential growth in galaxy sizes in different environments (Cooper *et al.*, 2012; Lani *et al.*, 2013). However, such differences in galaxy sizes are found to disappear in the local universe (Maltby *et al.*, 2010; Huertas-Company *et al.*, 2013). It is clear that the picture still remains incomplete as to whether and, if so, when galaxy size evolution depends on the environment. In this chapter, I aim to examine the role of environment on the galaxy stellar mass–size relation in the $0.4 < z < 0.8$ redshift range since this could be the transition epoch when the putative environmental differences found at higher redshifts cease to be present.

I address this observed evolution in galaxy sizes by comparing stellar mass–size relation for cluster and field galaxies. In order to do that, I constructed mass-selected samples of galaxies, subdivided both by colour and morphology, taken from the ESO Distant Cluster Survey (described in Chapter 2). This work is published in Kelkar *et al.* (2015).

3.1 Introduction

It is well established that galaxies have shown remarkable evolution in their physical properties such as their sizes over cosmic time. Observations of present-day galaxies

clearly show that their sizes are correlated with their stellar masses, and that this correlation evolves significantly over look-back time. This size evolution was put forth by some of the first works published on this topic showing that massive quiescent galaxies at high redshift ($z > 1$) were much more compact than their local counterparts (van Dokkum *et al.*, 2008; Daddi *et al.*, 2005; Buitrago *et al.*, 2008; Shen *et al.*, 2003; McIntosh *et al.*, 2005). This growth in galaxy sizes was found to be particularly dependent on morphology at a given stellar mass (Trujillo *et al.*, 2006, 2007): spheroids were four times more compact at $z \sim 1.5$ than their local counterparts, whereas $z \sim 1.5$ disk-like galaxies were twice as compact as $z \sim 0$ ones. Also, it was observed that such size evolution was mostly observed in massive galaxies with low star-formation rate (Franx *et al.*, 2008).

Several processes are being considered as possible drivers of the observed size evolution. Rapid mass loss of cold gas from the central regions due to AGN feedback (Fan *et al.*, 2008) could explain the size growth of massive spheroidal galaxies. Size evolution could also be triggered by environment-dependent processes such as ‘dry’ mergers, resulting in the increase in size of the stellar distribution in early-type galaxies but without any further star formation due to lack of gas (van Dokkum, 2005). The accretion of stars following a merger could also lead to the growth of a galaxy’s size due to an envelope being formed around the merger remnant (Naab *et al.*, 2007).

Hierarchical models of galaxy formation and evolution predict that the densest regions collapsed first and therefore cluster galaxies would form earlier compared with field galaxies of similar mass (De Lucia *et al.*, 2004). In essence, cluster galaxies would have had a ‘head-start’ in their evolution as compared to field galaxies. These predictions seem to have some observational support. Lani *et al.* (2013) find that the mass–size relation of quiescent galaxies at $1 \leq z \leq 2$ shows some environmental dependence: galaxies in dense environments appear to be larger than those in low-density regions, suggesting that the galaxy growth may have happened earlier in the densest environments. This dependence gets weaker from $z \sim 1$ to $z \sim 0.5$, indicating, perhaps, that size evolution in the low-density regions is ‘catching up’ with that in denser ones (See also Cimatti *et al.*, 2008; Rettura *et al.*, 2010). However, it is not clear whether the observed dependency of size evolution with environment is due to

the fact that galaxies in high-density environments are, on average, older or if it is due to environment-driven processes.

Furthermore, Huertas-Company *et al.* (2013) find no environmental dependence of the mass–size relation between $z \sim 1$ and the present. There is also extensive evidence indicating that at $z \sim 0$ the mass–size relation for galaxies with a given morphology does not depend significantly on environment either (Shen *et al.*, 2003; Maltby *et al.*, 2010; Rettura *et al.*, 2010; Poggianti *et al.*, 2013), although some subtle differences may still be present (Cebrián & Trujillo, 2014). This seems to suggest that there must be an epoch when the environment ceases to affect galaxy sizes, perhaps because the growth has already been completed in all environments.

There are, however, very significant difficulties when comparing different studies at different redshifts. The details governing the sample selection (e.g., galaxy mass and redshift range), sample division (e.g., by galaxy colour, visual morphology, Sérsic index, quiescence) and the exact definition and measurement of the environment are critical. Subtle (and not-so-subtle) differences make direct comparisons dangerous. Some of these difficulties may be behind the discrepancies found in different studies. For instance, Raichoor *et al.* (2012) used morphologically-selected early-type galaxies at $z \sim 1.2$ and found that the high mass ($10 < \log(M_*/M_\odot) < 11$) cluster galaxies are significantly more compact than similar field galaxies, whereas Cooper *et al.* (2012) and Papovich *et al.* (2012) found an opposite trend, albeit at higher redshift. It is also important to remember that, as Valentinuzzi *et al.* (2010) found, progenitor bias plays a crucial role when introducing spurious size-evolution while comparing high- with low-redshift morphological samples.

It is clear that the picture still remains incomplete as to whether and, if so, when galaxy size evolution depends on environment. In this Chapter, therefore, I aim to examine the role of environment on the galaxy stellar mass–size relation in the $0.4 < z < 0.8$ redshift range since this could be the transition epoch when the putative environmental differences found at higher redshifts cease to be present. I will compare samples of cluster and field galaxies by constructing mass-selected samples of galaxies, subdivided both by colour and morphology, in cluster and field environments taken from the spectroscopic sample.

Table 3.1: The spectroscopic and photometric subsamples by environment, morphology and colours, selected from Table 2.2. The morphology and colour subsamples are constructed by rejecting bad fits, as discussed in Section 3.2.

	Spectroscopic			Photometric		
Mass range	$10.6 \leq \log \left(\frac{M_*}{M_\odot} \right) \leq 11.8$			$10.2 \leq \log \left(\frac{M_*}{M_\odot} \right) \leq 12.0$		
Morphology	E	S0	Sp	E	S0	Sp
Cluster	39	29	90	224	116	605
Field	21	15	83	35	22	160
Colour	Red	Blue		Red	Blue	
Cluster	80	78		272	673	
Field	46	73		54	163	

3.2 Galaxy sizes from single Sérsic fittings

Table 3.1 summarises the photometric and spectroscopic subsamples used in this analysis.

I used the data pipeline GALAPAGOS (Galaxy Analysis over Large Areas: Parameter Assessment by GALFITting Objects from SExtractor; Barden *et al.*, 2012) on each galaxy in the ten high- z clusters using the *HST* I -band images. This pipeline uses SExtractor (Bertin & Arnouts, 1996) for source detection in the input images and GALFIT (Peng *et al.*, 2002, 2010a) to fit a 2-D Sérsic (1968) $r^{1/n}$ model to the individual sources. This best-fit model is obtained by χ^2 -minimisation using a Levenberg-Marquardt algorithm. GALFIT also determines several structural parameters along with the Sérsic index n , and the effective radius R_e along the semi-major axis of the 2-D surface brightness distribution. Since the resultant *HST* I -band images have regions with high and low exposures (Section 2.1), I implemented GALAPAGOS separately on the region with high exposure time. This results in executing the pipeline twice on the *HST* images per cluster- one with the entire mosaic of the cluster field as the input image and one with just the central region of the cluster. Each cluster, therefore, was associated with two catalogues generated by GALAPAGOS consisting of SExtractor output for source detection and output structural parameters from GALFIT. The final catalogues were then combined to yield objects detected in both high and low exposure

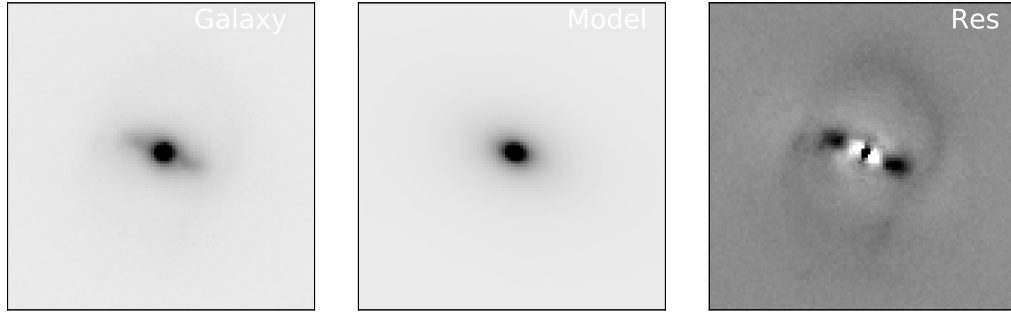


Figure 3.1: An example GALFIT datacube of a galaxy from the sample. The left panel is the image stamp of the original galaxy created from the *HST* *I*–band mosaic. The middle panel represents the model light-distribution created by GALFIT. The right panel shows the residual light left behind after removing the majority of the light using the model.

regions of the *I*–band image without any overlap detections.

Comparing these results with those obtained using the GIM2D software (Simard *et al.*, 2002; Valentinuzzi *et al.*, 2010), I found that GALAPAGOS is much more robust in giving reliable fits in crowded regions as it simultaneously fits neighbours. A detailed analysis and comparison of both these codes is given in Häussler *et al.* (2007). The measurement of R_e thus obtained is used to compute the physical sizes of galaxies to investigate the mass–size relation of galaxies (Section 3.3).

GALAPAGOS further generates image stamps of all the galaxies detected in the *HST* mosaics, along with corresponding model and residual images created by GALFIT after the Sérsic model has been subtracted (Figure 3.1). The size of each image stamp is uniquely computed using an aperture defined by constructing an ellipse whose semi-major axis is the radius of Kron aperture¹, and with a scale factor of 3. Refer to Barden *et al.* (2012), for the detailed method. The residual images are utilised for computing quantitative structural measurements which will be discussed in Chapter 4.

To ensure that the sizes used in this study are robust, I visually inspected all the fitted models and the residuals to reject unreliable sizes. I found that fits yielding unphysical values of the parameters ($R_e \geq 5''$ and/or $n < 0.2$ or $n > 6$) were almost always unreliable, leaving very significant residuals. The converse is also true: when the inspected residuals indicated that the fitted model was not a reasonable representation of

¹I use the following definition of radius of the “Kron aperture”: $2.2r_1$, 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.

the galaxies' surface brightness distribution, the fitted parameters were often unphysical. The reasons for this were varied. Some galaxies were affected by uncertain sky subtraction in very crowded regions. A few were very close to the edges of the images or had relatively bright stars nearby. There is also a significant number of galaxies showing strong perturbations caused by interactions or undergoing mergers. It is not surprising therefore that in all these cases a Sérsic model fails to provide a good description of the light distribution of the galaxies. Since Sérsic models are not suitable to fit these objects, the derived model parameters (including the effective radii) are meaningless and cannot be trusted. The fractions of field and cluster objects rejected this way were comparable ($\sim 20\text{--}30\%$), and no obvious environment-dependent biases were apparent. These objects were removed from the samples and not considered in my subsequent analysis. As a sanity check, I confirmed that including them would not change the main conclusions. It could be argued that since including these objects in this analysis does not change the conclusions, I could leave them in the sample. However, the advantage gained by increasing the sample size is lost because including these objects only adds noise to the statistical tests. On balance, I decided not to include the objects with $R_e \geq 5''$ and/or $n < 0.2$ or $n > 6$. However, these rejected galaxies are included again in the subsequent Chapters.

3.3 Observed mass–size relation of galaxies

Before studying the effect of the environment on galaxy sizes, it is important to check that the stellar mass distribution of the galaxies in the subsamples we compare are similar. Vulcani *et al.* (2013) found that the mass distributions for red and blue galaxies do not significantly depend on the global (i.e., cluster vs. field) environment at redshifts comparable to ours. Furthermore, Calvi *et al.* (2013) found that at lower redshifts the variations of the mass functions with global environment for galaxies with similar morphologies are quite small and subtle, and possibly only affect galaxies with the highest masses². Two-sample Kolmogorov–Smirnov (K–S) tests were performed to determine the probability p that the field and cluster samples are derived from the same stel-

²Note that we have eliminated the brightest cluster galaxies from our sample.

lar mass distribution, both separated by morphology (Figure 3.2) and by colour (Figure 3.3). Environmental differences on the mass distributions were considered to be significant if $p < 0.05$, that is, when the significance is larger than 2σ . I found that by dividing the samples by morphology the K–S tests failed to detect significant differences in the mass distributions of field and cluster galaxies (Figure 3.2). Similarly, I found that the mass distributions for red and blue galaxies do not significantly depend on their global environment (Figure 3.3). The variations in the mass distribution for the photometric sample can be attributed to the higher numbers of low mass blue galaxies in field, and high mass red galaxies in clusters. Also it is worth recalling that the photometric cluster sample utilises the spectroscopic field sample for comparison, but with a stellar-mass limit of $\log M_*/M_\odot = 10.2$ (cf. Section 2.2.2). I am therefore confident that the mass distributions of the galaxy samples we compare are similar in clusters and in the field.

Next, I compare the stellar mass–size relation for the field and cluster galaxies divided by morphology (Figures 3.4 and 3.5) and rest-frame colour (Figures 3.6 and 3.7) for the spectroscopic and photometric samples. Each figure presents the mass–size relation for the galaxies in each sample, together with averaged values in stellar-mass bins. These bins are arbitrary, and are only shown for illustration. The statistical analysis is carried out using the full cumulative distributions, also shown in the figures. Two-sample K–S tests were carried out to estimate the probability p that the field and cluster samples are derived from the same R_e distribution. Environmental differences on the mass–size relations were considered to be significant if $p < 0.05$, that is, when the significance is larger than 2σ .

Note that it makes no physical sense to compare the mass–size relations of all cluster and field galaxies disregarding their morphology or colour. The morphology/colour mix of the cluster population is very different from that of the field (e.g., Butcher & Oemler, 1984; Dressler, 1984; Desai *et al.*, 2007). Since early- and late-type galaxies have very different mass–size relations, any observed differences in the mass–size relations of the cluster and field global populations would be driven by differences in the morphology/colour mix, and therefore the samples need to be divided accordingly. Since different mass–size relation studies often use different criteria to divide

the galaxy population into sub-populations, in order to assess whether these different criteria yield different results I decided to divide the sample both by morphology and rest-frame colour (as described in Section 2.2.4).

It is very important to emphasise here that it is also necessary to separate elliptical and S0 galaxies in this analysis since they have very different profiles and formation histories. Indeed, Bernardi *et al.* (2013) and Huertas-Company *et al.* (2013) found significant differences in the mass–size relation for ellipticals and S0s. My data confirm these findings: as Figures 3.4 and 3.5 show, ellipticals are systematically larger (by $\sim 20\text{--}25\%$) than S0s with similar masses ($p = 0.01$ for spectroscopic sample and $p = 0.03$ for photometric sample).

3.3.1 Mass–size relation for morphologically-selected samples

Figures 3.4 and 3.5 show the stellar mass–size relation for the spectroscopic and photometric samples divided by morphology into Spirals, Ellipticals and S0s. K–S tests comparing the cumulative size distributions of field and cluster galaxies with the same morphology indicate that the probability that the field and cluster samples have the same R_e distribution is always over $\sim 50\%$ ($< 1\sigma$ significance). This clearly indicates that this analysis has not detected any significant effect of the galaxy environment on galaxy sizes. This result is in agreement with the work of Maltby *et al.* (2010) who found that at $z \sim 0.167$ no significant environmental effect was evident on the sizes of cluster and field galaxies of a given morphology. Reassuringly, entirely consistent results were obtained with the spectroscopic sample, smaller but more robust, and with the photometric sample, larger but with smaller reliability for individual galaxies.

Finding no significant differences in the galaxy size distributions in clusters and the field implies either that such differences do not exist or that, if they do, they are too small to be detected in our sample. In order to estimate how large a difference has to be in order to be detectable with these data, I built artificial field samples by randomly increasing the sizes of the cluster galaxies by different average amounts and compared these artificial samples with the original cluster samples via K–S tests. This procedure ensures that the numbers of field and cluster galaxies compared are the same as in the original tests. Moreover, by construction, the simulations use the observed size

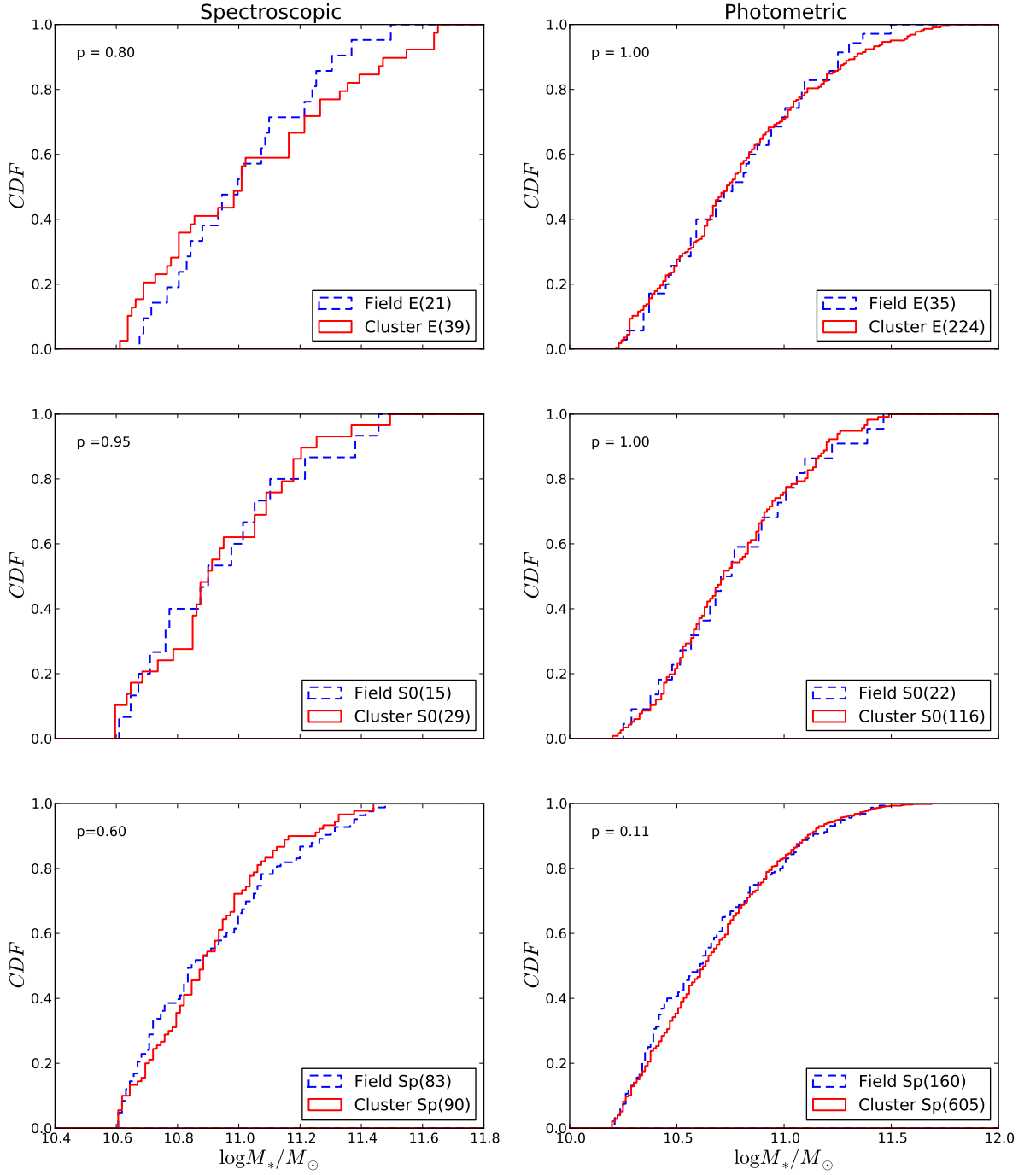


Figure 3.2: Stellar mass distributions for the spectroscopic and photometric morphology-selected samples. Each panel shows the $\log M_*/M_\odot$ cumulative distribution function (CDF) for the Elliptical, Lenticular and Spiral galaxies. The dashed blue and red lines correspond to the field and cluster samples respectively. The numbers within each CDF plot correspond to the p -value derived from the K-S tests discussed in the text. The numbers in the boxes denote sample sizes.

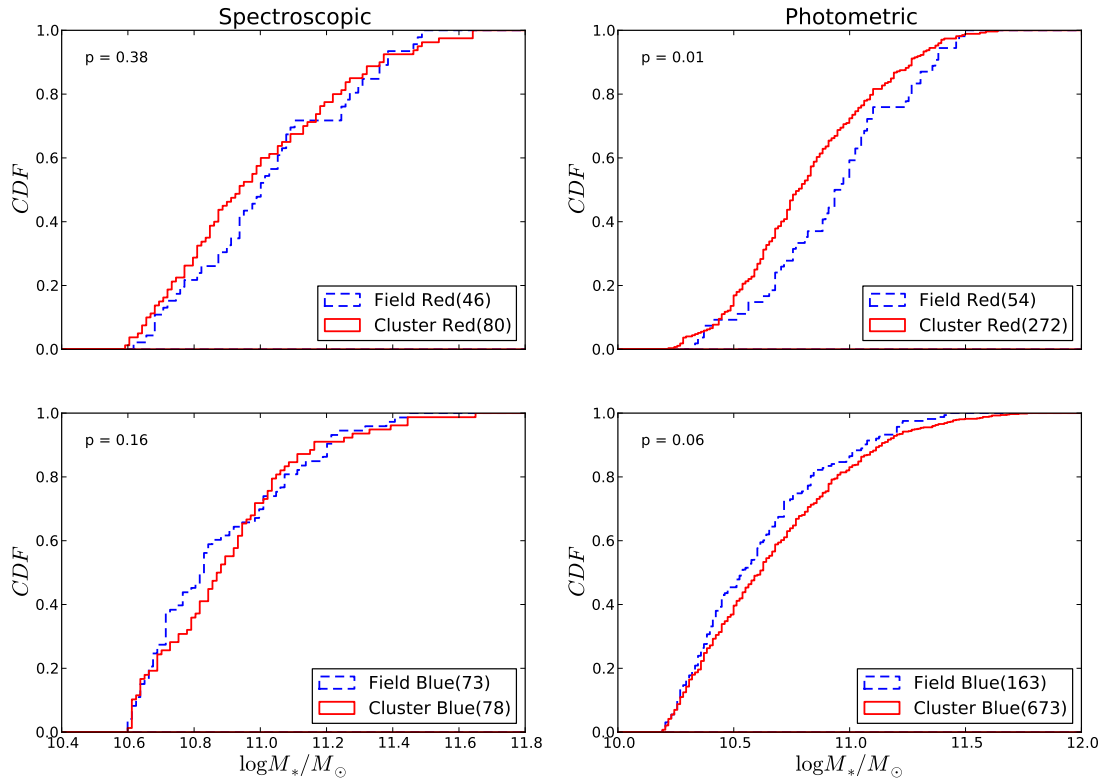


Figure 3.3: As Figure 3.2, but for colour-selected sample.

distributions of the cluster and field samples, thus retaining any putative intrinsic differences. I conclude that we would have been able to detect an average size difference of $\sim 20\%$ ($\sim 10\%$) in R_e with 2σ significance had it been present in the photometric (spectroscopic) sample. Therefore size differences of such magnitude are ruled out between field and cluster galaxies of a given morphology.

3.3.2 Mass–size relation for colour-selected samples

Having found no significant difference between the mass–size relations of cluster and field galaxies with similar morphologies, it is interesting to carry out a parallel exercise dividing the galaxy samples by colour since several studies use colour selection when reliable morphological or structural information is not available (e.g., Lani *et al.*, 2013). Figures 3.6 and 3.7 show the stellar mass–size relation for the spectroscopic and photometric samples of field and cluster galaxies divided by colour, together with their respective cumulative size distributions. As before, K–S tests fail to detect any sig-

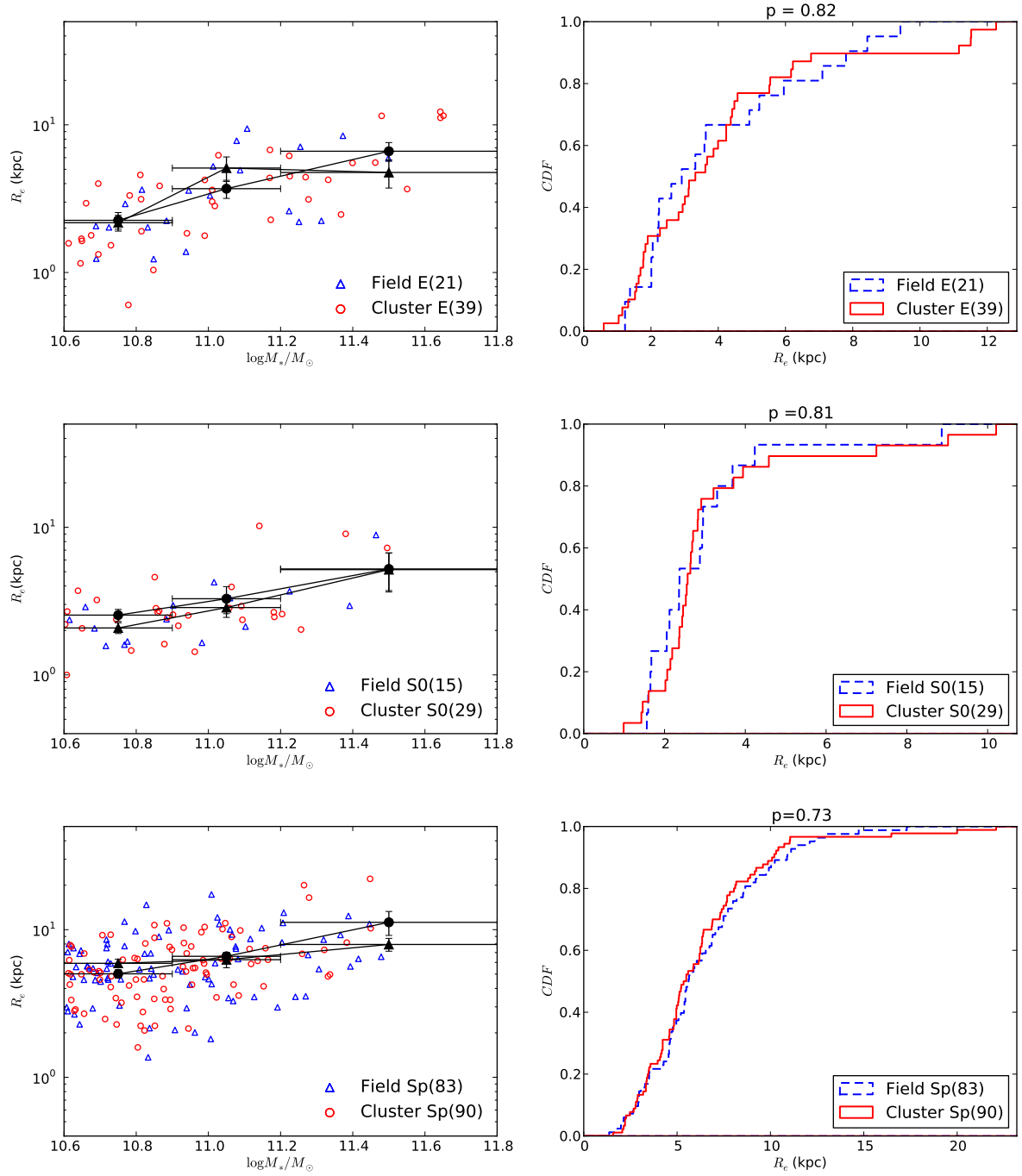


Figure 3.4: Stellar mass–size relation for the spectroscopic morphology–selected samples. *Left:* The stellar mass–size relations for Elliptical, S0, and Spiral field (blue triangles) and cluster (red circles) galaxies. The larger black triangles and circles show average values in arbitrary mass bins for the field and cluster galaxies respectively. The horizontal error bars span the size of each bin, and the vertical error bars correspond to 1σ -errors in the mean R_e of each bin. *Right:* The corresponding R_e cumulative distribution function (CDF) for each of the morphologies. The dashed blue and red lines correspond to the field and cluster samples respectively. The numbers above each CDF plot correspond to the p -value derived from the K–S tests discussed in the text. The numbers in the boxes denote sample sizes.

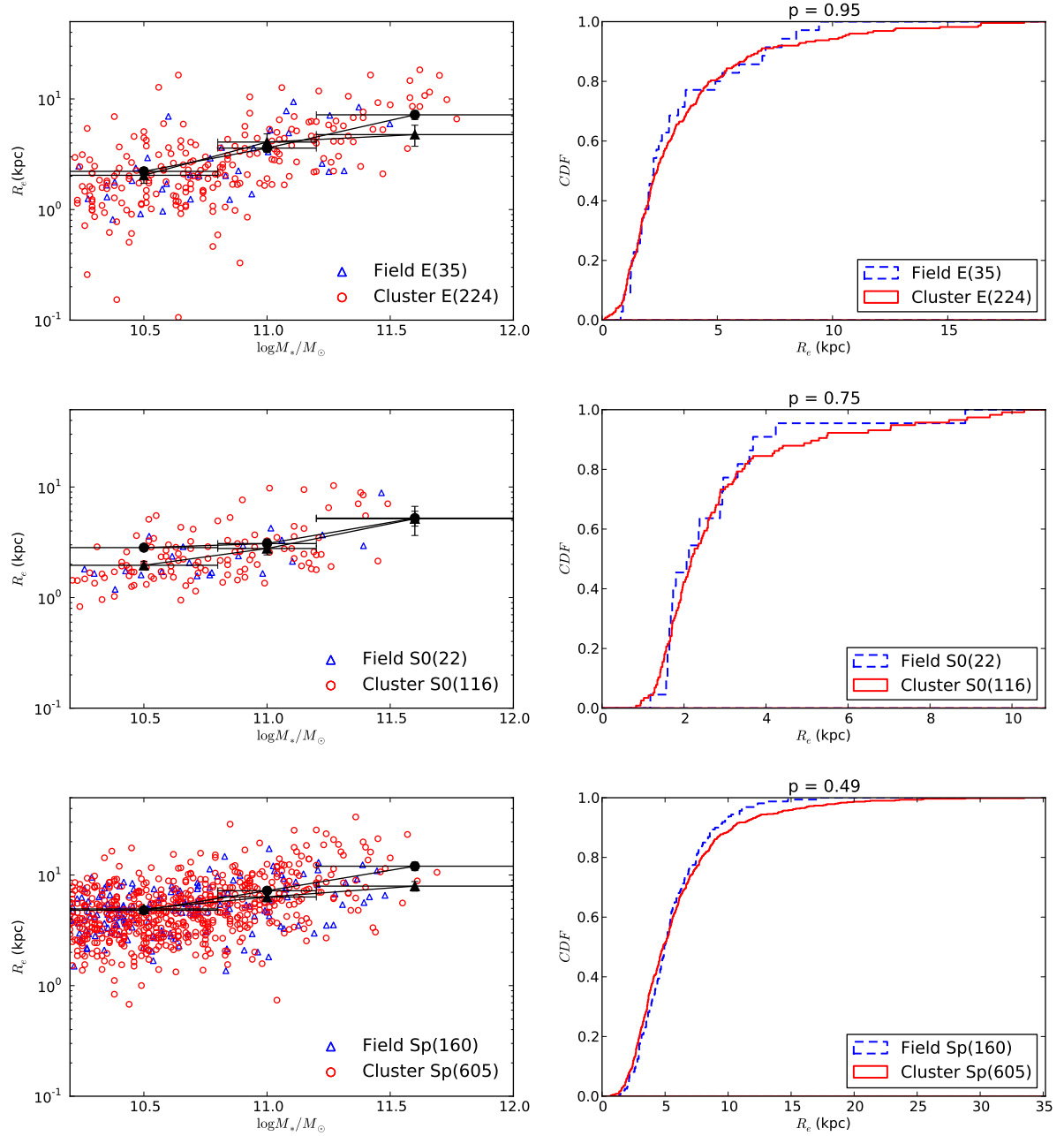


Figure 3.5: As Figure 3.4, but for the photometric morphology-selected samples.

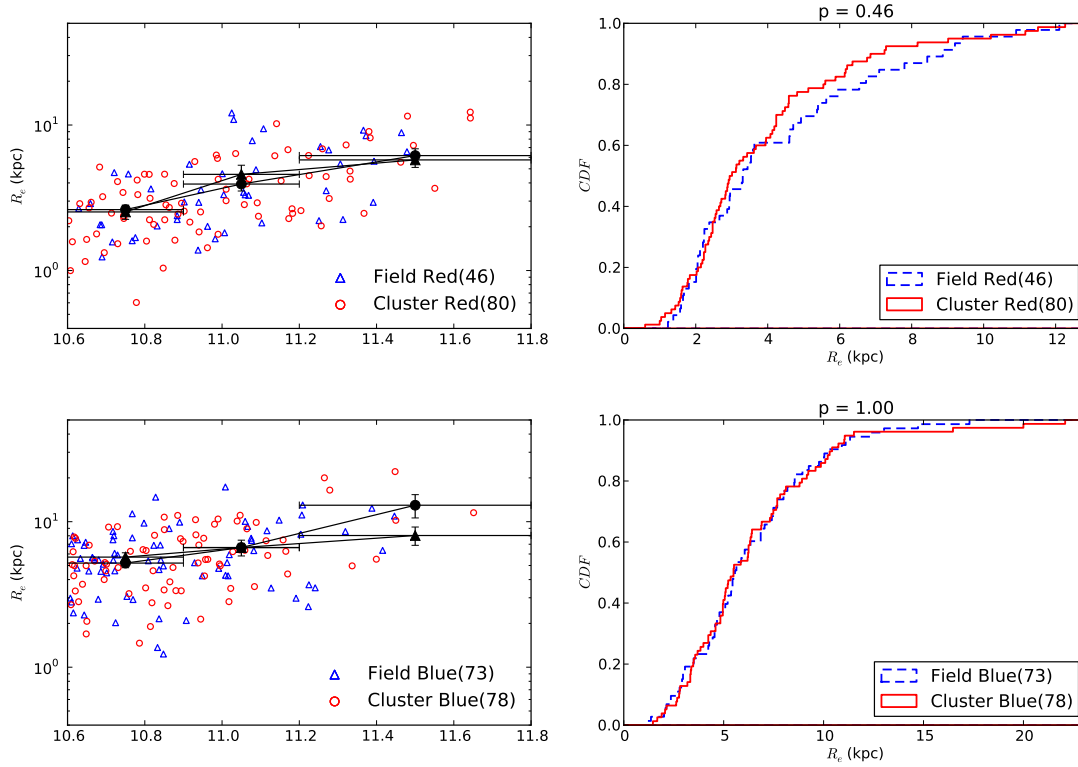


Figure 3.6: Stellar mass–size relation for the spectroscopic colour-selected samples. *Left:* The stellar mass–size relations for blue and red field (blue triangles) and cluster (red circles) galaxies. The larger black triangles and circles show average values in arbitrary mass bins for the field and cluster galaxies respectively. The horizontal error bars span the size of each bin, and the vertical error bars correspond to 1σ -errors in the mean R_e of each bin. *Right:* The corresponding R_e cumulative distribution function (CDF) for the red and blue samples. The dashed blue and red lines correspond to the field and cluster samples respectively. The numbers above each CDF plot correspond to the p -value derived from the K–S tests discussed in the text. The numbers in the boxes denote sample sizes.

nificant effect of the cluster environment on galaxy sizes. Entirely consistent results are derived for the spectroscopic and photometric samples. These results are also robust against reasonable modifications of the red–blue boundary. As with the morphological analysis, I conclude that we would have been able to detect an average size difference of $\sim 20\%$ ($\sim 10\%$) in R_e with 2σ significance had it been present in the photometric (spectroscopic) sample. Therefore size differences of that magnitude are ruled out between field and cluster galaxies of a given colour.

In this Chapter I present a direct comparison of the mass–size relations of field and cluster galaxies whose sizes and masses are determined in completely consistent ways. A direct comparison with mass–size relations derived by other studies is far from straightforward because of important differences in sample selection, redshift range,

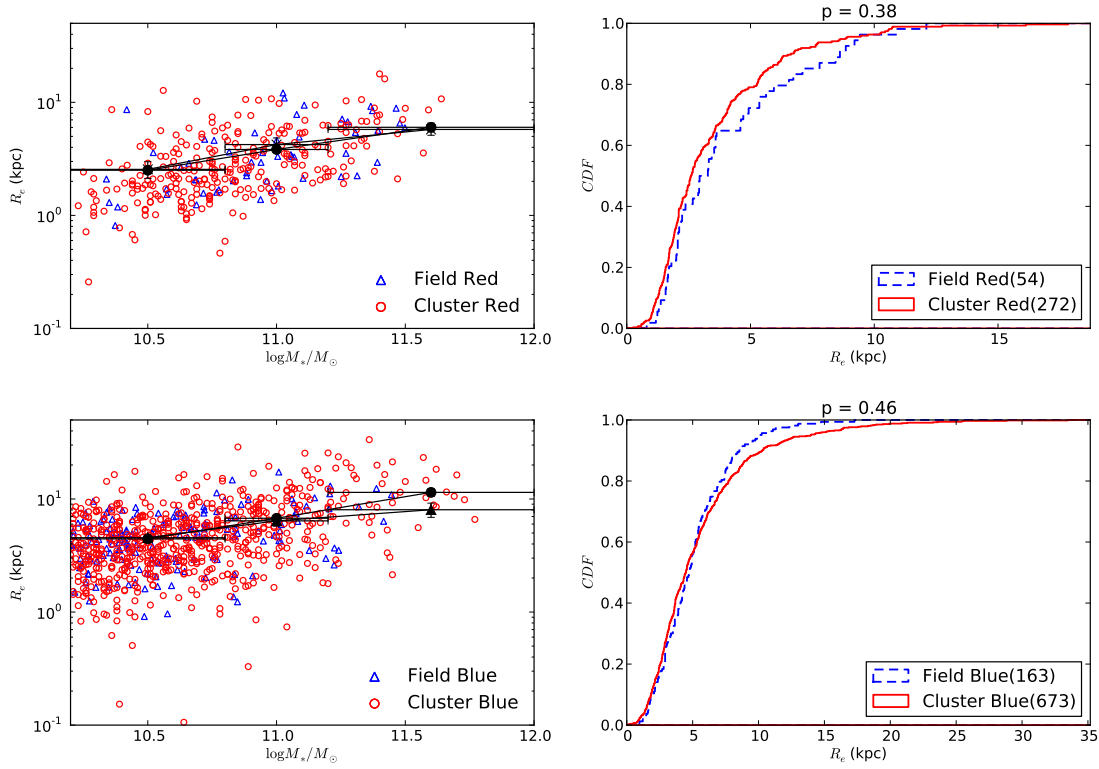


Figure 3.7: As Figure 3.6, but for the photometric colour-selected samples.

mass estimation method, IMF, size measurements and definitions, etcetera. Nevertheless, a qualitative comparison of Figures 3.4 and 3.5 with Figure 8 of van der Wel *et al.* (2014) indicates that our mass–size relations are broadly compatible. Note also that I use the galaxies effective semi-major axes to estimate sizes. This is the right thing to do for disk galaxies, where the observed semi-major axis measures the size of disks almost independently of inclination. For ellipsoids, a circularised radius would be more appropriate, since it would average out different intrinsic axis ratios and inclinations. Since disk galaxies (spirals and S0s) dominate my samples, I have used semi-major axis sizes throughout. However, my conclusions do not change if I use circularised sizes consistently for all my samples.

3.3.3 The effect of the cluster and galaxy masses

Given the broad range of velocity dispersions (and thus masses) that the clusters in the sample have (Table 2.1) I tested whether the cluster mass has any effect on our

results. I used the velocity dispersion (σ_{cl}) of the clusters as a proxy for cluster mass and subdivided our sample into low- and high-mass clusters at the median σ_{cl} value. I then compared the mass–size relations for galaxies in high- and low-mass clusters with those of field galaxies, divided by morphology and colour (Appendix A). Bearing in mind that the cluster samples are halved in this comparison, thus reducing the sensitivity of the tests, I found no significant cluster–field differences, regardless of the cluster mass.

Finally, it was tested whether the galaxy mass affects our findings by splitting all the galaxy samples in half at the median stellar mass. Once again, I found no statistically-significant difference in the size distributions of field and cluster galaxies for any of the subsamples.

3.4 Conclusions

I examined the mass–size relations of cluster and field galaxies from the ESO Distant Cluster Survey (EDisCS) in the $0.4 < z < 0.8$ redshift range. I divided the galaxies into cluster and field environments using both spectroscopic and photometric redshifts. The stellar mass range of the spectroscopic sample is $10.6 \leq \log M_*/M_\odot \leq 11.8$, while the photometric sample had stellar masses in the $10.2 \leq \log M_*/M_\odot \leq 12.0$ range. By comparing galaxies in the widest possible range of available environments my study has been able to assess whether the environment has any effect on the sizes of galaxies with similar morphologies or colours. The main conclusions of this study are:

- 1 I find no significant difference in the size distributions of cluster and field galaxies of a given morphology (E, S0 and Spiral). I rule out average size differences larger than 10–20% between field and cluster galaxies of similar morphology and mass.
- 2 Similarly, I find no significant difference in the size distributions of cluster and field galaxies of similar rest-frame $B - V$ colours (red sequence and blue cloud). Once again, I rule out average size differences larger than 10–20%.

I obtain entirely consistent conclusions with the spectroscopic sample, smaller but more robust, and with the photometric sample, larger but with smaller reliability for individual galaxies. These results apply to the full range of masses explored in this analysis. Moreover, these findings do not depend on cluster velocity dispersion (or cluster mass). However, some effect may remain for the highest mass clusters, which are not well covered by these data.

These results have important consequences for the physical process(es) responsible for the size evolution of galaxies, in particular the effect of environment on such evolution. The remarkable growth in size observed from $z \sim 2.5$ to the present (by a factor of 2–3 for disks and 4–5 for spheroids) has been reported to depend on the environment at higher redshifts ($z > 1$), particularly for early-type/passive/red galaxies. For instance, Cooper *et al.* (2012) find that early-type galaxies in higher density regions tend to have 25% larger effective radii than their counterparts of equal stellar mass and Sérsic index in lower density environments. The stellar mass range explored by these authors is comparable with this study. Similarly, Lani *et al.* (2013) find that the most massive ($M_* > 2 \times 10^{11} M_\odot$) quiescent galaxies at $1 < z < 2$ are on average $\sim 50\%$ larger in high-density environments. Although my analysis covers a broader stellar mass range than Lani *et al.*, the most massive galaxies in our sample do not show such environmental-dependent size differences.

It is important to point out that the current evidence for an environmental dependence of the mass–size relation at high- z is often limited by small samples and large uncertainties, resulting sometimes in contradictory results (e.g., Saracco *et al.*, 2014; Newman *et al.*, 2014). Regardless, my results indicate that large environmentally driven differences in the mass–size relation are not present below $z \sim 0.8$ –1. This study complements the work of Huertas-Company *et al.* (2013), who found very similar results when comparing field and group galaxies at similar redshifts and stellar masses. The main difference between both studies is that my sample contains a much larger fraction of massive clusters, while their group and cluster sample is dominated by lower-mass systems. The combined results of both pieces of research clearly show that at $z < 1$ galaxies with a broad range of stellar masses, morphologies and environments show mass–size relations which are independent of environment (at fixed

morphologies and/or colours). Interestingly, using a relatively large sample of ~ 400 early-type galaxies in clusters at $0.8 < z < 1.5$, Delaye *et al.* (2014) found that the size distribution of cluster early-types is skewed towards larger sizes compared with that of the field. This results in the average size of cluster early-types being $\sim 30\text{--}40\%$ larger, while the median size is similar in clusters and in the field. Such a difference is not evident in my sample, which spans a lower redshift range. If both results are correct, it would indicate that the transition epoch when the field galaxy size distribution has become similar to the cluster one is somewhere between the redshift range $z \sim 0.8\text{--}1$, the redshift boundary between both works. This is, of course, highly speculative, and it would require a homogeneous study spanning the full redshift range of these two works to confirm this.

The combination of all these results implies that, if the reported environmental size difference at higher- z is real, the size growth of field galaxies has caught up with that of the cluster galaxies by $z \sim 0.8\text{--}1$ to the present. Any putative mechanism proposed as responsible for galaxy growth has to account for the existence of environmental differences at high redshift, if these are confirmed to be real, and their absence (or significant weakening) at lower redshifts. Hierarchical models of galaxy evolution tend to predict moderate-to-strong environmental dependence of galaxy sizes, with the median size increasing by a factor of $\sim 1.5\text{--}3$ when moving from low- to high-mass host haloes at $z \sim 0$ (see, e.g., Shankar *et al.*, 2014). Since such dependence has been ruled out by observations at almost all redshifts, significant improvement is still needed on the modelling front. Furthermore, larger and more robust observational studies of the galaxy size evolution at all redshifts and in all environments are clearly needed to reduce the uncertainties and tighten the constraints.

Chapter 4

Galaxy structure, star formation and global environment

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.

In this Chapter, I seek to explore the interconnected relationships between galaxy morphology, star formation properties, and environment, while introducing additional information about the irregularities in the stellar distribution, as well as interpretations of the probable cause of any disturbances. Focussing on galaxies in cluster and field environments from the EDisCS spectroscopic sample, I aim to quantify galaxy structure using quantitative analysis of galaxy images, as well incorporating visually determined information from galaxies. I further study the correlations of galaxy structure with the observed photometric properties of galaxies and global environment.

4.1 Introduction

When attempting to understand the connections between changes in star formation and structure, one key challenge is in identifying the *cause* of structural disturbances. There have been many methods developed for identifying and analysing specific gravitational interactions such as mergers (which are capable of leaving prominent signatures observable over long timescales). These approaches often involve measuring the structural properties in galaxy images, like the CAS (Conselice, 2003) or Gini- M_{20} (Lotz, Primack & Madau, 2004) systems. Other approaches include using multimode (M), intensity (I), and deviation (D) statistics to identify galaxies which are likely mergers (Freeman *et al.*, 2013), or analysing the residual light remaining when a smooth profile is removed (Hoyos *et al.*, 2012). Each of these methods is found to be sensitive to different stages or types of interaction, for example, the CAS criteria tends to pick out all major mergers, whereas the Gini/ M_{20} measures both minor & major mergers (Lotz *et al.*, 2008, 2010). However, none of these methods are able to produce a complete and uncontaminated sample of galaxy interactions or structural disturbances, highlighting the complexity of quantifying galaxy structure and interpreting it. Furthermore, these methods give no insight into the physical causes of any asymmetries (reflecting internal brightness fluctuations, or evidence of external gravitational influences), so visual interpretation of images is invaluable.

In this Chapter, I utilise the *HST* *I*-band images to define a quantitative measurement of galaxy structure, and devise a visual assessment indicating possible sources for structural disruptions. This analysis is performed by examining the galaxy images and the residual images retrieved from the single Sérsic fittings (cf. Section 3.2). I further look into variations of such qualitative and quantitative structure by considering galaxies from cluster and field subsamples (cf. Section 2.2.1), and eventually linking the intrinsic structure in galaxies with their photometric properties (cf. Section 2.2.4).

Table 4.1: Details of the new spectroscopic sample by environment and morphology, selected from Table 2.2. The mass-complete subsample has $\log(M_*/M_\odot) \geq 10.6$.

Spectroscopic sample		E	S0	Sp	Irr	Total
Cluster	All	104	46	195	16	361
	Mass-complete	65	30	95	4	194
Field	All	31	9	91	20	151
	Mass-complete	15	6	35	1	57

4.2 Sample selection

The analysis presented in this Chapter employs a smaller sample extracted from the spectroscopic parent sample and a mass-complete subsample containing 265 galaxies with a mass completeness limit of $\log M_*/M_\odot = 10.6$ (Vulcani *et al.*, 2010), described in Table 2.2. The mass-complete subsample will be used to ensure that no mass-related biases affect the conclusions.

Both these subsamples contain only galaxies whose spectra have a S/N ratio in the continuum that is larger than 2, and differ from the spectroscopic sample utilised in Chapter 3 (Table 3.1) where a cut in R_e and n was exercised. This ensures not only the reliability of the redshifts, but also a reasonable quality in the measurements of spectral features such as the 4000Å break, the [OII]λ3727 emission line, and several Balmer absorption lines. These spectral features will further be analysed in Chapter 5. Table 4.1 gives this new sample with cluster and field subsamples.

4.3 Visual classification of disturbances in galaxy structure

A variety of external physical processes may affect the stellar distribution within galaxies, and hence their internal structure. Complementing the information from visual morphologies (i.e. Hubble type) of galaxies, as discussed in Section 2.2.3, I qualitatively analyse galaxy ‘structure’ by studying the detailed distribution of galaxy light. For this purpose, I use visual ‘asymmetry’ to refer to departures from a symmetric light profile, and ‘disturbance’ to indicate our best evaluation of whether the cause of that deviation is external in origin. Therefore, a galaxy may have a combination of asymmetry

and disturbance properties, e.g. symmetric and undisturbed; internally asymmetric but undisturbed (e.g. an otherwise symmetric spiral galaxy with a prominent HII region); or asymmetric due to an external distortion (e.g. gravitational interaction).

Visual asymmetry class

The *HST* *I*-band images of galaxies in the spectroscopic sample were visually inspected to qualitatively assess whether they had structural asymmetries. Three classifiers (Kelkar, Aragón-Salamanca, Gray) performed independent classifications, wherein each classifier inspected each galaxy in the sample.

The visual asymmetry was used as an indicator to identify structural disturbances in the galaxy sample. Galaxies were classified as ‘asymmetric’ if they possess asymmetric features in addition to the features attributed to their morphology, and ‘symmetric’ in absence of them.

Visual disturbance class

For those galaxies with visual asymmetry, we further designed a morphology-independent classification scheme to identify the probable cause of the disturbance. Figure 4.1 gives a graphical representation of the classification scheme, described below.

- **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 which may be acting on the target galaxy. These galaxies are assigned a non-zero asymmetry but no disturbance index and constitute only $\sim 7\%$ of the total sample. However, note that such internal asymmetries may well still be the result of external causes (see e.g. Bournaud, Duc & Emsellem, 2008), even though these may not be apparent.
- **Galaxy interaction (i/I)** : Galaxies in this class showed features indicating interactions with a companion galaxy.

- **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.
- **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 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.
- **Chaotic/Undefined systems (C/X)** : The final class contained a small number of galaxies (less than 1% of the total sample) displayed structures that were chaotic or could not be associated with any of the categories above.

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 (ie weak/strong), individual indices of ‘0’ was 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 given to each galaxy was in terms of final disturbance index and a final asymmetry index, which 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. In a small number of

cases where a classifier was not confident in the assessment, the individual contribution was downweighted to 0.5.

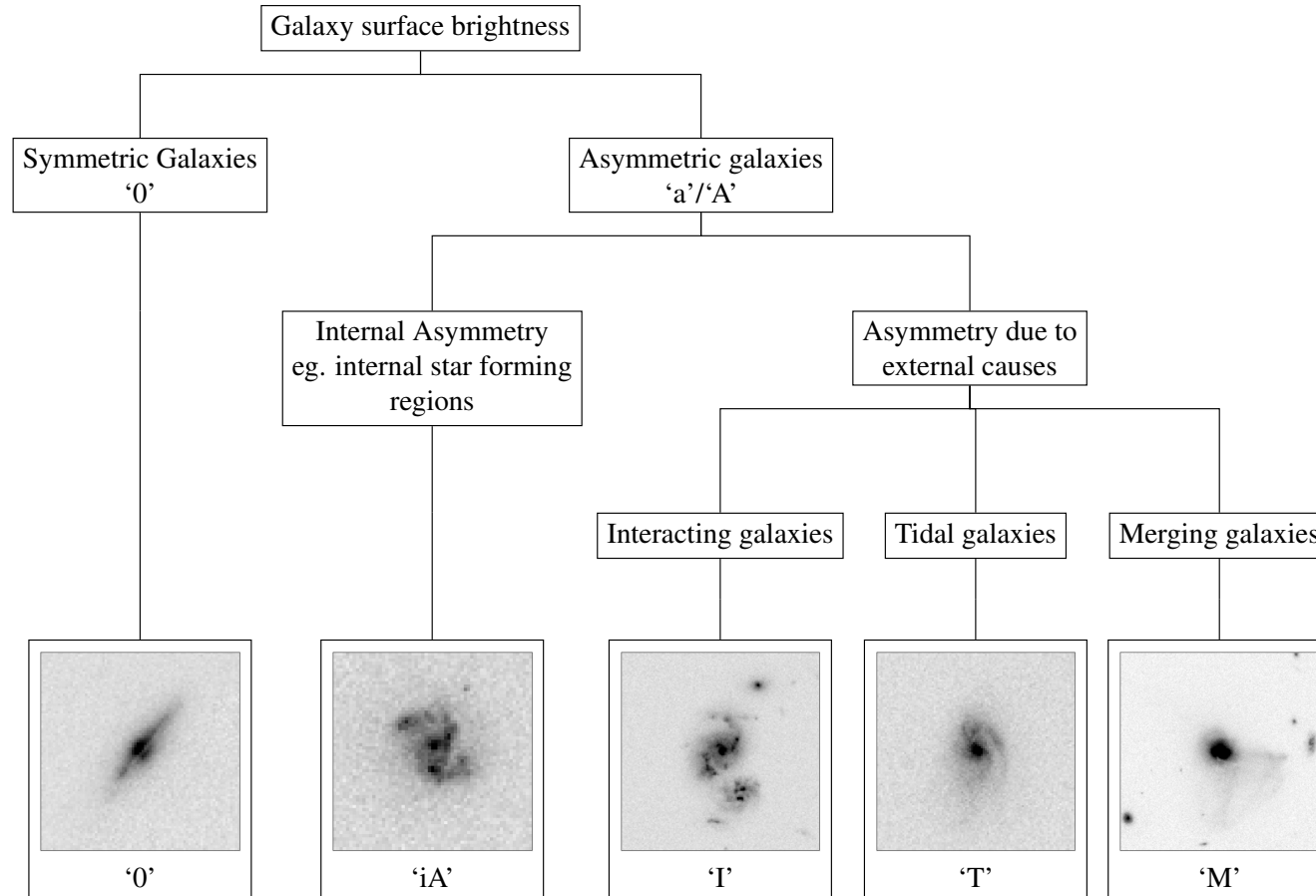


Figure 4.1: Graphical representation of our classification scheme for identifying structural disturbances. We use a two-stage process: first visually identifying galaxies with some form of asymmetry in their surface brightness distribution, then further refining that classification based on an evaluation of the probable cause of the disturbance (whether internal or external in origin). The images are *HST* thumbnails of representative galaxies from the sample identified in each class. Additionally, a small number galaxies classified as ‘Chaotic’ (C) or ‘Undefined’ (X), and are not included in this diagram. Please refer to Section 4.3 for details regarding classification scheme.

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 4.2 gives the fractions of galaxies in each disturbance class in the cluster and field environment with respect to the entire sample. I use the Wilson (1927) binomial confidence interval to compute the 1σ uncertainty in the fractions δf_i

$$\hat{f}_i \pm \delta \hat{f}_i = \frac{N_i + \kappa^2/2}{N_{\text{tot}} + \kappa^2} \pm \frac{\kappa \sqrt{N_{\text{tot}}}}{N_{\text{tot}} + \kappa^2} \sqrt{f_i(1 - f_i) + \frac{\kappa^2}{4N_{\text{tot}}}}, \quad (4.1)$$

where $f_i = N_i/N_{\text{tot}}$, and κ is the $100(1 - \alpha/2)$ th percentile of a standard normal distribution (α being the error percentile corresponding to the 1σ level (refer also to Brown, Cai & DasGupta 2001) and equals 0.9944. These fractions will be discussed in Section 4.7.1. Note that even if $N_i = 0$, the estimated value of f_i is not necessarily 0.

4.4 Quantitative measurement of structural properties of galaxies

In addition to the *qualitative* assessment of galaxy asymmetry and disturbance, I also further explore *quantitative* measurements of galaxy structure. Specifically, I 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 timescale.

Table 4.2: The relative fractions for galaxies identified as undisturbed, internally asymmetric (possessing asymmetry but with no obvious external cause), interacting galaxies, tidal galaxies and galaxies experiencing an ongoing merger, for a fixed morphology in cluster and field environment. Refer to Section 4.3 for detailed discussion.

Morphology	Environment	Undisturbed (0)	Internally asymmetric (iA)	Interacting (I)	Tidal (T)	Merger (M)
Ellipticals (E)	Cluster	0.79 ± 0.04	0.01 ± 0.01	0.17 ± 0.04	0.02 ± 0.01	0.02 ± 0.01
	Field	0.64 ± 0.08	0.08 ± 0.05	0.14 ± 0.06	0.11 ± 0.05	0.08 ± 0.05
Lenticulars (S0)	Cluster	0.93 ± 0.04	0.01 ± 0.01	0.07 ± 0.04	0.01 ± 0.01	0.01 ± 0.01
	Field	0.85 ± 0.11	0.05 ± 0.05	0.15 ± 0.11	0.05 ± 0.05	0.05 ± 0.05
Spirals (Sp)	Cluster	0.35 ± 0.03	0.25 ± 0.03	0.18 ± 0.03	0.09 ± 0.02	0.11 ± 0.02
	Field	0.36 ± 0.05	0.22 ± 0.04	0.20 ± 0.04	0.11 ± 0.03	0.11 ± 0.03
Irregulars (Irr)	Cluster	0.03 ± 0.03	0.38 ± 0.12	0.15 ± 0.08	0.09 ± 0.06	0.32 ± 0.11
	Field	0.02 ± 0.02	0.21 ± 0.09	0.12 ± 0.07	0.21 ± 0.09	0.40 ± 0.11

4.4.1 Measuring Asymmetries in galaxy residual images (A_{res})

Using the CAS (Concentration, Asymmetry, Clumpiness Bershadsky, Jangren & Conselice, 2000) system, the asymmetry ' A_{res} ' in the residual images of the galaxies (cf. Section 3.2) is defined to measure the extent of residual light under a 180-degree rotation around a point that minimises the asymmetry of the galaxy image (Hoyos *et al.*, 2012). It is defined as:

$$A_{\text{res}} = \left(\frac{\sum_{i,j} |I_{i,j} - I_{i,j}^{180}|}{\sum_{i,j} |I_{i,j}|} \right) - \left(\frac{\sum_{i,j} |B_{i,j} - B_{i,j}^{180}|}{\sum_{i,j} |I_{i,j}|} \right), \quad (4.2)$$

Here $I_{i,j}$ represents the flux at pixel (i,j) in the galaxy residual image whereas $I_{i,j}^{180}$ represents the same image rotated through 180 degrees. The second term in the equation accounts for the background contribution. A background noise image was constructed 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 individual 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 (cf. Section 2.1). 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 Kron aperture and are minimised independently. I implement a slightly modified method for minimising these terms, deviating from the original recipe described in Conselice, Bershadsky & Jangren (2000). I 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-degree 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, while for real galaxy images A ranges from 0 to 1.

Figure 4.2 graphically describes one iteration for the computation for A_{res} using the galaxy example from Figure 3.1, with $A_{\text{res}} = 0.40$.

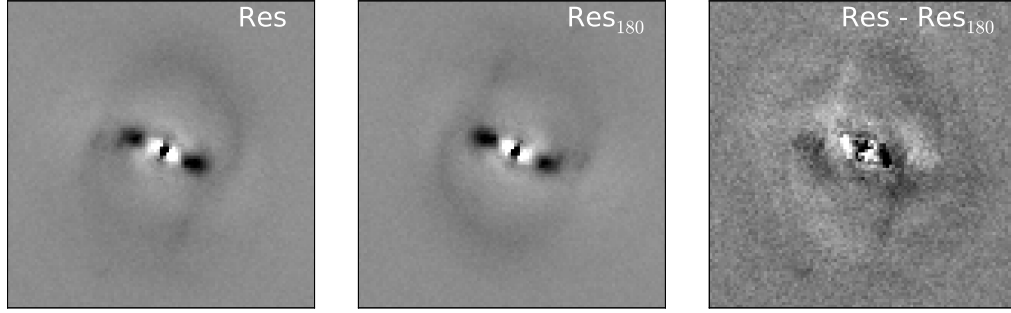


Figure 4.2: Taking forward the example from Figure 3.1, the residual image is rotated by 180 degrees (middle panel) and subtracted from the original residual image (third panel). This panel represents the subtraction after rotating the residual image about the SEXTRACTOR-defined centre. The ‘ A_{res} ’ is computed over this subtracted image within the Kron aperture, and is equal to 0.40 for this particular example. This procedure is then repeated for different centres of rotation as described in Section 4.4.1.

4.4.2 Residual flux fraction (RFF)

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

$$RFF = \frac{\sum_{i,j} |I_{i,j} - I_{i,j}^{\text{GALFIT}}| - 0.8 \times \sum_{i,j} \sigma_{i,j}^{\text{bkg}}}{\sum_{i,j} I_{i,j}^{\text{GALFIT}}}, \quad (4.3)$$

where $I_{i,j}$ represents the flux at pixel (i,j) in the galaxy image, while I^{GALFIT} is the model created by GALFIT. The *rms* of the background is $\sigma_{i,j}^{\text{bkg}}$. As discussed previously, I use the same galaxy residual images for computation of RFF over the Kron aperture. For a pure Sérsic galaxy, the RFF is expected to be 0.0, as GALFIT could compute an exact model to fit the galaxy. However, in presence of independent errors, the properties of the residual image thus generated would not be blank but be very similar to those of Gaussian white noise. Thus by utilising the residual image generated by subtracting GALFIT model of a simulated Sérsic galaxy, the factor of 0.8 guarantees the expectation value of RFF for purely Gaussian noise error image of constant variance to be 0.0 (Hoyos *et al.*, 2011). This factor of 0.8 was derived through hypothesis testing procedure.

4.5 Defining galaxy structure

Originally intending to detect minor mergers, Hoyos *et al.* (2012) nevertheless show that A_{res} and RFF are capable of automatically detecting general 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 RFF vs 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 that nevertheless display ‘roughness’ or ‘texture’, and the other one almost devoid of any merging galaxies (a powerful null test).

The same technique is used to divide our mass-complete spectroscopic sample to identify a subsample of structurally disturbed galaxies to compare with our qualitative identifications. I define RFF vs A_{res} as a diagnostic applied to the entire population of galaxies in our sample of morphologically classified galaxies with reliable spectra. The sample was statistically divided by defining a separating border as a second order polynomial in the A_{res} that maps the RFF and separates visually identified mergers from non-mergers.

The statistical quality of the two populations is determined by the F -score, F_β (Rijsbergen, 1979) given by

$$F_\beta = \frac{(1 + \beta^2) \times p \times r}{(\beta^2 \times p + r)}, \quad (4.4)$$

where ‘ r ’ denotes the sensitivity or completeness of the method, and ‘ p ’ denote specificity or the true negative rate. The factor β is a control parameter which determines the relative importance of r and p . In this analysis, a value of $\beta = 1.25$ is used to be consistent with Hoyos *et al.* (2012). This border is then optimised such that it maximises the F -score.

In order to apply the F -score maximisation for detection of galaxy structure, I use a training sample of galaxies classified visually as mergers from our parent sample to calculate r and p of the sample. Figure 4.3 shows both the 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 completeness of 90% ($r = 0.90$) and a contamination of 25% ($1 - p = 0.25$) by galaxies not classified as mergers (refer to Hoyos *et al.* 2012, for the detailed method).

I 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 Figure 4.3. It is thus clear that this method gives a clean sample of non-merging galaxies. Comparing to Hoyos *et al.* (2012), a significant flattening is seen 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 the mentioned work. This is also reflected in the range of RFF and A_{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, it is evident that this technique is consistent in separating structurally disturbed galaxies. Figure 4.4 shows the merging, tidal and interacting galaxies on the RFF vs A_{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, interacting galaxies are found to reach lower RFF values. Therefore, in accordance with the classification scheme, the ‘true’ interacting galaxies are separated from the visually symmetric interacting galaxies (dark triangles), despite the presence of a companion. It is noted that, as expected, the symmetric interacting galaxies (dry merger candidates, or ‘0&i’) are the objects populating the region below the separating border on the RFF vs A_{res} .

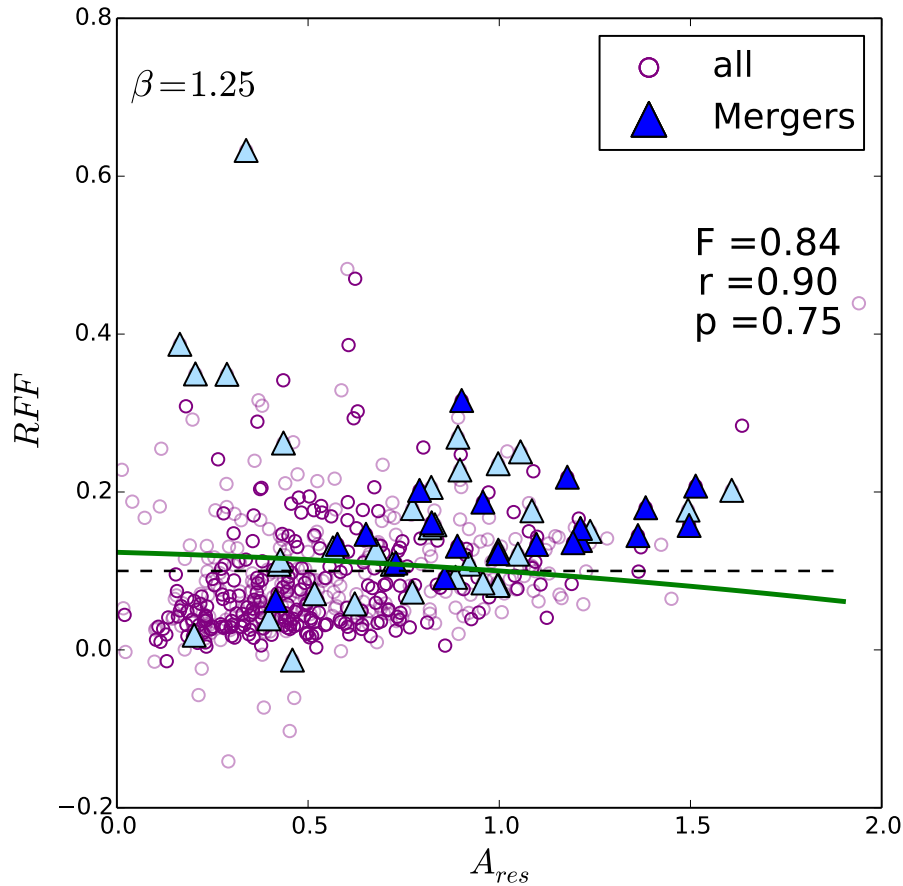


Figure 4.3: The RFF vs A_{res} plane with the statistical best border (green) for galaxies classified as mergers, constructed using a mass-complete sample. The light blue triangles and faded purple circles denote low-mass galaxies excluded from the analysis. The dashed line indicates the initial approximation used to compute the border. The r and p values illustrate the completeness and purity of the division: 90% of mergers from the training sample lie above the border (true positives) while 75% of non-mergers lie below the border (true negatives). Note that the final border remains nearly horizontal, indicating that RFF alone provides a good indication of merger status for our sample.

4.6 Link between the *qualitative* and *quantitative* structure

I next connect the quantitative measures of galaxy structure with our visual classification scheme, recalling the need to control for morphology. Using the CAS system, Conselice (2003) evaluate the relative variation in the ‘Asymmetry’ of galaxies when their morphologies are considered. Galaxies with early-type morphologies displayed lower asymmetries compared to late-type, star-forming or disk galaxies. I do find consistent results while comparing A_{res} of galaxies with mild/strong visual asymmetry for a fixed morphology (Figure 4.5). The galaxies with elliptical/lenticular morphology

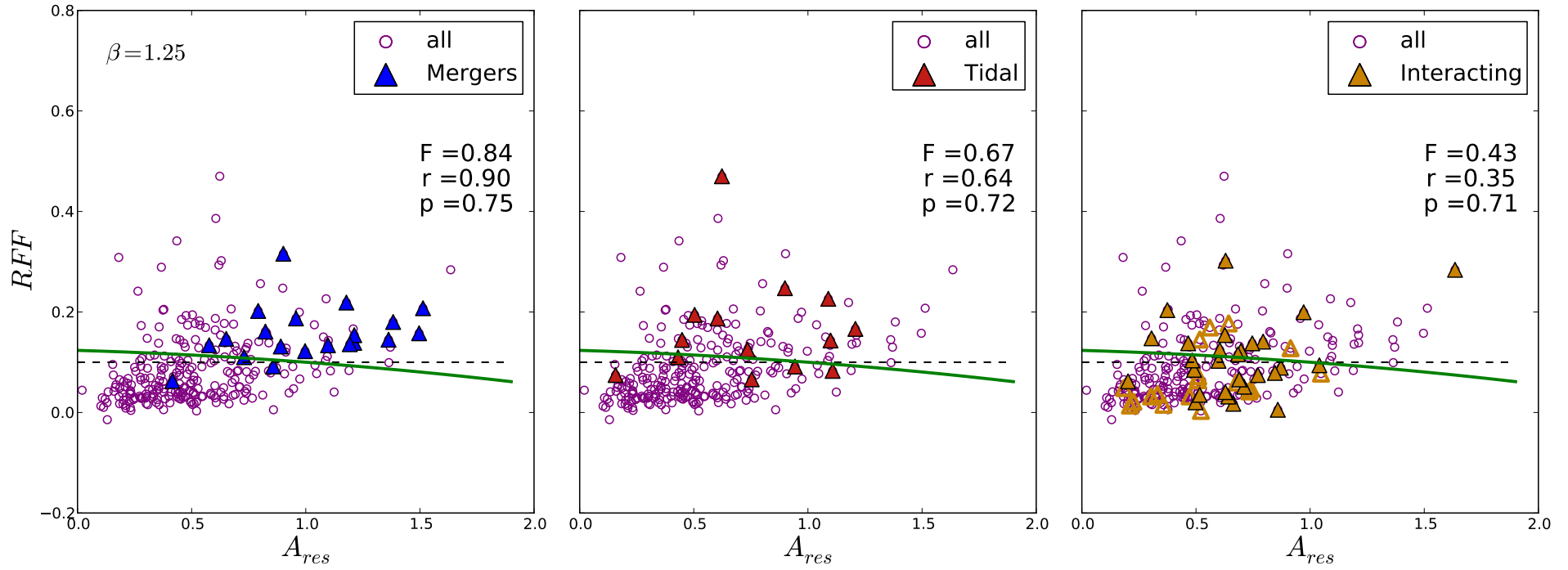


Figure 4.4: Comparison of the RFF vs A_{res} plane for all externally disturbed classes of galaxies: mergers (left), tidal (centre), and interacting (right), using the mass-complete sample. As in Figure 4.3, the dashed and green lines indicate the initial approximation and the final border computed using the merger class of galaxies (blue). The F -score, r and p values for each class of galaxies are computed using this border. The open triangles in the right panel denote the subclass of interacting galaxies nevertheless classified as ‘symmetric’ according to our classification scheme (discussed in Section 4.3)

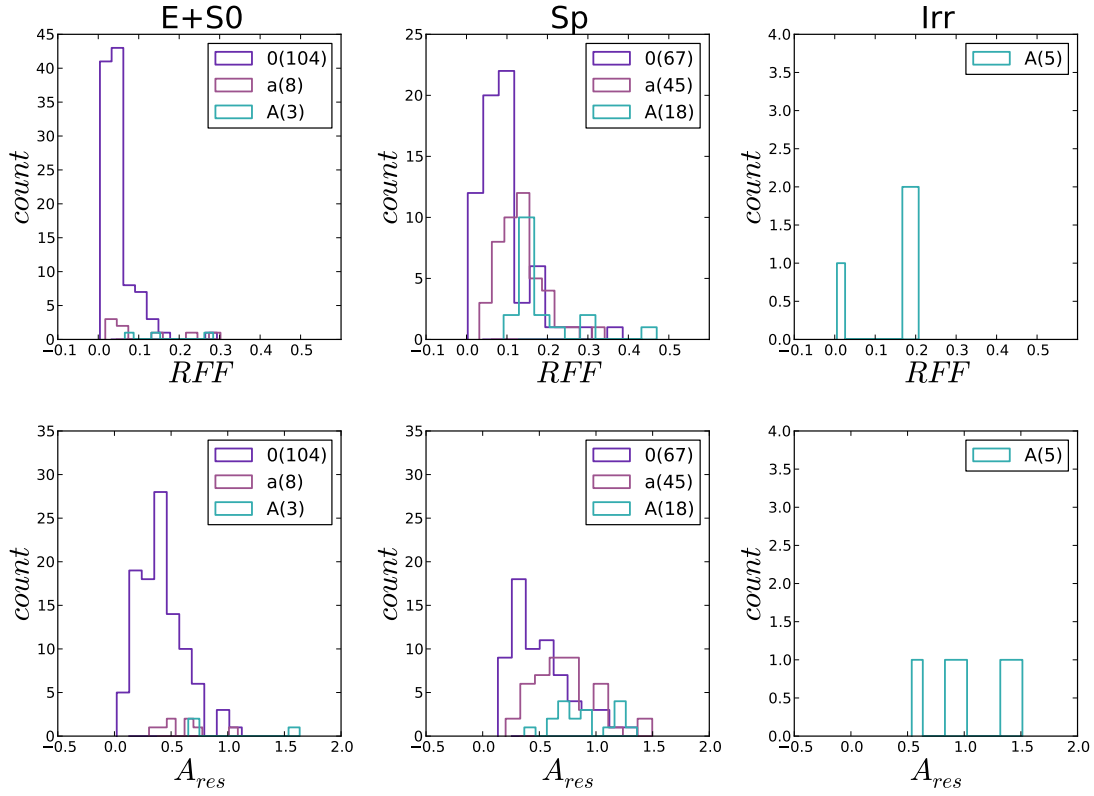


Figure 4.5: Separating quantitative measurements of structure by visual asymmetry. The histograms show the distributions of RFF and A_{res} for visually symmetric (0), mild (a) and strongly asymmetric (A) galaxies at fixed morphology. Early-type galaxies (E+S0) show little quantitative or qualitative evidence for asymmetry or disturbance. Both top and bottom panels for spiral galaxies (middle) clearly show a shift in RFF and A_{res} , with higher values corresponding to the strongest visual asymmetries.

are generally found to be visually symmetric ('0') with very low structural asymmetry in their residuals. The spiral galaxies, however, show a distinct separation in structural asymmetry in the residuals for mildly and strongly visually asymmetric galaxies, confirming that visual and structural asymmetry are strongly correlated. The irregular galaxy sample is small, but as expected they are all asymmetric with typically high RFF and A_{res} values.

I next consider the variation of quantitative measures of structure with the visually determined causes of disruption. Figure 4.6 shows the distribution of RFF and A_{res} for galaxies disrupted due to different mechanisms. If we consider only the RFF of galaxies, it is found 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

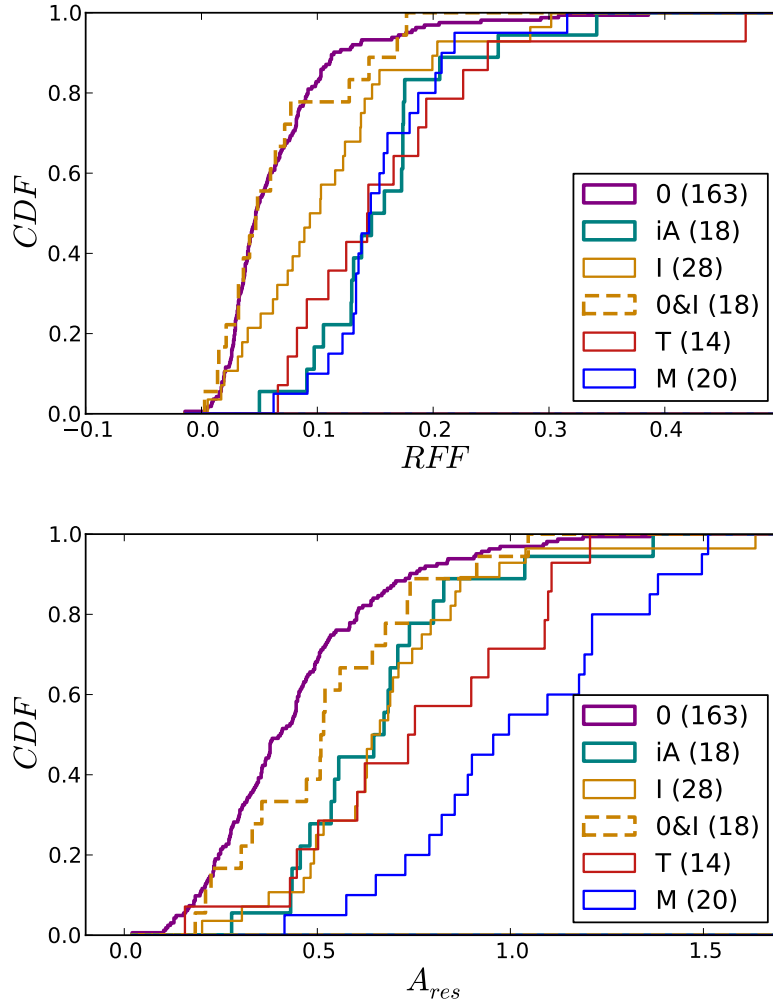


Figure 4.6: Distributions of two quantitative measurements of structure by visual disturbance class. This figure shows the cumulative distributions of RFF (top) and A_{res} (bottom) for galaxies separated according to the degree and source of any visual disturbance. The distributions are labelled according to the physical processes introduced in Section 4.3 and Table 4.2. However, for the interacting galaxies, I have plotted the separate distributions for the subclass of symmetric interacting galaxies ('0&I') whereas 'T' denotes the main class of interacting galaxies displaying obvious visual asymmetry. Note that while RFF clearly separates symmetrical galaxies ('0', '0&I') from the remaining classes, A_{res} has further discriminatory power according to the *cause* of any asymmetry, with internal asymmetries ('iA') and interacting galaxies ('I') having some of the lowest values and mergers ('M') having the largest among the disturbed classes.

demonstrated when comparing the best border for galaxies in different disturbance classes in Figure 4.4. However, the tidal galaxies do seem to spread towards higher RFF . Additionally, the subclass of symmetric interacting galaxies ('0&I') seems 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 Figure 4.6 shows the distribution of A_{res} for different disturbance classes. Interestingly, a significant stratification is seen in the distribution of A_{res} for different disturbance classes, with undisturbed galaxies having a low A_{res} and mergers showing extreme values of A_{res} .

These observations assert 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_{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_{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.

4.7 Effect of global environment on galaxy disturbances

The classification scheme proposed enables us to separate galaxies based on various possible mechanisms that could cause disruption in galaxy structure. These mechanisms are thought to be effective in different cluster regions. Galaxy-galaxy interactions, and tidally disrupted galaxies are found in cluster outskirts (Heiderman *et al.*, 2009; Adams *et al.*, 2012) whereas ram-pressure stripping, starvation and strangulation due to dense ICM are prevalent in cluster cores (Gunn & Gott, 1972; Balogh *et al.*, 1997).

This analysis uses the spectroscopic sample with visual classifications for the global comparison of cluster and field environments rather than a more continuous measure of local environment. Since a redshift-controlled field sample is built for this analysis (cf. Section 2.2.1), the low sample numbers due to mass completeness are compensated for by including low-mass galaxies in clusters and field within the same redshift

slice. Further, to remove additional effects brought in by morphology dependence on the environment (Dressler, 1984; Treu *et al.*, 2003; Desai *et al.*, 2007), I look at the disturbance content of galaxies in clusters and field at fixed morphology (Table 4.2). I find that the fraction of galaxies classified visually as interacting, tidal and merging do not seem to depend on the environment.

4.7.1 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, we do observe a quenching in the star formation of galaxies in dense environments (Balogh *et al.*, 2007; Haines *et al.*, 2013; Kovač *et al.*, 2014), though stellar population ages are found to be independent of galaxy environment (Thomas *et al.*, 2010). With the aim of studying the possible links between the quenching of star formation and the morphological change in galaxies, I look at the star formation properties of structurally disturbed galaxies by using the rest-frame UVJ colour plot (cf. Section 2.2.4) to distinguish the passive and star-forming population in the sample.

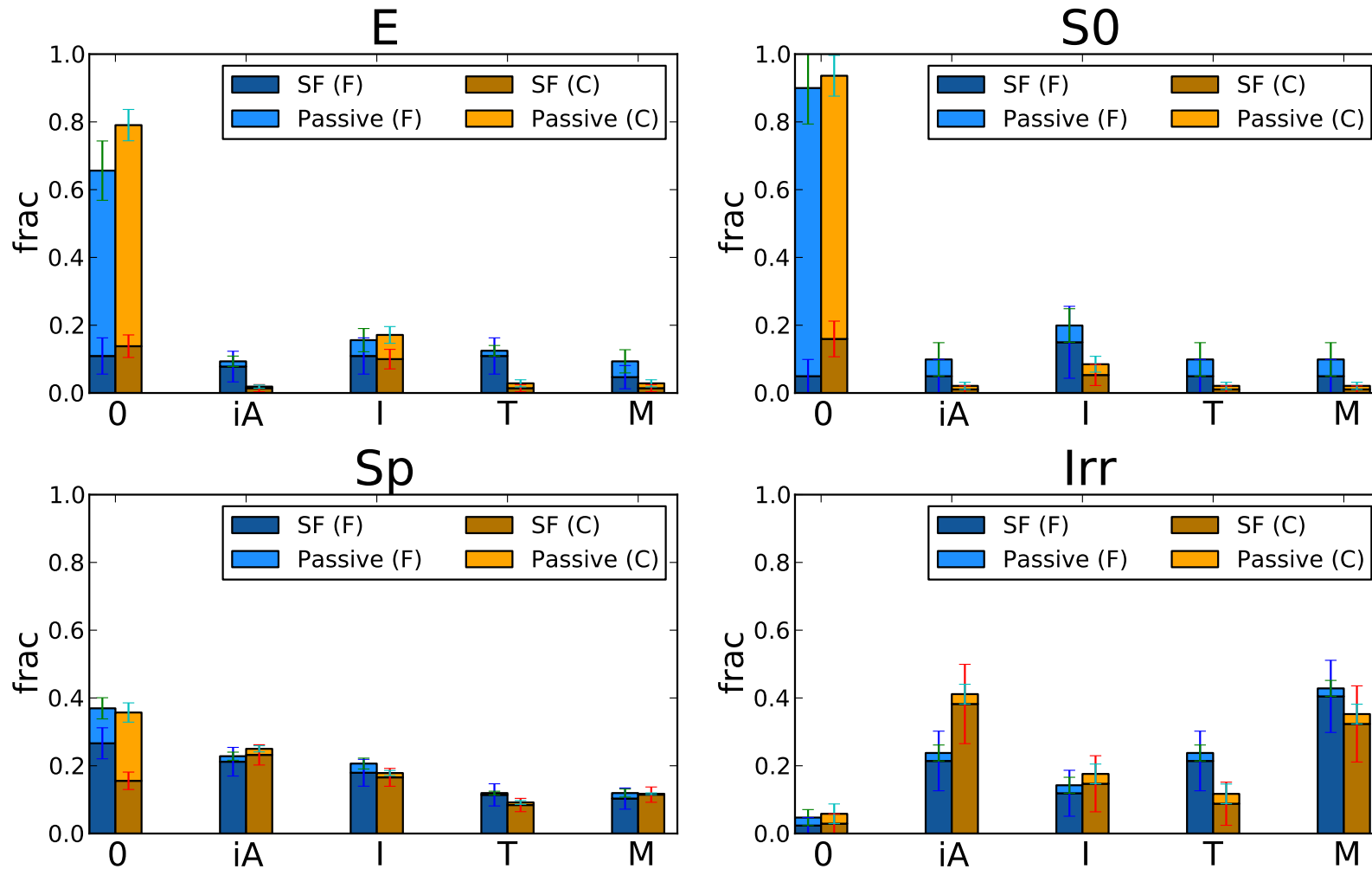


Figure 4.7: Visual galaxy structure at fixed morphology according to the global environment. Each panel shows the fractions of galaxies in different disturbance classes for a given morphology, in the field (blue) and cluster (yellow) environments. The dark shaded region in each bar shows the fraction of star-forming galaxies in that class of morphology, disturbance class, and environment. In both cluster and field environments, less than half of all spiral galaxies are visually symmetric ('0'), while for asymmetric galaxies the causes of the disturbance are roughly equally distributed between internal causes ('iA'), interactions ('I'), tidal forces ('T'), and mergers ('M'). Note also that for symmetric spirals, a significantly higher fraction (2.3σ) in cluster environments are passive than in the field. Conversely, passive spirals are only found in the visually symmetric class.

Figure 4.7 shows the fraction of passive and star-forming galaxies of each morphology type in various structural disturbance classes, and global environments. It is evident from each of the four panels that galaxies with early-type morphology are visually smoother as compared to the galaxies of late-type/irregular morphology, which is expected from the distinguishing physical properties of these two sub-populations.

Most spirals show asymmetries, and for those, a flat distribution of spirals across the disturbance classes (most of which are external in origin) is observed. Furthermore, in each disturbance class nearly all are star-forming, indicating a strong correlation of star formation with external causes of structural disturbances. Likewise, all of the irregulars are both disturbed according to their stellar distribution, and star-forming according to their photometry. We can, thus, say that external processes lead to star formation in galaxies irrespective of their morphology. However, the star formation can also be triggered internally in galaxies. In general, it is seen that the passive population in the sample – irrespective of their morphology – tend to have lower RFF and lower A_{res} , and hence are structurally smoother and symmetric. This correlation, however, seems to be independent of the global environment.

4.7.2 Passive spiral fraction in clusters

I make particular note of those spiral galaxies that are simultaneously classified as visually smooth/undisturbed and passive. Furthermore, the majority ($> 70\%$) of these passive undisturbed spirals have stellar masses greater than the mass-completeness limit, both in cluster and field environment. This observation agrees with the findings from works such as Poggianti *et al.* (1999); Wolf *et al.* (2009), Rodriguez del Piño *et al.* (2016, MNRAS, in press), 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) report that optically passive spiral galaxies in clusters, at a given mass, tend to have lower star formation rates and smoother morphologies as compared to the galaxies in field.

I introduce Figure 4.8 & Figure 4.9, where the rest-frame UVJ colour-colour plot is colour-coded with respect to RFF and A_{res} , for cluster and field galaxies. Complementing Figure 4.7, both panels in Figure 4.8 show that these passive undisturbed spirals have lower RFF , indicating a smoother structure. This is further enhanced in Figure 4.9, where we see that passive spirals in clusters are much more symmetric with low A_{res} . This observation combines the result from Figures 4.6 and 4.7 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.

I use two-sample K–S tests to check whether the RFF and A_{res} distribution for these passive spirals, and the regular undisturbed spirals are statistically similar. Figure 4.10 shows a comparison of RFF and A_{res} distribution for passive spirals and regular undisturbed spirals, both in cluster and field environment. The K–S test yielded probabilities of 1.6×10^{-3} and 0.04 for the RFF distribution, emphasizing that the passive spirals show a smaller range in the RFF values irrespective of their global environment. However, both regular and passive spirals show a statistically similar broader distribution of A_{res} .

This result reinforces the findings from Figure 4.7, implying that the higher fraction of passive spirals in clusters indicates that the role of global cluster/field environment is perhaps towards only increasing the fraction of passive undisturbed spiral galaxies relative to the total spiral galaxies in clusters, while their morphological classification remains unchanged. This implies that gas removal mechanisms must be at play affecting only the star formation in dense environments, leaving the galaxy structure largely intact but smoother. This is in agreement with the findings presented in Bösch *et al.* (2013) in the low-redshift STAGES field (Gray *et al.*, 2009), which show that red spiral galaxies display distinct asymmetries in their gas rotation curves, and hence are preferentially experiencing ram-pressure stripping as compared to normal spiral galaxies.

Turning our attention to lenticular (S0) galaxies, Figure 4.7 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 relatively large, there seems to be 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 which is absent in the field. Specifically, I do not find a single symmetric undisturbed star-forming S0 in the field, although the expectation value of their fraction shown in Figure 4.7 is not 0 (cf. Equation 4.1). Although the undisturbed lenticulars have a wide spectrum of stellar masses in both global environments in the sample, a majority ($> 80\%$) of these smooth star forming cluster lenticulars have masses less than the mass 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 putative 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 disk star formation has ceased. In this scenario, the gas is removed from the disk 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 therefore be cluster-specific. That 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. These star-forming lenticulars are overplotted in the left panels of Figures 4.8 and 4.9, denoted by stars colour-coded with RFF and A_{res} .

4.8 Conclusions

I present the analysis of structure at intermediate- z ($0.4 < z < 0.8$), using optical data from the ten high-redshift clusters from EDiSCS and a complementary field galaxy sample. A visual analysis of galaxy structure is performed, indicated by visual asymmetry and signatures from possible gravitational interaction. I make use of the information embedded in the galaxy residuals to define a quantitative measure of galaxy structure. I employ the non-parametric structural diagnostic of RFF vs A_{res} on residual images of galaxies after removing the bulk signal, and compare to our qualitative classifications. Exploiting the photometric information, I connect galaxy structure with star formation and environment. The main findings of this structural analysis include:

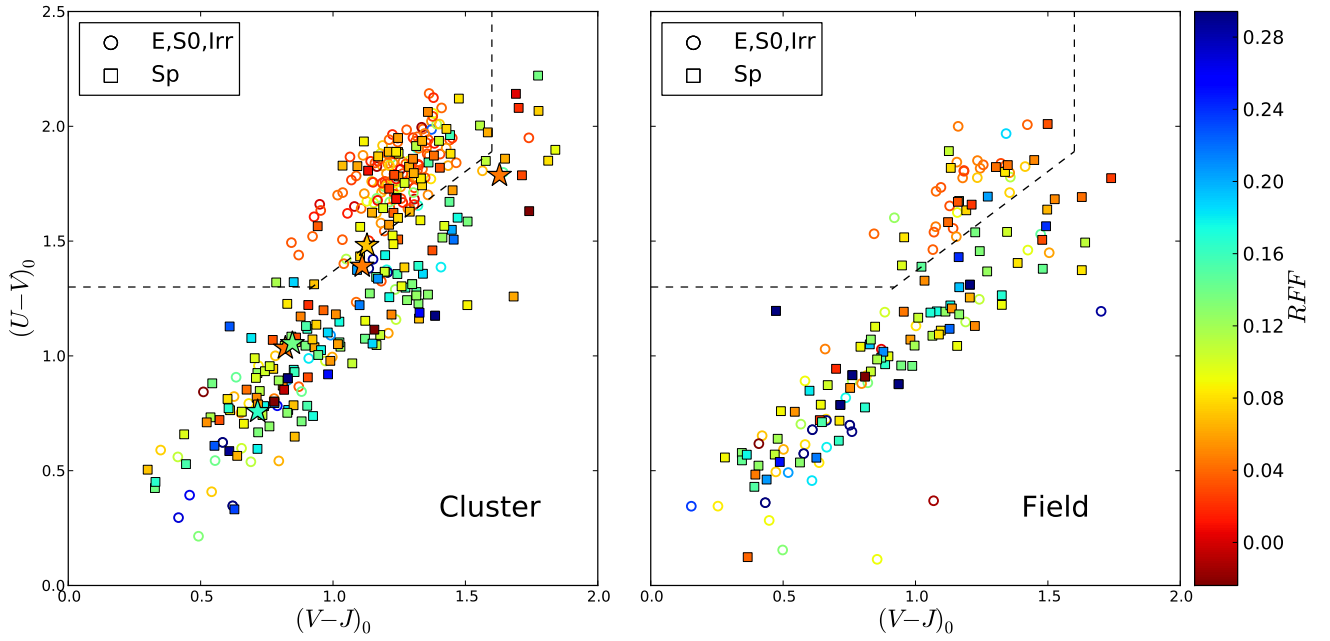


Figure 4.8: Linking star formation, morphology, structure, and environment. The UVJ plot is colour-coded according to RFF values for the cluster (left panel) and field (right panel) galaxies: redder colours indicate smoother, undisturbed galaxies while bluer colours denote ‘roughness’. As in Figure 2.5, the dashed lines show the selection boundaries for passive galaxies. In agreement with Figure 4.7, I note a higher fraction of smooth passive spiral galaxies and smooth star-forming lenticulars (overplotted as stars) in the cluster relative to the field.

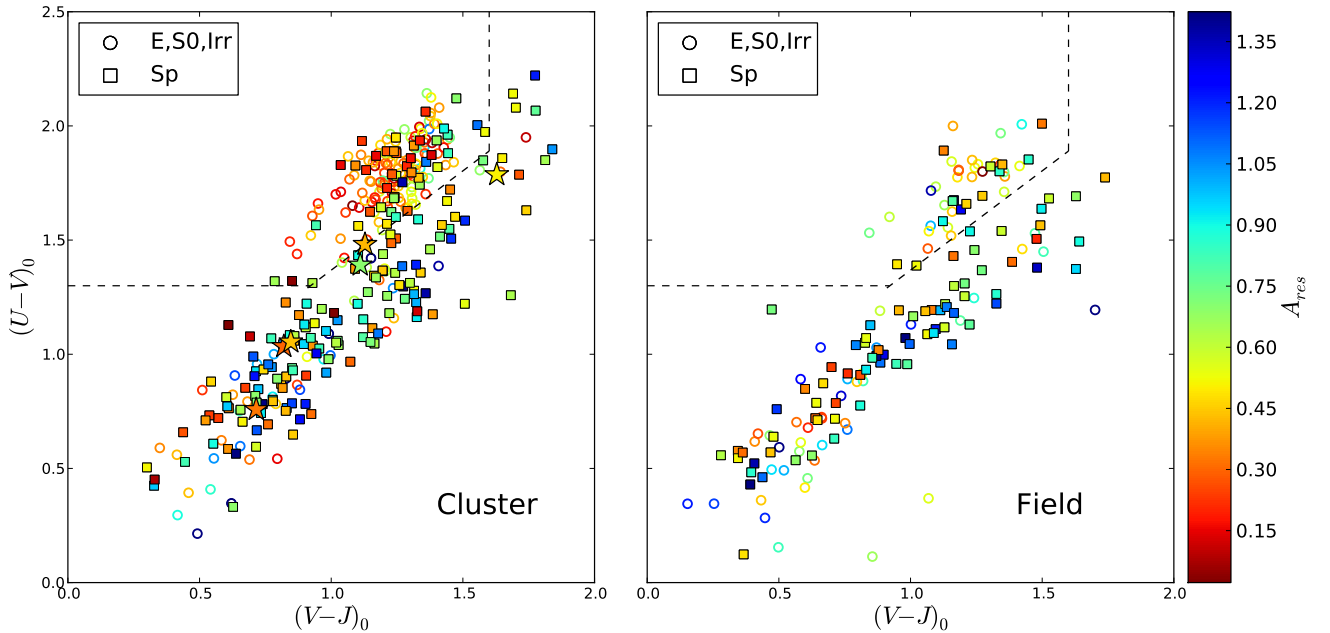


Figure 4.9: Similar to Figure 4.8, the UVJ plot is here colour-coded according to A_{res} for cluster (left panel) and field (right panel) galaxies. Star-forming galaxies are consistently found to be more quantitatively asymmetric than passive galaxies irrespective of the morphology or global environment.

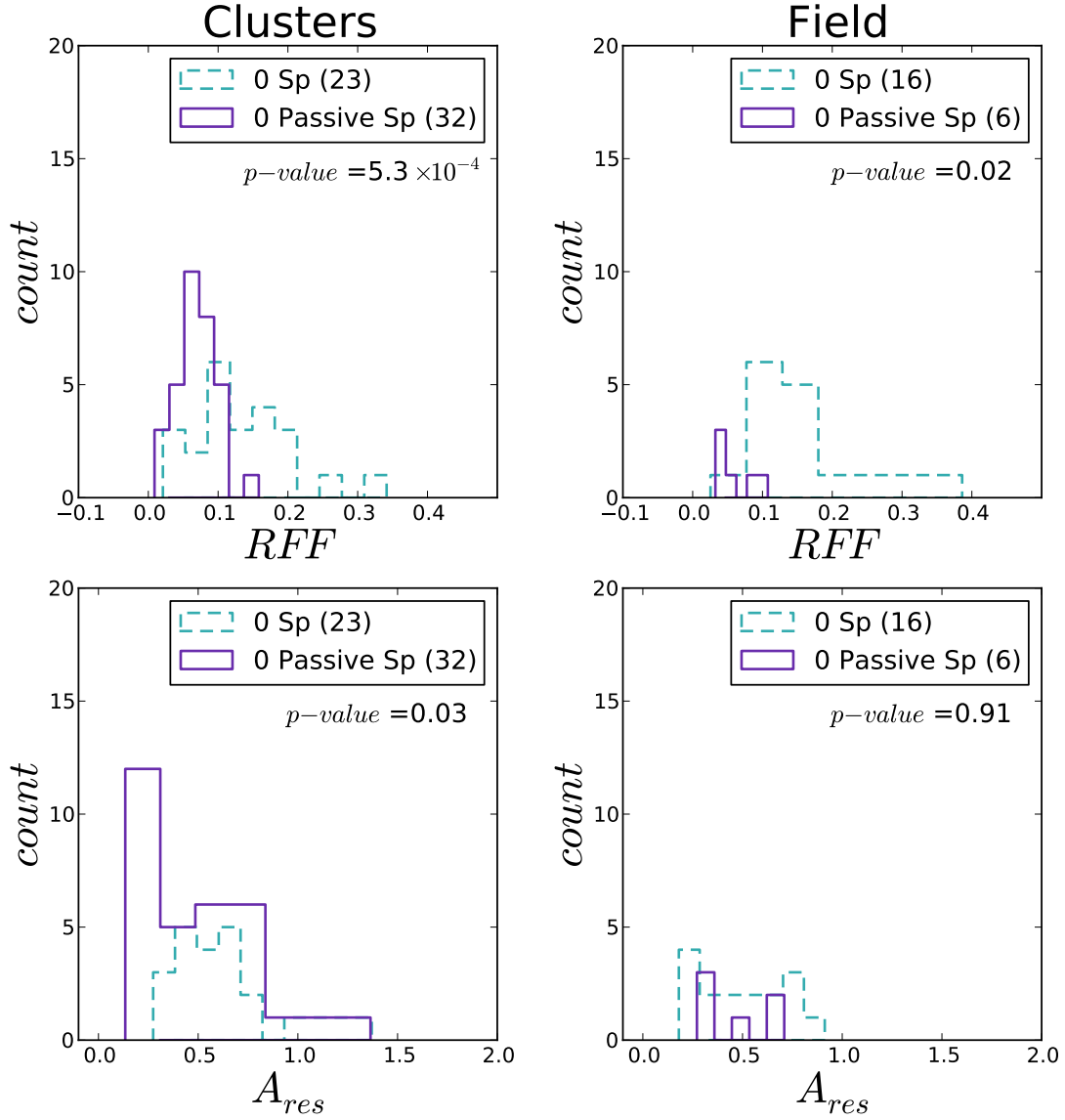


Figure 4.10: RFF and A_{res} distributions for spiral galaxies. The purple line shows the subset of passive symmetric spirals, as discussed in Section 4.7.2. The inset ‘ p -values’ give the probability that the two distributions are the probabilities from two sample K-S test, showing that in addition to being visually symmetric, they are quantitatively ‘smoother’.

- 1 Qualitative (visual classification) and quantitative (RFF and A_{res}) assessments of galaxy structure provide consistent and complementary information.
- 2 RFF can be used as a measure of the *degree* of structural disturbance, while A_{res} provides information on its *cause*. A combination of both parameters can therefore be used to provide information on both the degree and the cause of galaxy deviations from symmetry.

I then link this structural information with the galaxies’ masses, morphologies and star-formation histories, and conclude that:

- 1 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.
- 2 Over 60% 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.

Finally, the global environment (cluster vs. field) of the galaxies is taken into consideration, and we find that:

- 1 There are no significant differences in disturbance class at fixed morphology between cluster and field environments.
- 2 There is a population of passive undisturbed spirals, which are twice as abundant in clusters as in the field. The significance of this result is only 2.3σ , so this needs to be taken with some caution. In addition to being visually symmetric, these galaxies are also quantitatively ‘smoother’: consistent with a mechanism efficient in removing the gas from the galaxy on encountering the cluster environment but without affecting the galaxy structure.
- 3 Secondly, while nearly all lenticulars are visually undisturbed in both cluster and field, *all* of those in the field are passive, while nearly $\sim 20\%$ in the cluster are star-forming.

Recently, it has been demonstrated that the dominant process leading to the cessation of star formation depends on both stellar mass and environment, with quenching mechanism transiting from environmentally driven to mass- driven (Peng *et al.*, 2010b; Thomas *et al.*, 2010). Previous studies at lower redshift (Baldry *et al.*, 2006; Wetzel, Tinker & Conroy, 2012) and at higher redshift (Muzzin *et al.*, 2012) show that the quiescent fraction is correlated with stellar mass and environment, and this relationship is maintained until $z \sim 1$. Moreover, with the importance of environmental quenching increasing with cosmic time and decreasing with stellar mass, this analysis brings

out the effects at intermediate mass regime, where possibly both stellar mass and environment are playing significant roles in shutting down the star formation in cluster galaxies.

In addition, the internal galaxy structure at fixed morphology is seldom taken into account while studying the evolution of star formation in galaxies over a range of environments. These results have significant implications for the evolution of spiral galaxies falling onto 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 be reasonably gentle, affecting primarily the gas while leaving the galaxies stellar structure largely unchanged. This scenario may be ram-pressure stripping or starvation processes where gas is either stripped or the supply truncated, enabling galaxies to stop forming stars before they can change their morphologies. This scenario is in agreement with observations indicating a rapid build of red-sequence galaxies earlier than the build up of early-type galaxies as seen in clusters (Desai *et al.*, 2007; De Lucia *et al.*, 2007; Rudnick *et al.*, 2012; Cerulo *et al.*, 2016). However, my analysis does not provide insight on the exact mechanism leading to such a build up of passive spiral galaxies, only that the morphology remains unaltered with the intrinsic structure becoming smoother. Concurrently the higher fraction of low-mass star-forming lenticulars in clusters direct towards a possible environment-driven mechanism like stripping of the gas from the low mass spirals disks whilst leading to a burst of star formation in bulges (Johnston, Aragón-Salamanca & Merrifield, 2014), or rapid consumption of the gas in the outer disk as compared to the inner gas. The lack of texture or roughness in such star-forming lenticulars may hint towards the residual star formation located more centrally in the galaxy. In summary, these scenarios therefore imply that low-mass spirals have already transformed into lenticulars while the intermediate-mass spirals have their star formation quenched before they transform structurally. This places my analysis in a unique regime where I discover that galaxy structure is more subtly affected than star formation with changes in galaxy environments and stellar masses.

Chapter 5

Projected Phase–Space: a view of galaxy structure and star formation history in cluster environments

Observations of galaxy clusters since $z \sim 2$ have substantiated that the cluster environment is harsh to the star formation in galaxies. This, when taken into account with the discernible colour bimodality in clusters, advocates the plausible role environment might be playing in transforming the blue star-forming galaxies to the red passive galaxies, and inducing a related morphological change.

In this Chapter, I seek to explore the links between the deviations in the stellar distribution in galaxies, as introduced in Chapter 4, with the star formation history of galaxies derived from spectroscopic information. Further, focussing on the cluster galaxies, I aim to investigate the behaviour of these structural distortions in galaxies over the dynamical cluster environment, given by a 2-D plane defined using the line-of-sight velocities and the cluster-centric distances of galaxies. On connecting these trends with the relative stellar ages of cluster galaxies, I attempt to further our knowledge regarding the observed morphological and star formation transition in galaxies as they experience the cluster environment.

5.1 Introduction

Revisiting the global picture of galaxy evolution in the context of cluster environment, radial trends are observed in various galaxy properties, like star formation (von der Linden *et al.*, 2010; Mahajan, Raychaudhury & Pimbblet, 2012), when observed as a function of distance from the cluster centre. In the cluster cores, the early-type passive galaxies are found to have lower line-of-sight velocities as compared to the late-type star-forming counterparts, indicating star formation evolution on a radial and dynamical scale within the cluster. These observations suggest the possibility of using the radial information as well as the line of sight velocities of galaxies in clusters, to analyse the galaxy properties in a dynamical environment. This ‘phase-space’, in effect, uses the projection of cluster observables, and associates galaxies to different stages of their lifetime in clusters. Indeed, Gill, Knebe & Gibson (2005) discovered that the satellite galaxy populations are better separated on this 2-D phase-space, as compared to just 1-D clustercentric radius. Moreover, it is also found that $\sim 50\%$ galaxies within $2R_{200}$ have already passed through the core at least once (Balogh, Navarro & Morris, 2000). Recently Mahajan, Mamon & Raychaudhury (2011) and Oman, Hudson & Behroozi (2013) demonstrate that it is possible to trace orbital histories of galaxies by analysing 3-D phase-space using simulated galaxy clusters representing the local population. Such assembly history of galaxy clusters enables us to associate cluster galaxy populations to various regions of this phase-space. This can separate the galaxies which are infalling from the galaxies which are virialised in the cluster core, and identify galaxies which have undergone at least one pericentric passage through the core (known also as ‘backsplash’ galaxies). This analysis, therefore, presents a powerful tool to address current questions like quenching and group pre-processing (see also Section 4) in galaxies, and their transformation by observing them ‘in action’ in dynamical environments. This approach has been utilised to study the velocity modulation of various galaxy properties like quenching timescales (Muzzin *et al.*, 2014; Taranu *et al.*, 2014), HI stripping in galaxies (Jaffé *et al.*, 2015), and dust temperatures in galaxies (Noble *et al.*, 2016).

Exploiting this unique method of assessing dynamic galaxy environment, this Chapter presents the analysis of the spectroscopic sample (Table 4.2) towards understand-

ing the correlation of the star formation histories of galaxies and their quantitative structure. Employing the 2-D projected phase-space, the variations of RFF , A_{res} (cf. Section 4.4) and stellar ages of galaxies are evaluated as a function of the projected phase-space co-ordinates.

5.2 Star formation history from spectral indices

A galaxy which has experienced a recent burst of star formation (1–3 Gyr ago), or has had its star formation recently truncated shows strong Balmer absorption lines in its spectrum, especially $H\delta$ and $H\gamma$ lines. This is because Balmer absorption lines, attributed to A-type stars, peak in strength after the hot O and B stars have ceased their evolution. The $H_{\delta A}$ and $H_{\gamma A}$ indices (incorporating the EW of the $H\delta$ and $H\gamma$ lines), therefore are indicative of the time since the recent episode of star formation in the galaxies (Worthey & Ottaviani, 1997). Moreover, these indices also depend on metallicity and α/Fe ratio, which is important for older stellar populations (Thomas, Maraston & Korn, 2004). The overall age of the stellar population, on the other hand, is best represented by the strength of the break occurring at 4000Å (Balogh *et al.*, 1999, D_n4000 hereafter). This break depends on metallicity and arises due to the accumulation of metal absorption lines on the blue side of the spectrum. Kauffmann *et al.* (2003a) shows that the locus of the plane constructed using these spectral indices give an excellent measure of the star formation history of galaxies. Moreover, the variation in $H_{\delta A}$, $H_{\gamma A}$, and D_n4000 is relatively insensitive to dust extinction or metallicity, making them a reliable diagnostic to assess whether star formation occurred in bursts or in continuous mode.

The star formation history (SFH hereafter) of galaxies in the spectroscopic sample was determined through the indices obtained using the spectral decomposition of the galaxies and with the empirical mass completeness of $\log M_*/M_\odot > 10.4$ (Rudnick *et al.* 2016, submitted). Although the detailed spectroscopic decomposition is performed as a part of the work presented in Rudnick *et al.*, the analysis pertaining to studying the interlink between SFH and galaxy structure adopts the above the mass-completeness limit. Specifically, I use the $H_{\delta A}$ and $H_{\gamma A}$ indices, and D_n4000 in the continuum of

the spectra to investigate the SFH of galaxies. I further improve the S/N of Balmer absorption by taking the average of $H_{\delta A}$ and $H_{\gamma A}$ indices.

Figure 5.1 shows the $(H_{\delta A} + H_{\gamma A})/2$ vs D_n4000 for the all the galaxies in the sample with the mass completeness of $\log M_*/M_\odot = 10.4$ (Refer to Section 2.2.2). The points are colour-coded by the $[\text{OII}]\lambda 3727$ EW which traces the current star formation in galaxies (Gallagher, Hunter & Bushouse, 1989; Kennicutt, 1992). Further, to understand the distribution of points on this plane, I use the model tracks with solar metallicity derived from the Bruzual & Charlot (2003) stellar population synthesis code. These model tracks include single burst model of star formation, a constant star formation history model, and three models with exponentially declining SFHs with a timescale of 0.3, 1, and 2 Gyr. All the models extend to an age of 6 Gyr, which roughly corresponds to star-forming at $z = 2.5$ for a galaxy observed at the lower end of the EDisCS redshift range $z = 0.4$.

Following from Figure 5.1, galaxies are separated based on their relative stellar ages as galaxies with - ‘young’ (top left), ‘intermediate’ (middle), and ‘old’ (bottom right) stellar populations. The line dividing the galaxies with older stellar populations was determined based on the isolation of the peak of these galaxies in the histogram of the galaxy sample. Thus, for the ‘old’ stellar ages, it was required that no more than 2% of stars should have been formed in the past 1 Gyr, and the star formation must have ceased at least 1.5 Gyr before the epoch of observation. The rest of the galaxies were then split into galaxies with intermediate and young stellar populations. The division for these galaxies was chosen to split the difference in the Balmer absorption and D_n4000 strength between the exponential SFH with a timescale of 2 Gyr and a constant SFR model. A detailed description of these borders is presented in Rudnick et al. 2016 (submitted).

Figure 5.1 also shows the post-starburst or ‘k+a’ galaxies in the sample. The relative fractions of ‘k+a’ galaxies were studied by Poggianti *et al.* (2009), who use Gaussian line fitting technique to determine the EWs of Balmer absorption. In the present work, the ‘k+a’ galaxies are defined using more accurate Balmer absorption from $H_{\delta A}$ and $H_{\gamma A}$ indices. The specific selection criteria I use are $\text{EW}[\text{OII}] < 5\text{\AA}$, and $(H_{\delta A} + H_{\gamma A})/2 > 3\text{\AA}$. The sample of galaxies thus identified as ‘k+a’ are all clus-

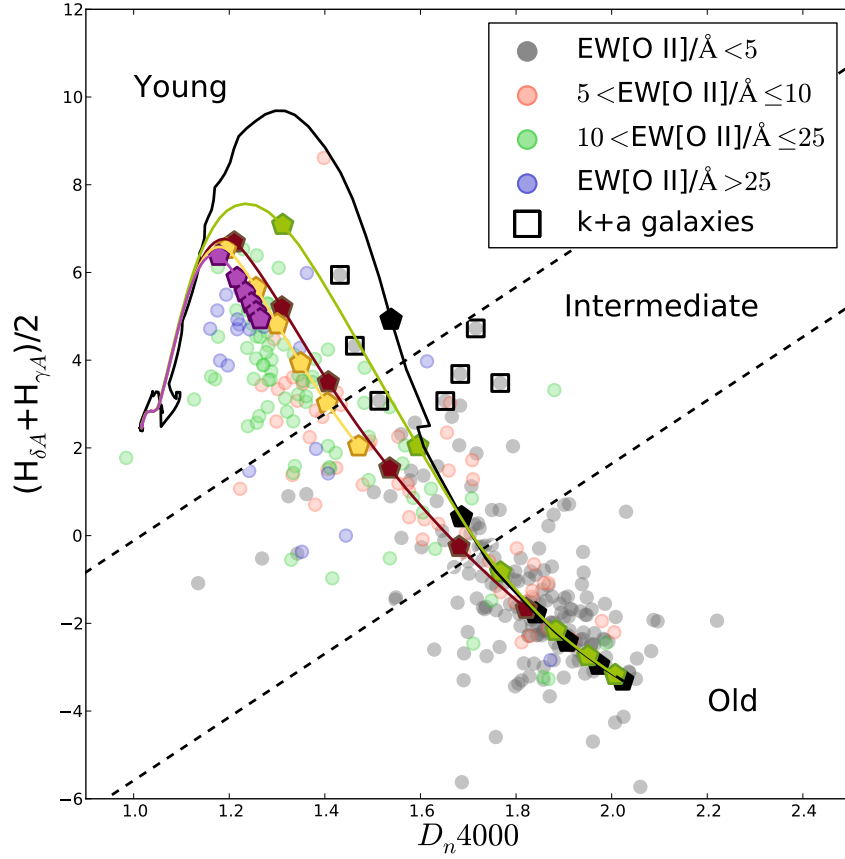


Figure 5.1: The $(H_{\delta A} + H_{\gamma A})/2$ vs D_n4000 plane for all the galaxies with $\log M_*/M_\odot > 10.4$ in EDisCS spectroscopic sample. The colour of the points indicate the $EW[OII]$ and hence a measure of star formation rate (SFR). The galaxies are further divided into galaxies with young, intermediate and older stellar populations (black dashed lines). The overplotted tracks denote the modelled evolution of stellar population (Bruzual & Charlot, 2003) formed in a single burst (black), displaying constant star formation (magenta), and the three exponentially declining SFH with timescales of 0.3 Gyr (green), 1 Gyr (red) and 2 Gyr (yellow). All the points on these model tracks are spaced at 1 Gyr intervals increasing to lower right. In addition, the ‘k+a’ galaxies in the sample are represented by black squares.

ter members (except one), and is different to that explored in Poggianti *et al.* (2009), primarily because their method was different and less robust. These galaxies will be further investigated in Section 5.4.

5.3 Correlation of star formation history with galaxy structure and environment

Analysis presented in Chapter 4 brings forth a strong correlation between RFF and A_{res} with the visual structural disturbances and the observed galaxy morphology (cf. Figure 4.5 & Figure 4.6). Moreover, the analysis of the UVJ colour plane reveals that passive galaxies are mostly structurally smoother and more symmetric, with low values of RFF and A_{res} (cf. Figure 4.8 & Figure 4.8). This link between galaxy ‘roughness’, ‘asymmetry’ and star formation, therefore, advocates the possible correlation of intrinsic galaxy structure with the SFH of galaxies.

I therefore investigate the variations in RFF and A_{res} with the evolution of star formation over a global cluster and field environment. I use the cluster sample and the redshift-controlled field sample for this analysis, as described in Section 2.2.1. Figures 5.2 & 5.3 show the average Balmer absorption plotted against D_n4000 for the spectroscopic sample and colour-coded with RFF and A_{res} . At a glance, the RFF and A_{res} display a strong interdependence with the SFH of galaxies indicated by the average age of their stellar population. Indeed, galaxies with recent star formation are asymmetric and show a higher degree of roughness/texture while galaxies with high D_n4000 display smoother structure with low RFF and A_{res} values. This observation is further strengthened by the distribution of galaxy morphology on this plane. As expected, galaxies displaying early-type morphologies populate the lower right region with high D_n4000 , while the late-type/irregular galaxies show ongoing star formation as indicated by relatively higher average Balmer absorption and [OII] emission (cf. Figure 5.1). Comparing both the panels of Figures 5.2 & 5.3, the only environmental effect seen is the build-up of older population in clusters. This implies that irrespective of morphology or global environment, it is possible to identify galaxies with different SFHs based on the roughness and asymmetry in structure. This result has important connotations as both RFF and A_{res} are purely structural quantities measured from the deviations in the galaxy light independent of the star-forming activity of the galaxy.

Revisiting the ‘k+a’ galaxies as described in Figure 5.1, it is worth noting that all the

‘k+a’ galaxies in the sample are detected in clusters¹ and lie in the region which has high $RF\bar{F}$ and A_{res} on the average Balmer absorption vs D_n4000 plane. Moreover, the $RF\bar{F}$ and A_{res} of these ‘k+a’ galaxies have an average value of 0.05 and 0.5 respectively, which is on the border of the definition separating the rough/smooth and symmetric/asymmetric galaxies in the sample (cf. Section 5.5). This result may support the findings of Pawlik *et al.* (2016) which show that the shape asymmetry of galaxies, an identical but slightly different measure of quantitative morphology, is found to be strongly correlated with the age of starburst galaxies with young starbursts displaying distinct asymmetric features indicative of recent merger activity. However, my subsample is too small to robustly confirm this result with the measurement of $RF\bar{F}$ and A_{res} .

¹The only field ‘k+a’ galaxy is not considered in the redshift-controlled field sample.

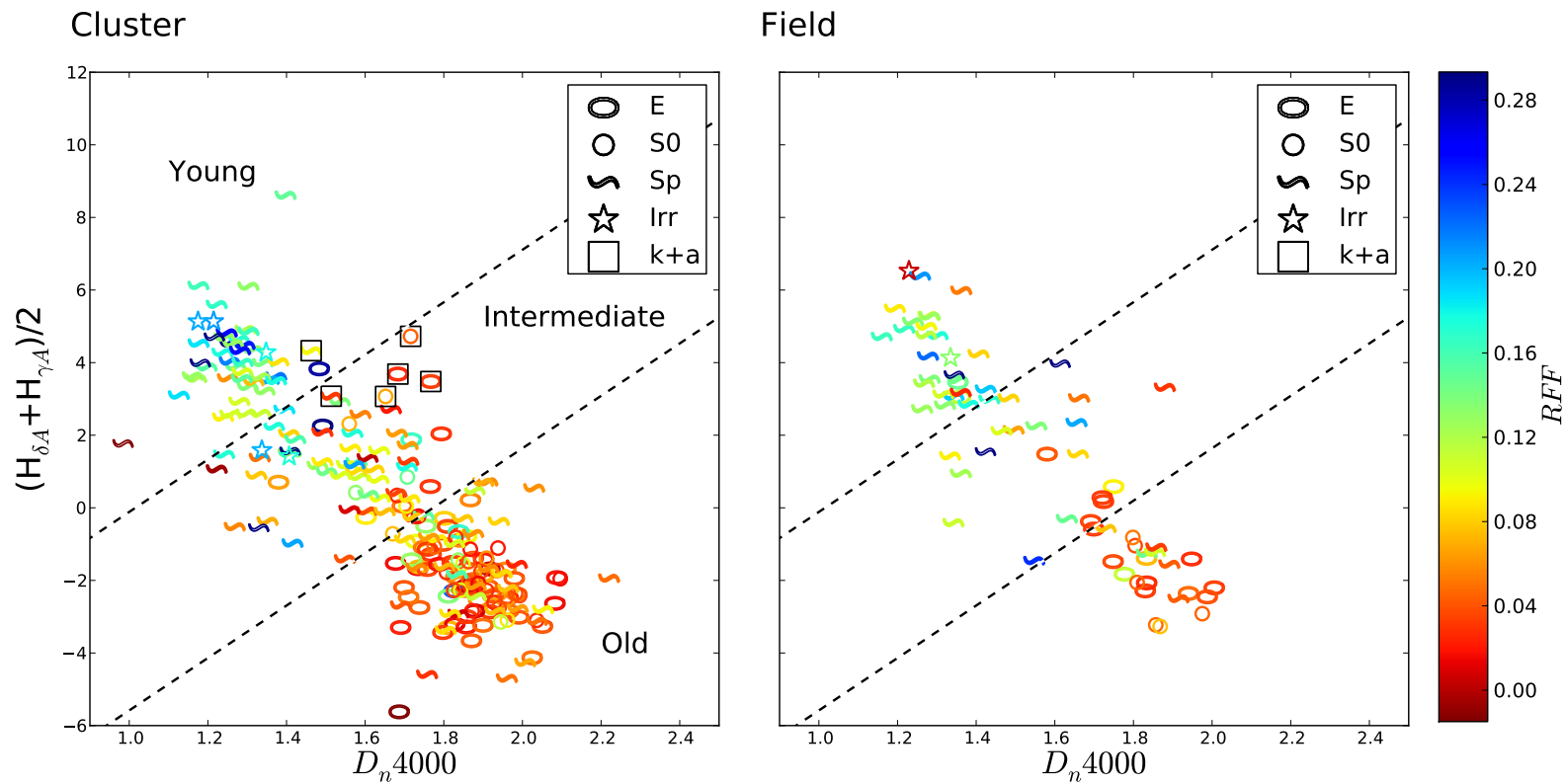


Figure 5.2: The $(H_{\delta A} + H_{\gamma A})/2$ vs D_n4000 plane is colour-coded according to RFF values for the cluster (left panel) and field (right panel) galaxies: redder colours indicate smoother, undisturbed galaxies while bluer colours denote ‘roughness’. The symbols indicate the morphology of galaxies, as explained in Section 2.2.3. As in Figure 5.1, the dashed lines show the selection boundaries for galaxies with young, intermediate and older stellar populations. Galaxies with ongoing star formation or with younger stellar populations are consistently found to be ‘rougher’ irrespective of morphology or global environment.

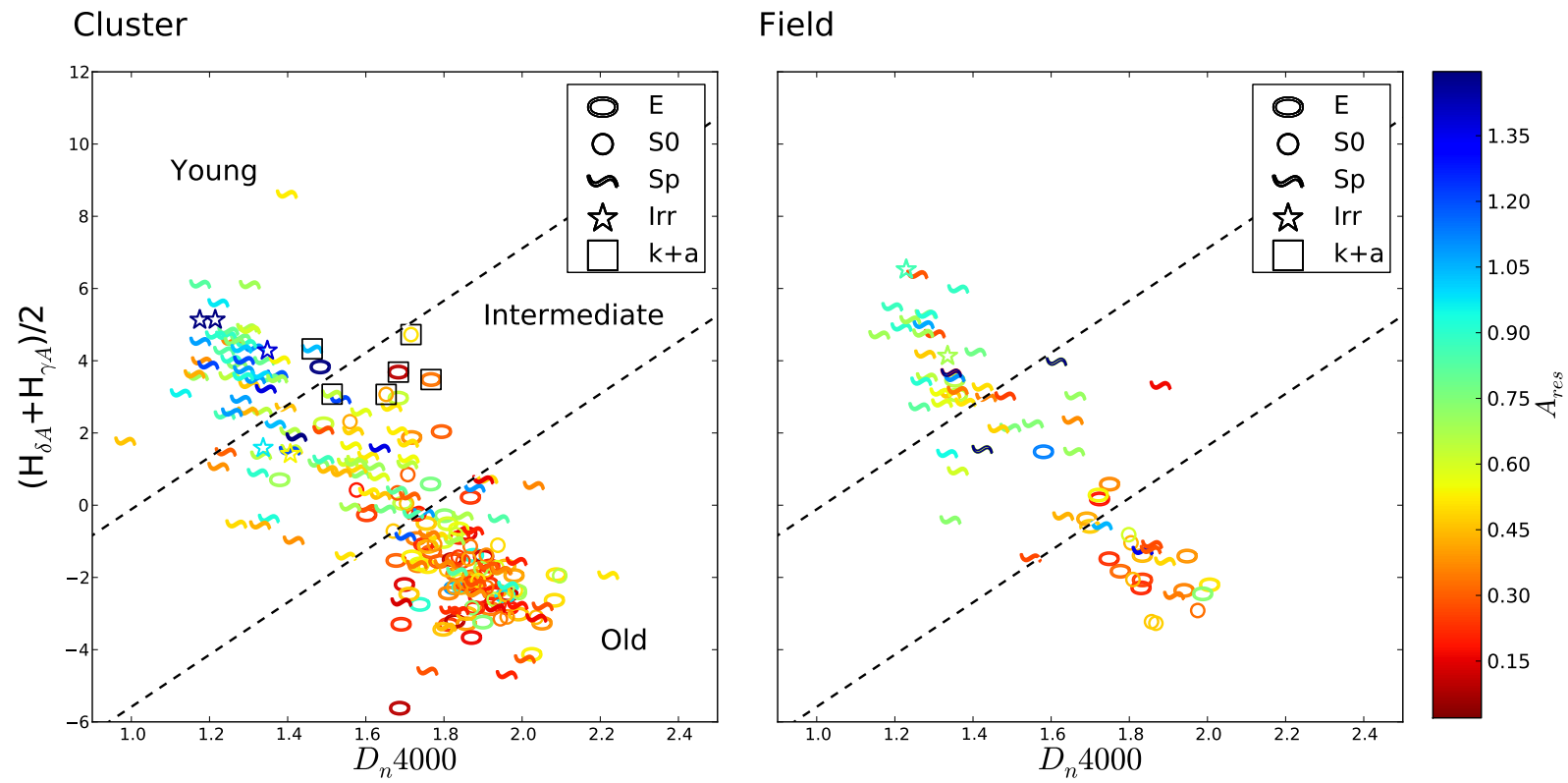
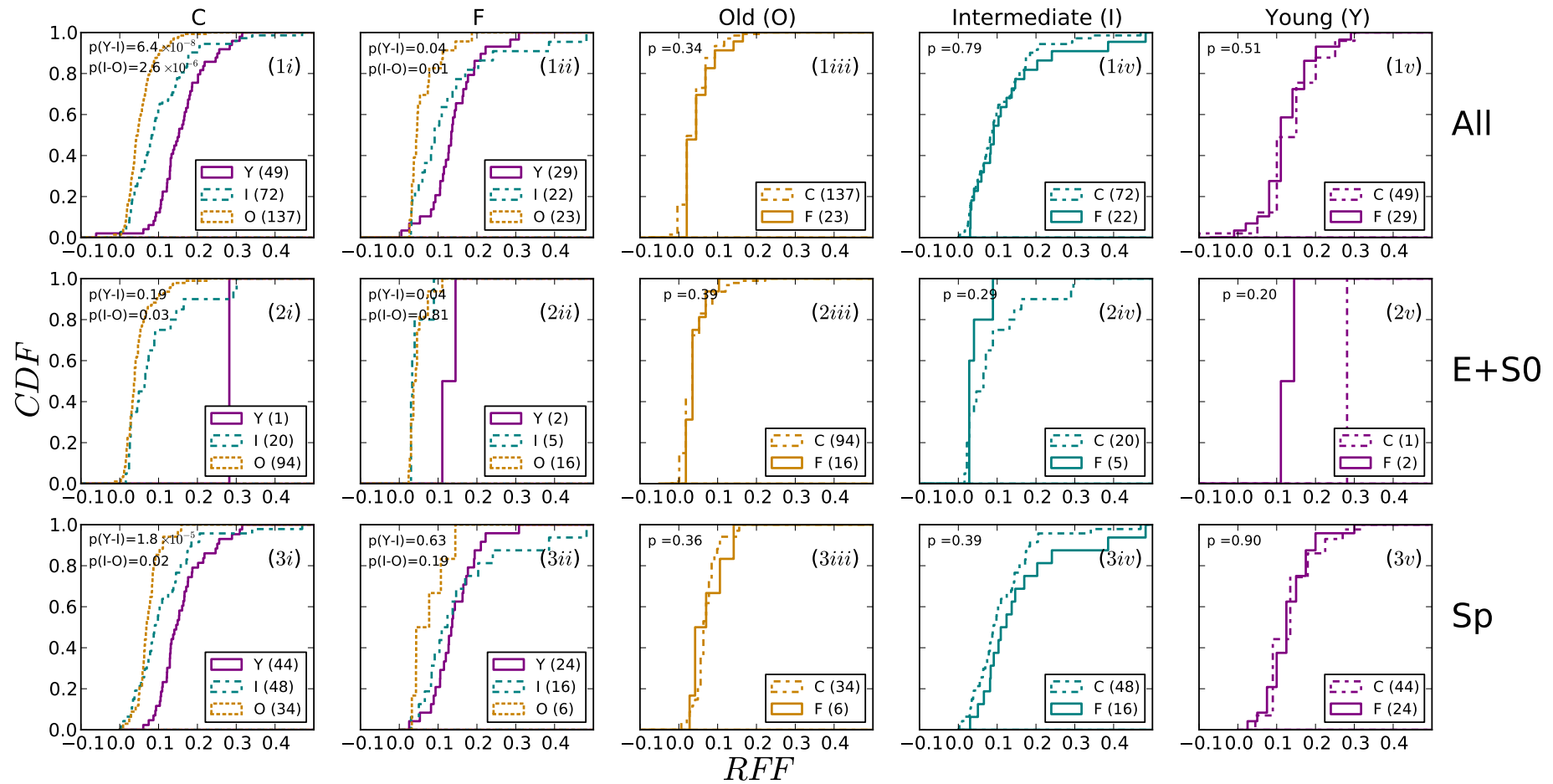


Figure 5.3: Similar to Figure 5.2, the $(H_{\delta A} + H_{\gamma A})/2$ vs D_n4000 plane is colour-coded according to A_{res} for cluster (left panel) and field (right panel) galaxies: redder colours indicate symmetric galaxies while bluer colours denote higher asymmetry. Star-forming galaxies are consistently found to be more quantitatively asymmetric than passive galaxies irrespective of morphology or global environment.



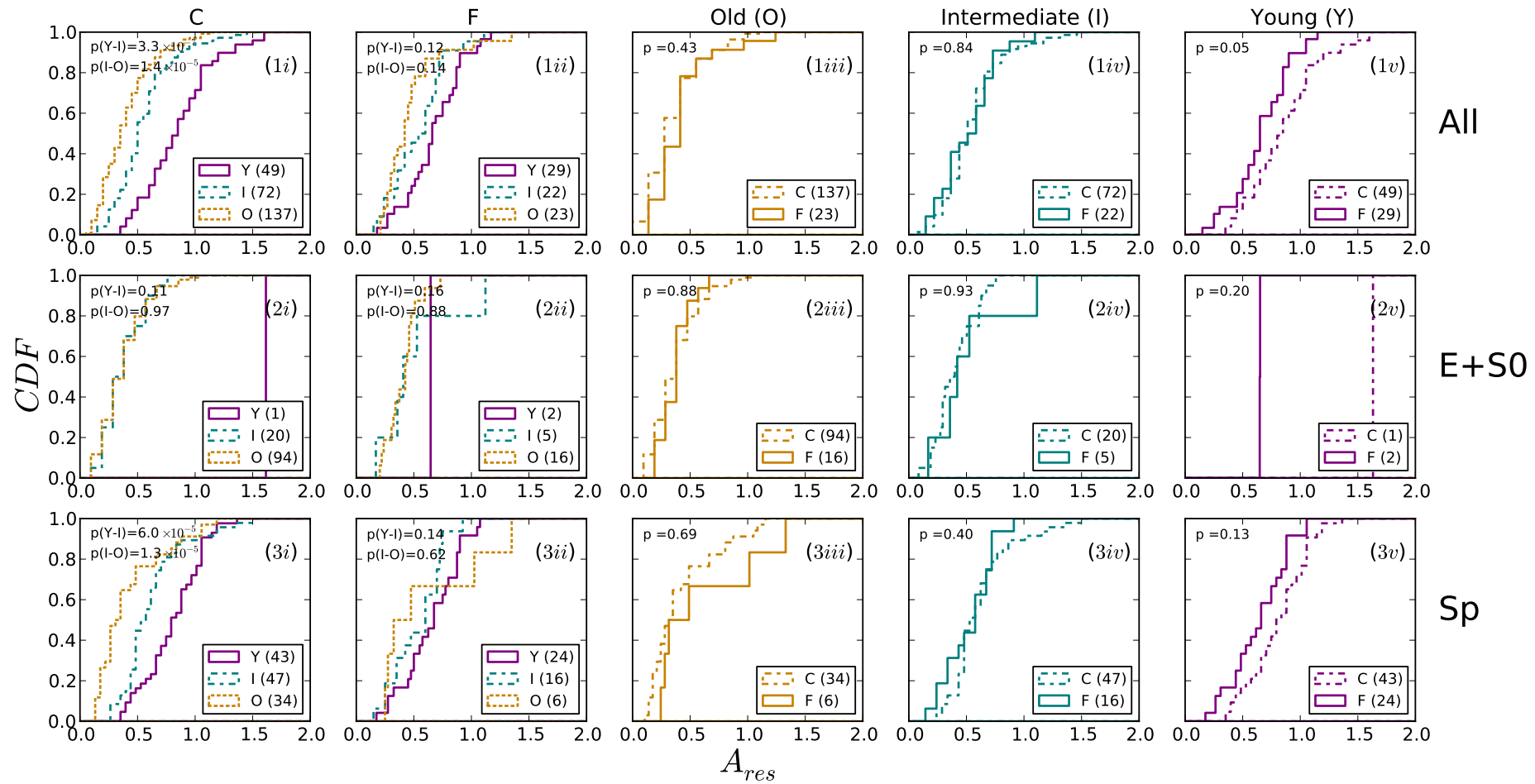


Figure 5.5: Similar to Figure 5.4, A_{res} distribution for the galaxies with Old (O), Intermediate (I) and Young (Y) stellar ages in Cluster (C)/Field (F) environment. Comparing panels (-i) and (-ii), it is evident that the older stellar ages display lower A_{res} values as compared to the intermediate and younger stellar ages, and this effect is stronger in cluster environment. Further, the A_{res} distribution for galaxies with younger, intermediate and older stellar populations are similar irrespective of their incidence in the cluster or field environments.

To test how well the galaxies can be separated based on their quantitative structure, I evaluate the distributions of RFF and A_{res} for each galaxy subpopulation defined by their stellar ages. Figures 5.4 and 5.5 show the distribution of RFF and A_{res} for galaxies with old, intermediate and young stellar ages across cluster and field environments. I next use the two-sample Kolmogorov-Smirnov (K-S) tests to check the significance of the variation in the RFF and A_{res} distributions for different stellar ages, under the null hypothesis that each sample of cluster and field galaxies with different ages are drawn from the same RFF and A_{res} distribution. From panels (1i) and (1ii) in both Figures, there is a strong stratification of RFF and A_{res} across stellar ages in cluster environment ($\gg 3\sigma$ significance). However, this difference is less significant in the field galaxy population due to the smaller sample size. Recalling Figure 4.5, the morphology dependence of these two structural diagnostics is taken into account by evaluating the cumulative distribution function (CDF) at fixed morphology (Figures 5.4 and 5.5, Panels 2i, 2ii, 3i, 3ii). ‘Old’ E+S0 are smoother as compared to ‘intermediate’ E+S0 in the cluster environment. Further, as expected the ‘young’ E/S0 are in the minority (only 1) in clusters and show high RFF and A_{res} . In the field environment, however, this difference becomes less significant, but the numbers are very small. This difference is further emphasised for spiral galaxies in clusters. The ‘old’ cluster spirals are found to be smoother, and more symmetric than the ‘intermediate’ and ‘young’ cluster spirals with the difference disappearing in the field. Combining the results from Figures 5.2 and 5.3, this effect is attributed to the characteristic morphology content observed in clusters, with high-density environment harbouring early-type morphologies and older stellar populations.

Looking at all the galaxies together and at fixed morphology, there is little to no significant difference in the distribution of RFF and A_{res} for old, intermediate and young galaxies regardless of them being located in cluster or field environment. This is shown in panels (-iii) to (-v) which present the RFF and A_{res} distribution for the cluster and field galaxies, categorised by their stellar ages. No separation is seen amongst galaxies with older, intermediate or younger stellar populations regardless of their incidence in cluster or field environment. This suggests that star formation history of galaxies is strongly linked with their intrinsic structure alone.

In summary, the main determination of roughness and asymmetry in galaxy structure is the star formation history of galaxies and not the global environment. There is little to no significant difference in the distribution of RFF and A_{res} for galaxies with older, intermediate or younger stellar populations when separated by morphology over cluster/field environments. Environment changes the proportion of ‘old’ galaxies but does not alter the SFH and structure of galaxies, corroborating the results from Chapter 4 (See also, Thomas *et al.*, 2010). Indeed as discussed by Hoyos *et al.* (2016), my analysis supports their findings that it is not possible to know a priori whether observed ‘roughness’ enhances star formation activity or whether repeated episodes of star formation renders a galaxy structurally rougher and asymmetric, which eventually leads to a smooth structure as the galaxy becomes passive.

5.4 The Projected Phase–Space of EDisCS clusters

Galaxies are observed to have undergone transformation upon getting accreted into the clusters, with the effect of the environment seen in various galaxy properties like morphology, colours and star formation. Although difficult to isolate, various environmental processes are believed to play a significant role in aiding these transformations. With the analysis of quantitative structural measures like RFF and A_{res} , visual disturbances and star formation history over global environment, I aim to extend this analysis to study the effects of the internal cluster environment.

5.4.1 Construction of the stacked cluster

The projected phase–space (PPS hereafter) is constructed using derived cluster properties σ_{cl} , R_{200} and cluster centre, while assuming a spherical symmetry in the clusters. However as the number of spectroscopic cluster members from each EDisCS cluster is small, it is not possible to derive robust kinematics of each individual cluster. I therefore stack individual clusters together to create a stacked projected phase–space using the line-of-sight velocity and the clustercentric distance of the cluster galaxies. This method is based on the assumption of the universal mass profile for cosmological halos (Navarro, Frenk & White, 1997) and is widely used in constructing projected

phase-space of clusters (for example, Rines *et al.*, 2003). I selected clusters for this analysis, according to the following criteria:

- clusters for which we have robust spectroscopy and *HST* *I*–band imaging data.
- clusters which have reasonably symmetric distribution of peculiar velocities (by visual inspection) in the cluster rest-frame.
- clusters which have reasonably symmetric spatial distribution of galaxies (by visual inspection) in the sky with the brightest cluster galaxy located as centrally as possible.
- clusters which have spectroscopic coverage till at least $\sim 0.7R_{200}$, and have > 19 spectroscopically confirmed cluster members.

Refer to Milvang-Jensen *et al.* (2008) for the detailed spectroscopic, spatial and velocity information.

With these selection criteria, the new cluster sample comprises eight clusters/secondary clusters out of the original cluster sample (cf. Table 2.1). This stacked cluster has a mean redshift $\langle z \rangle \simeq 0.65$ and $\langle R_{200} \rangle \simeq 1.14$ Mpc. Note that this stacking is done after scaling the cluster-centric radius of galaxies by the R_{200} of the parent cluster, and the peculiar velocities by the velocity dispersion σ of the parent cluster (cf. Table 2.1). Figure 5.6 shows the distribution of R_{200} and σ for the new cluster sample. The final cluster sample for this analysis thus contains a total of 181 cluster galaxies. The complementary field sample is described in Table 4.1. Note that all the galaxies in this analysis have $\log M_*/M_\odot > 10.6$, which is the mass completeness for the parent spectroscopic sample (cf. Section 2.2.2).

Rhodes (2013) analysed the 3-D and projected phase-space for intermediate- z clusters matched with the EDisCS cluster sample from N-body simulations, and used the coordinates of galaxies on the phase-space to identify various regions out to $\sim 5R_{200}$. It was found from this analysis that there is $> 80\%$ probability of the cluster galaxy to be bound in the cluster potential within $0.5R_{200}$ at intermediate redshifts. Moreover, as the cluster assembles, infalling galaxies approach the cluster at higher radii while gaining velocity as they reach the cluster core. These galaxies then settle in the cluster

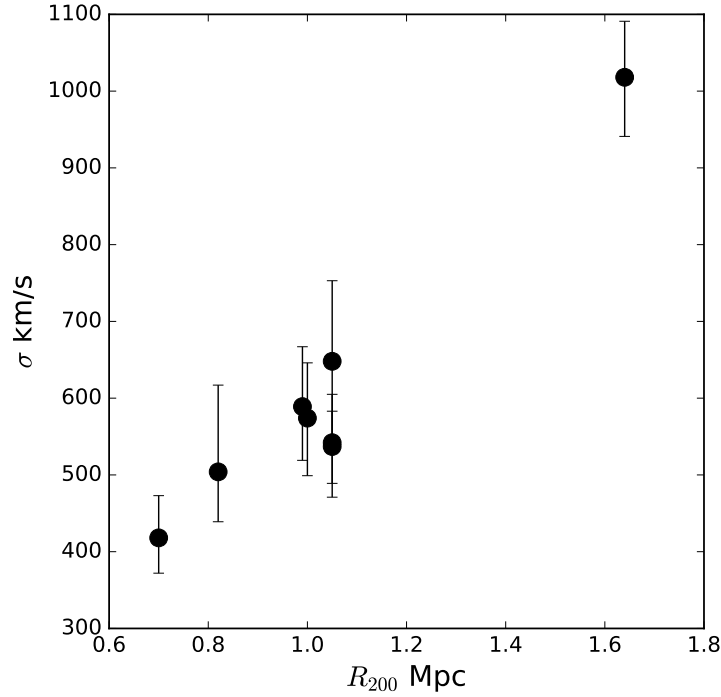


Figure 5.6: The distribution of R_{200} and σ for the new cluster sample comprising eight clusters/secondary clusters. The selection criteria for these clusters is discussed in Section 5.4.1.

due to dynamical friction. This process leaves a signature on the PPS, approximated best with a triangular shape (Mahajan, Mamon & Raychaudhury, 2011; Jaffé *et al.*, 2015). Thus, combining the findings from Mahajan, Mamon & Raychaudhury (2011) and Rhodes (2013), I define a triangular region located at $r \lesssim 0.5R_{200}$ and $|\delta v| < 2\sigma_{cl}$ on the PPS described earlier to mark out the likely virialised region. This region is then used to select the ‘virialised’ galaxies from the ‘infalling’ galaxies at higher $|\delta v|$ and higher r . It is also possible to identify ‘backsplash’ galaxies which are found to have low line-of-sight velocities and located around the virial region. However, the sample size of cluster galaxies used in this stacked PPS prevents us from using such detailed information of the location on the PPS.

Figures 5.7 and 5.8 show the PPS for the EDisCS cluster galaxies with different morphologies, colour-coded with RFF and A_{res} respectively. This PPS corroborates the observed distribution of galaxy morphology in galaxy clusters, with Table 5.1 showing the fraction of galaxies lying within and outside the virial region for each morphology type. It is interesting to note that although the majority of the late-type Sp galaxies are prevalent in the cluster outskirts, the early-type E/S0 galaxies show similar fractions in

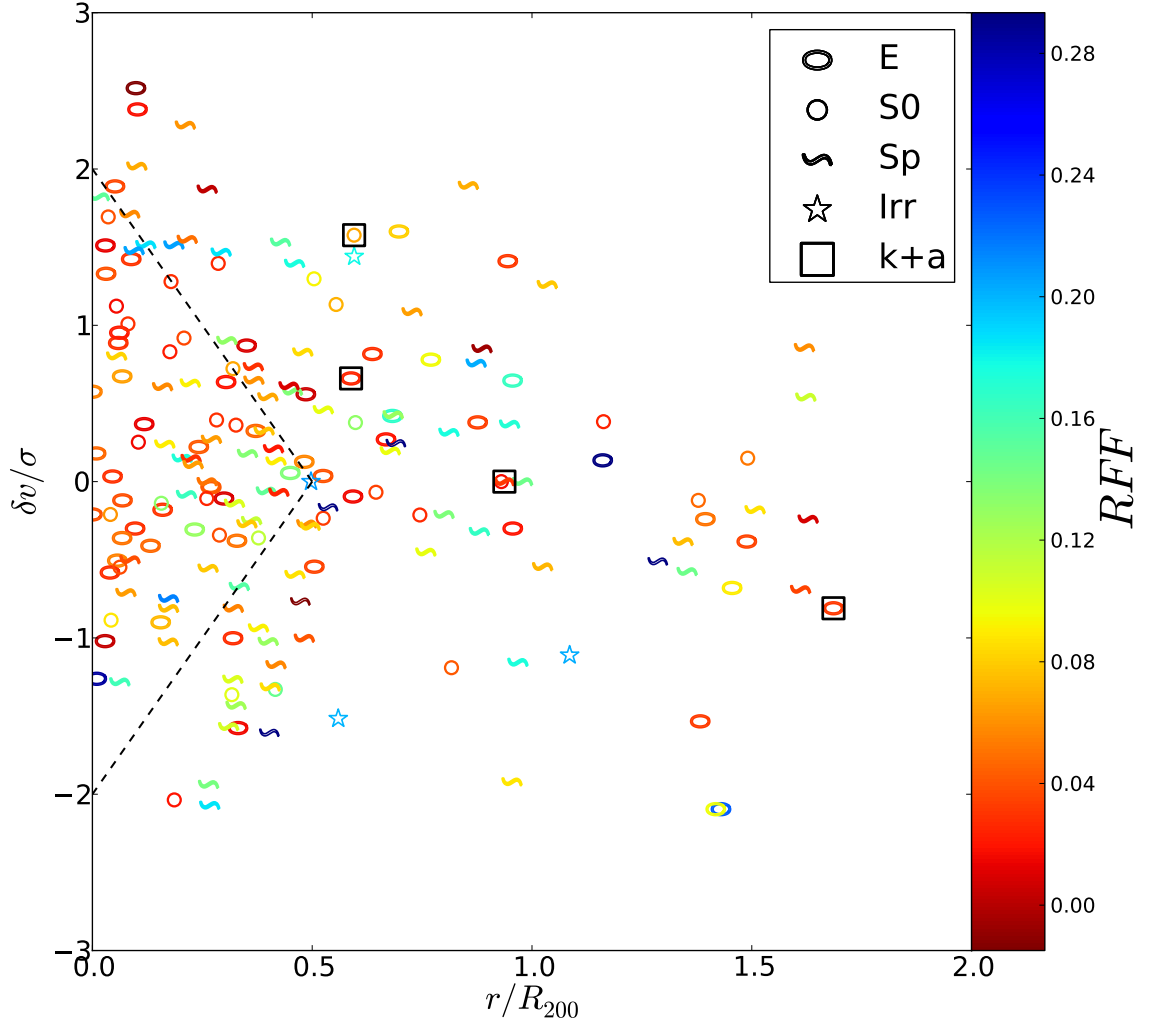


Figure 5.7: The observed PPS for the EDisCS cluster galaxies with different morphologies, colour-coded according to RFF . The dashed boundary encompasses the ‘virial’ region, as discussed in Section 5.4.1. All the galaxies outside this region are considered as infalling galaxies. This observed PPS corroborates the observed distribution of galaxy morphology in galaxy clusters: the majority of the early-type galaxies lie within the virial region while late-type galaxies are prevalent in the cluster outskirts.

both cluster regions. Also, 4 out of 6 ‘k+a’ galaxies lie on the cluster PPS. Noting their position on the PPS, it is clear that all these ‘k+a’ galaxies tend to avoid the cluster core, and hence denote a transitory cluster population (see also Muzzin *et al.* 2014).

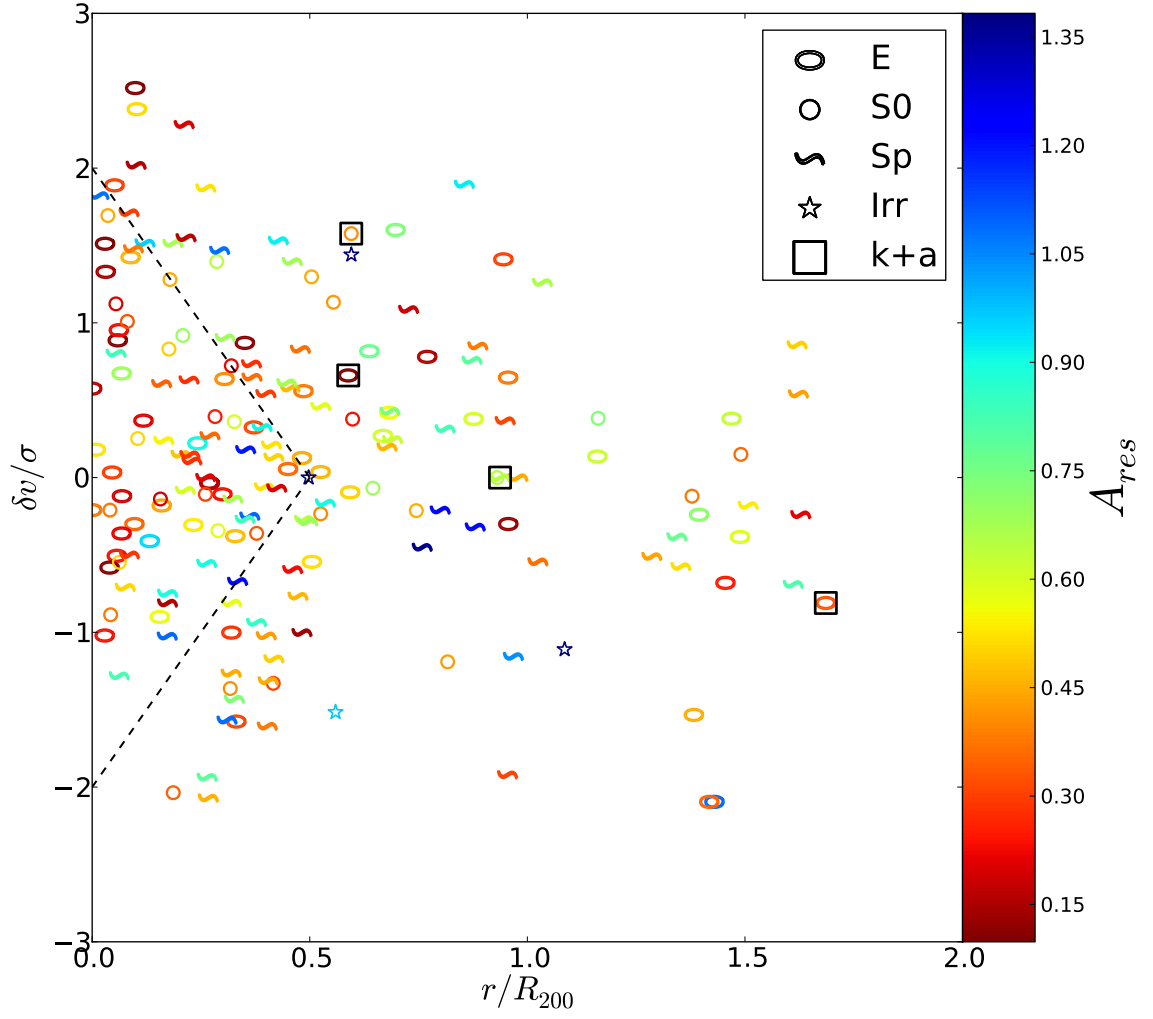


Figure 5.8: Similar to Figure 5.7, the observed PPS for the EDisCS cluster galaxies, colour-coded according to A_{res} .

Table 5.1: The relative fractions for galaxies in different cluster regions as shown in Figures 5.7 and 5.8, for fixed morphology. The errors on fractions denote the 1σ uncertainty computed over Wilson interval (cf. Section 4.3).

Morphology	Virial region	Infall region
	$r \lesssim 0.5R_{200}$ $ \delta v \lesssim 2\sigma_{\text{cl}}$	$r > 0.5R_{200}$ $ \delta v > 2\sigma_{\text{cl}}$
Ellipticals (E)	0.52 ± 0.07	0.48 ± 0.07
Lenticulars (S0)	0.50 ± 0.09	0.50 ± 0.09
Spirals (Sp)	0.32 ± 0.05	0.68 ± 0.05
Irregulars (Irr)	0.30 ± 0.20	0.70 ± 0.20

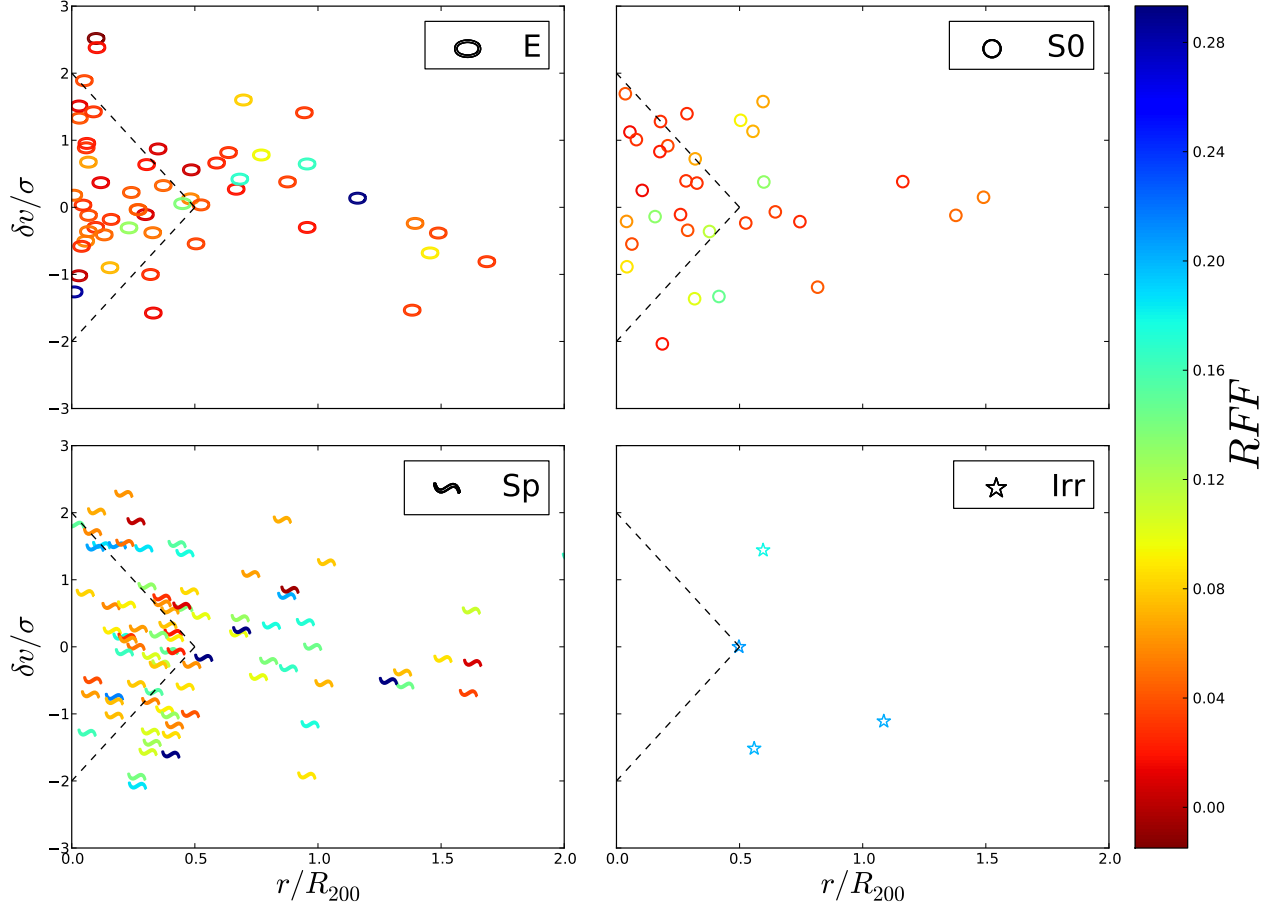


Figure 5.9: RFF distribution on the PPS for galaxies of each morphological type. Similar to Figures 5.7 & 5.8, the dashed boundary encompasses the ‘virial’ region. Although the majority of early-type galaxies (E+S0) are smooth, they show equal fractions of rough and smooth galaxies in the virial and infall regions of the cluster. For the spiral galaxies, the majority are rough with no obvious dependence on the local environment.

5.5 Galaxy structure and star formation history as a function of location on the PPS

The PPS thus constructed provides a unique snapshot into the clusters assembling their galaxies at $\langle z \rangle \sim 0.65$. From Figures 5.7 and 5.8, the variation in morphology across the PPS is prominent, and masks out any possible variation which may exist for RFF and A_{res} . Figures 5.9 and 5.10 show the PPS for each morphological type, colour-coded with RFF and A_{res} . Inspecting each panel, the PPS for the stacked cluster demonstrates that the early-type galaxies populate the cluster virial and infall region, while the late-type galaxies being more common in the cluster outskirts (Table 5.1).

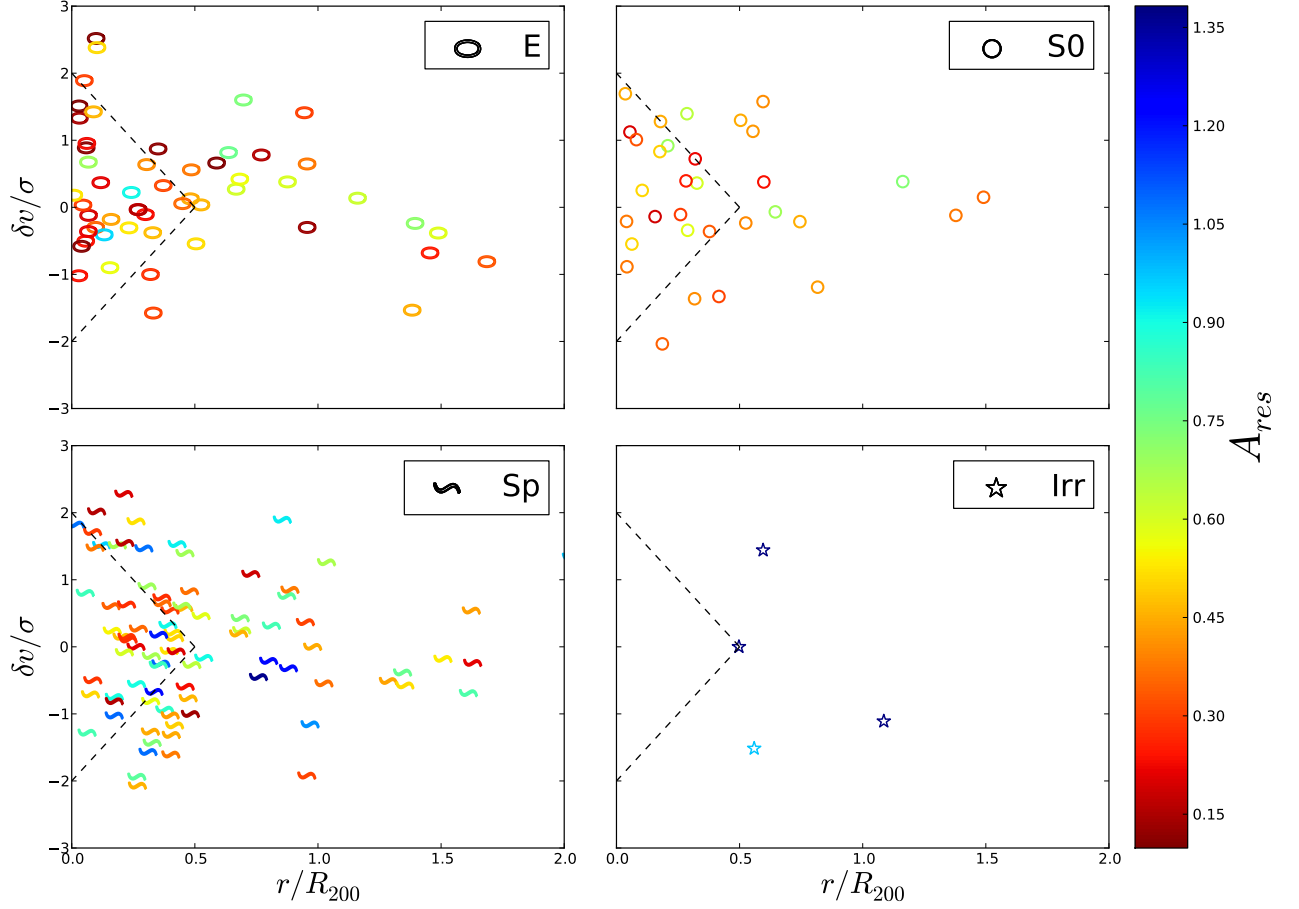


Figure 5.10: Similar to Figure 5.9, A_{res} distribution on the PPS for galaxies of each morphological type. Although the majority of early-type galaxies (E+S0) are symmetric, they show equal fractions of asymmetric and symmetric galaxies in the virial, and infall region of the cluster. For the spiral galaxies, the majority are asymmetric with no obvious dependence on the local environment.

This observation likely supports the findings from recent works like Biviano *et al.* (2016), where they observe that passive and star-forming galaxies have similar elongated orbits with increasing clustercentric radii at intermediate redshift. Moreover, these orbits are similar to those of star-forming galaxies in $z = 0$ clusters, suggesting a prominent orbital evolution for the passive galaxies with time.

5.5.1 RFF and A_{res} as a function of location on the PPS

In order to study the implications of galaxy structure on such a cluster-wide scale, I next look into the distribution of RFF and A_{res} on the PPS for each morphology type. To quantify the distribution of RFF on the PPS, I divide the galaxy sample

into ‘rough’/‘smooth’ galaxies based on the boundary in RFF distribution encompassing majority of the early-type (E+S0) galaxies (cf. Figure 4.5). This boundary was qualitatively determined using the median RFF of E+S0 galaxies as an initial approximation. Following this, galaxies with $RFF > 0.05$ formed the subclass of ‘rough’ galaxies while galaxies with $RFF \leq 0.05$ formed the subclass of ‘smooth’ galaxies. Using a similar approach to the A_{res} distribution, I classified galaxies as ‘asymmetric’ if they displayed $A_{\text{res}} > 0.5$ while galaxies with $A_{\text{res}} \leq 0.5$ were considered ‘symmetric’. Table 5.2 gives the fractions of quantitative structure for each morphology type in the virial and infalling regions as well for the field environment.

The elliptical galaxies show equal fractions of smooth, rough, symmetric and asymmetric galaxies across all cluster regions, and the field. The fact that elliptical galaxies show no significant changes in structure irrespective of their position on the PPS is surprising, especially if cluster infall affects the star formation in galaxies and the plausible quenching mechanisms. This trend is also mirrored in the fractions observed for the lenticular galaxies. As evident from the lower left panels in Figure 5.9 and 5.10 for spiral galaxies and Table 5.2, most spirals in the cluster are rough and asymmetric. However, there is no obvious difference in the RFF and A_{res} distributions of spiral galaxies across all environments.

I also look at the variation of visual disturbance classes (cf. Section 4.3; Table 5.3) for spirals in various cluster regions and the field. The majority of the spirals in the virial region are found to be visually undisturbed as compared to the cluster outskirts and the field. In contrast, the fraction of externally disturbed spiral galaxies does not seem to depend on the local environment. This observation supports the lack of environmental dependence of visual disturbance classes, as explored in Chapter 4 (cf. Section 4.7). In summary, galaxies of the same morphology in the virial region are not different from the infalling galaxies with respect to their RFF and A_{res} . These observations suggest there are no significant changes in the structure of galaxies irrespective of their position on the PPS; at the very least these changes perhaps are not observable on shorter timescales.

Table 5.2: The relative fractions for galaxies defined as rough, smooth, symmetric and asymmetric as described in Section 5.5.1, for a fixed morphology in different cluster regions and the field. The errors on fractions denote the 1σ uncertainty computed over Wilson interval (cf. Section 4.3).

Morphology		Virial region $r \lesssim 0.5R_{200}$ $ \delta v \lesssim 2\sigma_{cl}$	Infall region $r > 0.5R_{200}$ $ \delta v > 2\sigma_{cl}$	Field
Ellipticals (E)	Smooth	0.71 ± 0.08	0.69 ± 0.09	0.69 ± 0.11
	Rough	0.29 ± 0.08	0.31 ± 0.09	0.31 ± 0.11
	Symmetric	0.74 ± 0.08	0.61 ± 0.09	0.64 ± 0.11
	Asymmetric	0.26 ± 0.08	0.39 ± 0.09	0.36 ± 0.11
	Young	0.05 ± 0.04	0.02 ± 0.02	0.14 ± 0.08
	Intermediate	0.09 ± 0.05	0.28 ± 0.09	0.31 ± 0.11
	Old	0.88 ± 0.06	0.72 ± 0.09	0.58 ± 0.12
Lenticulars (S0)	Smooth	0.74 ± 0.11	0.50 ± 0.12	0.64 ± 0.18
	Rough	0.26 ± 0.11	0.50 ± 0.12	0.36 ± 0.18
	Symmetric	0.68 ± 0.11	0.79 ± 0.10	0.79 ± 0.15
	Asymmetric	0.32 ± 0.11	0.21 ± 0.10	0.21 ± 0.15
	Young	0.03 ± 0.03	0.03 ± 0.03	0.07 ± 0.07
	Intermediate	0.21 ± 0.10	0.26 ± 0.11	0.07 ± 0.07
	Old	0.79 ± 0.10	0.74 ± 0.11	0.93 ± 0.07
Spirals (Sp)	Smooth	0.16 ± 0.07	0.16 ± 0.05	0.12 ± 0.05
	Rough	0.84 ± 0.07	0.84 ± 0.05	0.88 ± 0.05
	Symmetric	0.40 ± 0.09	0.47 ± 0.06	0.37 ± 0.07
	Asymmetric	0.60 ± 0.09	0.53 ± 0.06	0.63 ± 0.07
	Young	0.19 ± 0.07	0.37 ± 0.06	0.52 ± 0.07
	Intermediate	0.33 ± 0.09	0.40 ± 0.06	0.35 ± 0.07
	Old	0.50 ± 0.09	0.24 ± 0.05	0.14 ± 0.05

Table 5.3: The relative fractions for spiral galaxies identified in each disturbance class (cf. Section 4.3), in different cluster regions and the field. As described in Table 5.2, the errors on fractions denote the 1σ uncertainty.

Spirals	Virial region	Infall region	Field
	$r \lesssim 0.5R_{200}$ $ \delta v \lesssim 2\sigma_{cl}$	$r > 0.5R_{200}$ $ \delta v > 2\sigma_{cl}$	
Undisturbed (0)	0.57 ± 0.09	0.40 ± 0.06	0.41 ± 0.07
Internally Asymmetric (iA)	0.19 ± 0.07	0.19 ± 0.05	0.20 ± 0.06
Interacting (I)	0.12 ± 0.06	0.19 ± 0.05	0.20 ± 0.06
Tidal (T)	0.05 ± 0.04	0.12 ± 0.04	0.16 ± 0.05
Mergers (M)	0.09 ± 0.05	0.11 ± 0.04	0.05 ± 0.03

5.5.2 Stellar ages a function of location on the PPS: a glimpse at accumulating passive galaxies

I next investigate the ages of stellar populations in galaxies as a function of the location on the PPS. Figure 5.11 shows the PPS for the galaxies of each morphological type colour-coded according to the age of their stellar populations (cf. Section 5.2). I find that

- The majority of the elliptical galaxies are ‘old’ and tend to populate the cluster core while the ‘intermediate’ ellipticals seem to avoid the cluster core. This observation is further supported by the fractions of ellipticals with old, intermediate, and younger stellar ages in the cluster regions and the field (cf. Table 5.2).
- The lenticular galaxies, however, show the interesting property that the vast majority of the field lenticulars harbour older stellar populations. In all cluster environments (the virial and infall regions), ‘old’ lenticulars are seen to be dominant but there are some cluster lenticulars with intermediate stellar ages. Although the number of field lenticulars is small, this could suggest that the evolutionary history of field and cluster lenticulars could be different. We could speculate that in clusters, the transformation of spirals into lenticulars is environmentally driven, while the field lenticulars could just be spirals which have ran out of gas.
- For the spiral galaxies, the fraction of ‘old’ spirals increases towards the core, indicating the build up of older populations in clusters. This is clearly a cluster

phenomenon, and likely depends on the amount of time spent by the galaxies in the cluster (indicated by the low r/R_{200} and $|\delta v|/\sigma_{cl}$). On the other hand, the fraction of spirals with younger stellar populations shows a complementary increase towards the field. Interestingly, the fraction of ‘intermediate’ age spirals remains approximately constant over all environments. While a fraction of these ‘intermediate’ age spirals may truly denote the spiral galaxies in transition at these redshifts, one must be careful while considering these spirals as their incidence in different cluster regions, may partially be attributed to projection effects.

The presence of ‘intermediate’ age cluster spirals and lenticulars, and the higher fraction of ‘old’ spirals in the cluster core illustrate the proliferation of passive old galaxies in clusters: the star formation in galaxies is shut down as they approach the cluster core, where they remain ‘old’ leading to the accumulation old cluster galaxy population. The associated morphological transition of ‘old’ spirals into early-type galaxies happens gradually with the ‘old’ spirals slowly losing the star formation in their disks due to loss of gas, and possibly transforming into lenticulars. These lenticulars may show a final episode of star formation in their centres (cf. Section 4.8 and Johnston, Aragón-Salamanca & Merrifield, 2014) building a larger bulge.

5.6 Conclusions

In this Chapter, I present the study of galaxy structure and star formation history (SFH), using the projected phase–space (PPS) analysis at intermediate- z ($0.4 < z < 0.8$) from the EDisCS cluster sample and a complementary field sample. Using spectroscopically derived galaxy properties, I link the quantitative structure, indicated by RFF and A_{res} , to the SFH of galaxies. Further, I analyse these non-parametric structural measures on the PPS to look for indications of possible variations in the structure of galaxies, thereby connecting the galaxy structure with the dynamical environment in clusters. The main results of this analysis are:

- 1 Quantitative structure correlates very well with the age of the galaxies’ stellar populations, as indicated by the $(H_{\delta A} + H_{\gamma A})/2$ vs D_n4000 plane. At a fixed

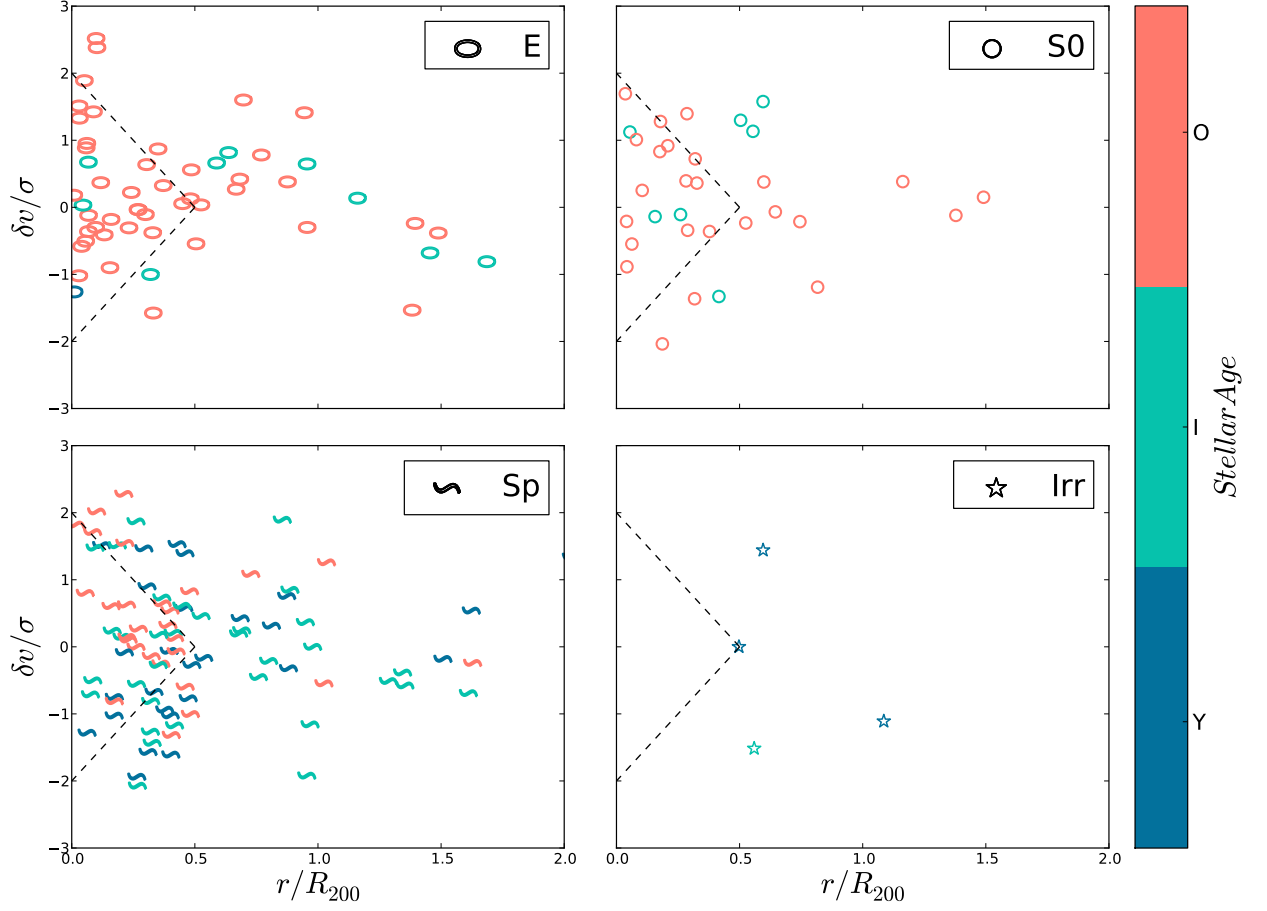


Figure 5.11: Distribution of stellar ages on the PPS for galaxies of each morphological type. As expected, ‘old’ early-type galaxies populate the virial region while the ‘intermediate’ galaxies seem to avoid the cluster core. This trend is enhanced for cluster spirals where ‘old’ spirals are found in the cluster core, and spirals with younger stellar population are found in the cluster outskirts.

morphology, young, star-forming galaxies are consistently rougher and more asymmetric, with the ‘texture’ in the structure waning with time since the latest episodes of star formation.

- 2 RFF and A_{res} show distinct separation in the cluster environment for galaxies with different stellar ages. This is likely due to the distribution of galaxy morphologies across the cluster environment.
- 3 The PPS analysis yields some correlation with stellar ages in galaxies, with the fraction of galaxies with old stellar populations increasing towards the cluster core irrespective of morphology. However, this effect is much less clear in the observed distributions of RFF and A_{res} across the PPS.

- 4 Incorporating the information from visual disturbances, a higher fraction of visually undisturbed spirals is found in the virial region, as compared to cluster outskirts and the field.

These results have important implications in the overall picture of galaxy transformation in the light of environmental effects. The dwindling fraction of spirals with younger stellar populations in the cluster core suggests that quenching likely happens as the galaxy is on its way to the cluster core. However, even if quantitative galaxy structure is correlated with stellar ages, this trend is clearly not observed when analysing RFF and A_{res} . This supports the findings from Chapter 4, where I found that the morphological/structural transformation occurs over timescales which are longer when compared to the variations in stellar ages. Galaxies start becoming structurally smoother and symmetric (or their ‘texture’ reduces) as the galaxies stop forming stars, but the actual morphological transformation happens later. Moreover, the consistently similar fractions of intermediate age spiral galaxies hint towards the steady build up of old passive galaxies in cluster cores. Alternatively, such an accumulation of old passive galaxies in cluster cores, and the apparent lack of any signatures in galaxies’ structure could also hint towards quenching mechanisms which are not caused by galaxy environment. Galaxies in cluster centres are older and passive maybe because they are massive and hence quenched by internal processes unrelated to the cluster environment.

Studies like Rudnick et al. (2016) show that older cluster galaxies with weak [OII] emission avoid the core region in clusters. Further, they argue that this may either be because the gas inside galaxies is ram-pressure stripped or because the galaxies have inhabited such densest regions of cluster for a long time. In essence, if the galaxy is old it will be structurally smoother and more symmetric. The actual morphological change will follow later after the star formation has already been truncated. The immediate effect of the environment is realised by the accumulation of the old early-type passive galaxies in the cluster core, although the plausible explanation for this could either be a gentle cluster-specific mechanism or the inherent formation history of clusters.

Chapter 6

Conclusions

In this thesis, I have investigated the role of environment on size, morphology, structure, and star formation history of galaxies within the ten high- z clusters from the ESO Distant Cluster Survey (EDisCS) at $0.4 < z < 1$. Focussing particularly on galaxy structure, I have extensively used *Hubble Space Telescope (HST)* I -band imaging to derive various structural measurements for the galaxies. Further, complementary measurements of the star formation properties were derived from the spectroscopic and photometric data for the galaxies in the clusters, and contemporary field.

This Chapter summarises the results of the analyses presented in this thesis, culminating with a brief discussion on the possible directions this work could take in the future.

6.1 Dependence of galaxy sizes on global environment

The remarkable growth in galaxy size observed from $z \sim 2.5$ has been reported to depend on the environment at higher redshifts ($z > 1$), with early-type/passive galaxies in higher density environments growing earlier (for example, Lani *et al.*, 2013). Such dependence disappears at lower redshifts (for example, Maltby *et al.*, 2010). The intermediate $0.4 < z < 0.8$ redshift range could be the transition epoch when the putative environmental differences found at higher redshifts cease to be present. Therefore, in order to assess whether the environment has a significant effect on galaxy sizes,

Chapter 3 compares the mass–size relations of cluster and field galaxies with similar morphologies and colours in this key redshift interval. The main conclusions of this study are:

- 1 No significant difference is found in the size distributions of cluster and field galaxies of a given morphology, ruling out average size differences larger than 10–20% between field and cluster galaxies of similar morphology and mass.
- 2 Similarly, there is no significant difference in the size distributions of cluster and field galaxies with similar rest-frame $B - V$ colours.
- 3 This observation is consistent across the entire range of cluster masses in the parent sample. Complementing previous studies at low- z , this analysis clearly shows that at $z < 1$ galaxies with a broad range of stellar masses, morphologies and environments show mass–size relations which are independent of environment (at fixed morphologies and/or colours).

The combination of all these results implies that, if the reported environmental size difference at higher- z is real, the size growth of field galaxies has caught up with that of the cluster galaxies by $z \sim 0.8$ –1. Any putative mechanism proposed as responsible for galaxy growth has to account for the existence of environmental differences at high redshift, if these are confirmed to be real, and their absence (or significant weakening) at lower redshifts.

6.2 Galaxy structure, star formation and global environment

Chapter 4 presents a detailed analysis of galaxy colour, morphology, and internal structure in cluster and field environments, with the aim of understanding the links between the truncation of star formation, the transformation of galaxy shapes, and environment. Utilising the *HST* images of a spectroscopic sample of cluster and complementary field galaxies, the internal structure of galaxies is explored by using quantitative non-parametric measures like residual flux fraction (RFF) and asymmetry in galaxy

residuals (A_{res}), which measure deviations from symmetric light distributions. Visual classifications were further used to identify the probable causes for such disturbances, whether internal asymmetries or external processes such as mergers, interactions, or tidal stripping. The main findings of this analysis are:

- 1 Combining the two approaches of assessing galaxy structure, it is found that the RFF is a good proxy for ‘roughness’ in the surface brightness distribution, being sensitive to the degree of structural disturbance. Conversely, A_{res} is more sensitive to the *causes* of the disruption, with merging galaxies having the highest values of A_{res} .
- 2 In agreement with previous applications of these parameters, the quantitative measurements can be used as a powerful null test to select a highly uncontaminated sample of undisturbed galaxies, or a highly complete sample of merging and tidal galaxies.
- 3 Incorporating visual morphology and environment, there are no significant differences in disturbance class between galaxies of fixed morphology in cluster and field environments.
- 4 Spiral galaxies with visual asymmetries show a flat distribution across disturbance classes, with the majority of asymmetries ascribed to external causes.
- 5 When combining measurements of star formation activity (via the UVJ colour-colour plot), and structure, I find a population of visually symmetric and passive spirals, which are twice as abundant in clusters as in the field (with a significance of 2.3σ). While being visually symmetric, these passive spirals are also significantly smoother than star-forming spirals. This suggests a gas-centric mechanism turning star-forming cluster spirals passive: not a strong gravitational process capable of disrupting the morphology of spirals, but one that is effective in removing gas. This scenario is likely to be ram-pressure stripping or starvation processes, which are specific to the cluster environment.
- 6 While nearly all lenticulars are visually undisturbed in both cluster and field, all of those in the field are passive, while $\sim 20\%$ in the cluster are star-forming and

have low stellar masses. This suggests a possible environment-driven mechanism like stripping of the gas from the low mass spirals disks whilst leading to a burst of star formation in bulges (Johnston, Aragón-Salamanca & Merrifield, 2014), or rapid consumption of the gas in the outer disk as compared to the inner gas.

In summary, the visual structure of galaxies is linked with the quantitative measurements of their intrinsic structure. While visual assessment of structure gives us information on the probable causes of disturbances, the quantitative structure of galaxies shows a strong correlation with their star formation activity. Further, the occurrence of transition subpopulations (for example, visually undisturbed passive spirals and undisturbed star-forming lenticulars) in clusters are consistent with relatively gentle processes acting on the gas content to modify the star formation properties of galaxies accreted into clusters, without large-scale disturbances in stellar structure.

6.3 Projected Phase–Space: a view of galaxy structure and star formation history in cluster environments

Chapter 5 investigates the links between the star formation history of galaxies, morphology, and internal structure. Further, complementing the global cluster/field environment, this Chapter utilises the projected phase–space as a tool to explore possible variations in galaxy structure and their stellar ages over the internal cluster environment. The main results of this analysis are:

- 1 As indicated by the Balmer absorption indices and the $4000\text{\AA}$ break strength, at a fixed morphology, the stellar ages of galaxies correlate with the quantitative structure given by RFF and A_{res} . Thus the young, star-forming galaxies are consistently rougher and more asymmetric than the galaxies with older passive stellar populations, and the ‘texture’/‘roughness’ of galaxies’ structure wanes with time since the latest episodes of star formation.
- 2 The distributions of RFF and A_{res} , when separated by morphology, show that galaxies with older stellar ages are consistently smoother and more asymmetric

in clusters as compared to those with younger stellar ages. Moreover, there is little to no significant difference in the distributions of RFF and A_{res} for galaxies with older, intermediate or younger stellar populations when separated by morphology over cluster/field environments. This suggests that star formation history of galaxies is strongly linked with their intrinsic structure alone.

- 3 Within the cluster environment, the analysis of projected phase-space shows a decrease in the fraction of galaxies with younger stellar populations in the cluster core when separated by morphology, with this trend being more pronounced for spirals. This effect, however, is much less clear in the observed distributions of RFF and A_{res} across the projected phase-space. This suggests that quenching likely happens as the galaxy is on its way to the cluster core, with the morphological/structural transformation occurring over timescales which are longer when compared to the variations in stellar ages.
- 4 Moreover, the consistently similar fractions of intermediate age spiral galaxies are observed across the projected phase-space and the field. This hints towards the steady build up of old passive galaxies in cluster cores.
- 5 Furthermore, integrating the information from the visual classification of galaxy structure, it is found that majority of the spirals within the virialised region are visually undisturbed.

Thus, the main determination of intrinsic galaxy structure is the star formation history and not the global environment. However, when the internal cluster environment is considered, galaxies show a stronger variation in their stellar ages as compared to the intrinsic structure. However, the immediate effect of the environment is realised by the accumulation of the old early-type passive galaxies in the cluster core. This signifies that the star formation in galaxies is shut down as they get accreted into clusters, while the structure of galaxies remaining more or less unaffected. The actual morphological change, therefore, will follow later after the star formation has already been truncated.

6.4 Reconstructing the overall picture: Galaxy transformation and environment

Through this thesis, I have explored the link between the SFH of galaxies and their internal structure, and the effect of environment- both the global (cluster/field) and the local (projected phase-space) environment. This, in the overall picture of galaxy evolution, furthers our knowledge towards understanding the galaxy transformations occurring in clusters.

Large-scale structural properties of galaxies, such as their sizes, cease to depend on the environment at $z < 1$ for fixed morphology. Going a step further from the morphological information we can obtain from galaxies, the internal structure of galaxies, as revealed by visual asymmetries and quantitative measures of structure, shows a strong correlation with the star formation activity in galaxies. Thus, on the whole, star-forming galaxies show ‘texture’ or ‘roughness’ in their structure along with asymmetric features, while galaxies with passive older stellar populations show smooth symmetric morphologies.

In the context of the cluster environment, my measurement of galaxy structure categorises the plausible external influences acting on galaxies. Quenching in star formation of galaxies likely happens as the galaxy is on its way to the cluster core. However, the effects of environment on the internal structure are less evident. Though galaxies start becoming structurally smoother and symmetric as they stop forming stars whilst in clusters, the actual morphological change occurs later after the star formation has already been truncated. Furthermore, the environmental processes capable of leaving the galaxy structure unaffected while shutting down the star formation would necessarily be gas-removal processes, with ICM mechanisms like ram-pressure stripping and starvation being the prime candidates.

6.5 Future Work

It is thus clear that a lot of work still needs to be done in order to disentangle the environmental effects in the observed properties of galaxies. Building up on the studies

put forth by this thesis, I outline here some probable future studies that could expand the current work as follows:

HI stripping in cluster galaxies

As it stands, the current open questions in relation to galaxy transformation (cf. Section 1.4) highlight the need for direct observations that would substantiate the role of environment in affecting galaxies' star formation, stellar distribution and structure. With the results presented in this thesis, it is clear that gas processes are the key to shutting down the star formation in cluster galaxies. A link to identifying such physical processes could be given by the raw material required for star formation in galaxies: the cold gas. This cold gas can be traced by the neutral Hydrogen (HI) in galaxies. Indeed many observations to date have shown that the HI in cluster galaxies is often disturbed and eventually exhausted (for example, Cayatte *et al.*, 1990; Bravo-Alfaro *et al.*, 2000; Chung *et al.*, 2009). Recently, studies like Jaffé *et al.* (2015, 2016) have exploited the projected phase-space to explore the effect of environment on HI in galaxies from the BUDHIES survey.

With the aim of identifying these physical processes affecting the gas, I am leading a study involving Abell 2670, a rich cluster at $z = 0.076$, mainly to understand the probable correlation of HI morphologies in galaxies with their intrinsic structure measured using RFF and A_{res} . For the structural analysis, I will be utilising wide-field deep imaging obtained from Dark Energy Camera (DECam), mounted on *Blanco* 4-m telescope, while the information on cold gas will be obtained with VLA HI data. With the imaging covering the cluster out to $2 - 3R_{200}$, this investigation will include visual identification of structural features indicative of the causes of the disturbance, the structure using RFF and A_{res} , and HI morphologies on the projected phase-space. Complementary spectroscopic and photometric information will be used to obtain robust cluster memberships and star formation properties of galaxies. This work is being carried out in collaboration with Y. L. Jaffé.

Probing structure of galaxies in cluster outskirts at low- z

In this thesis, I have explored the cluster/field and the internal cluster environment. Moreover, galaxy clusters are found to grow over time with the subsequent accretion of groups (Dressler *et al.*, 2013). The next step is, therefore, to explore the large-scale environment of galaxies like cluster outskirts, infalling groups and filaments, covering clustercentric distances $> 2R_{200}$. A prospective study could, therefore, be mapping the structural changes in galaxies in group environment and filaments for well studied local systems. Moreover, the data used extensively throughout this thesis encompasses a relatively narrow range of environments at intermediate- z . Hence, on a bigger scale, we need robust wide-field spectroscopic surveys at low- z , capable of covering extended galaxy environments. Thus, with the advent of WEAVE spectrograph on *William Herschel Telescope*, such a study can also be expanded aiming at infall regions of low- z clusters (PI: A. Aragón-Salamanca). Furthermore, such an investigation can also be conducted in extension to the study discussed previously. In addition to being a rich cluster, Abell 2670 is also a system with two probable subsystems merging along the line of sight. Further, additional information on the star formation histories of galaxies will give new insights in isolating effects of group pre-processing which the galaxies may have experienced before they enter clusters.

Application of structural techniques to understand AGN triggers at $z \sim 0.167$

Another ongoing topic of research is understanding the origins of the AGN activity in radio galaxies, which is believed to be triggered by external processes like galaxy mergers (See the review by Jogee, 2006). Although simulations predict AGN activity in galaxies accompanied by a burst of star formation induced by major mergers (for example, Di Matteo *et al.*, 2007), recent observations are hinting otherwise suggesting that perhaps minor mergers could be the trigger for radio activity in AGNs (for example, Dicken *et al.*, 2012). With the aim of exploring this connection, I am proposing a study with the STAGES multiple-cluster system (Gray *et al.*, 2009) to look at the intrinsic structure of galaxies towards understanding the possible minor merger

link to the origin of the AGN activity, and the effect of environment. This study will involve identifying AGNs using radio imaging data obtained with *GMRT*, and finding emission-line counterparts using complementary surveys like OMEGA–OSIRIS (Chies-Santos *et al.*, 2015). I then plan to utilise *HST* imaging to obtain information embedded in the galaxy residuals, and investigate faint disturbance signatures in AGNs as utilised in this work (introduced first by Hoyos *et al.*, 2012). This work would be carried out in collaboration with M.E. Gray and the STAGES collaboration.

As a concluding remark, I have explored in this thesis the intrinsic structure of galaxies and their star formation properties, and how they are affected by environment. Further, my analyses have contributed towards understanding the plausible mechanisms behind such transformations within cluster environments. Although we are steadily figuring out the complexities about galaxy evolution in general, current research has brought forth new challenging questions, and hence require further studies. At this stage, there is no doubt that this thesis demonstrates the extensive scope for future research in this field.

“The Beginning is always today”

–Mary W. Shelley
(1797-1851)

Appendix A

Mass–Size relations of galaxies

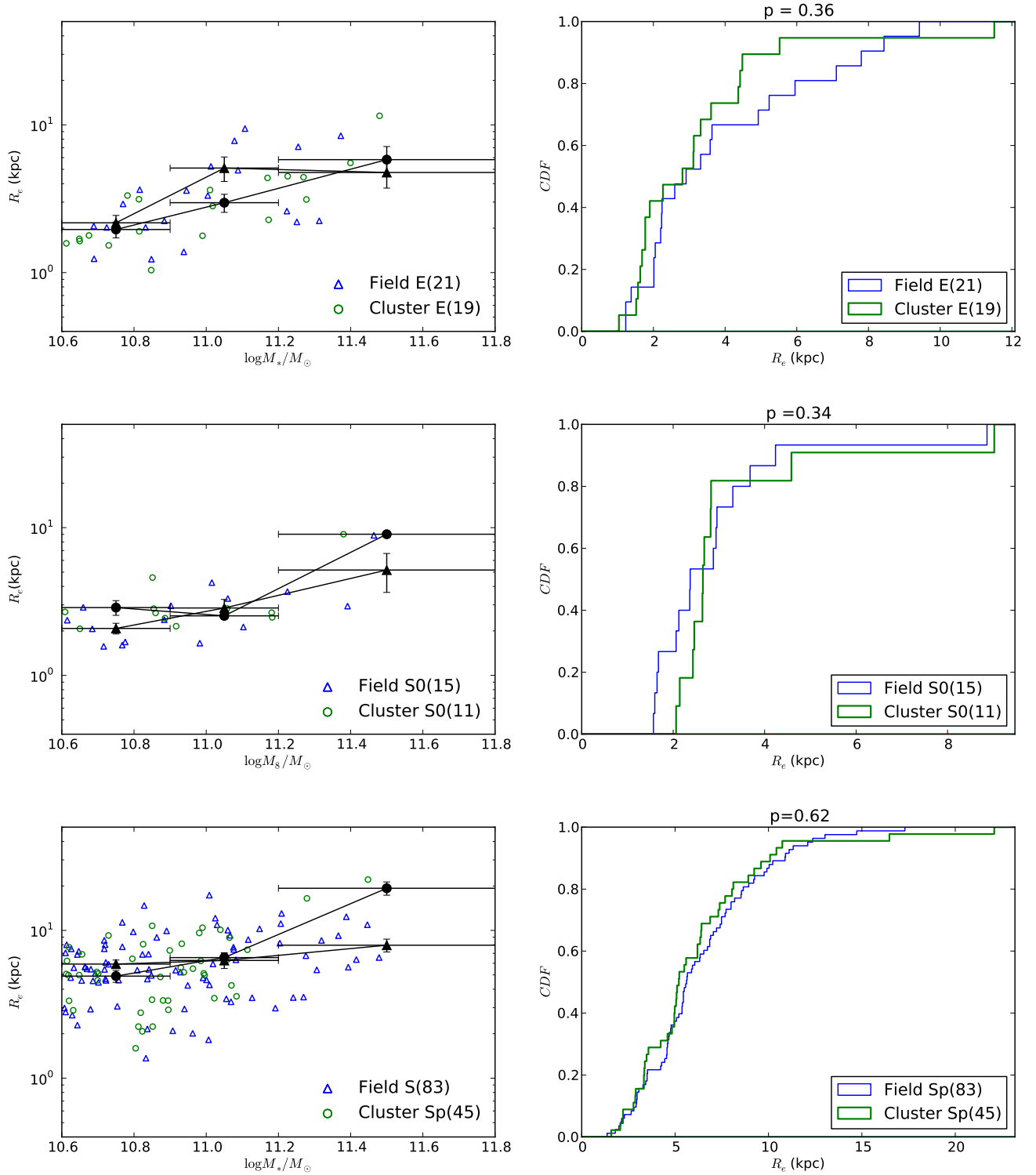


Figure A.1: Stellar mass–size relation for the spectroscopic morphology-selected samples from low-mass clusters. *Left:* The stellar mass–size relations for Elliptical, S0, and Spiral field (blue triangles) and cluster (red circles) galaxies from low-mass clusters (Section 3.3.3). The larger black triangles and circles show average values in arbitrary mass bins for the field and cluster galaxies respectively. The horizontal error bars span the size of each bin, and the vertical error bars correspond to 1σ -errors in the mean R_e of each bin.

Right: The corresponding R_e cumulative distribution function (CDF) for each of the morphologies. The dashed blue and red lines correspond to the field and cluster samples respectively. The numbers above each CDF plot correspond to the p -value derived from the K–S tests discussed in the text. The numbers in the boxes denote sample sizes.

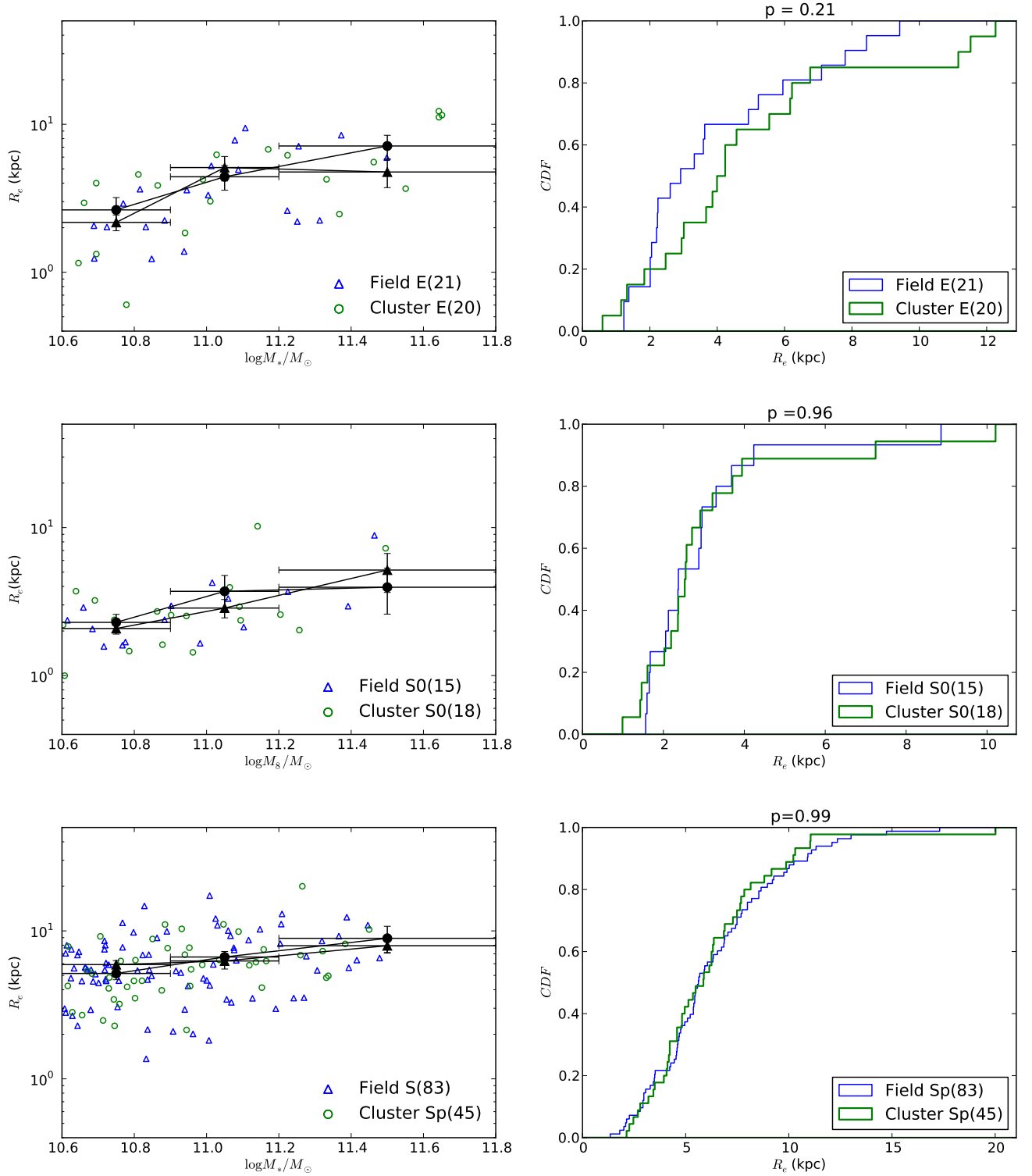


Figure A.2: As Figure A.1, but for the galaxies from high-mass cluster sample.

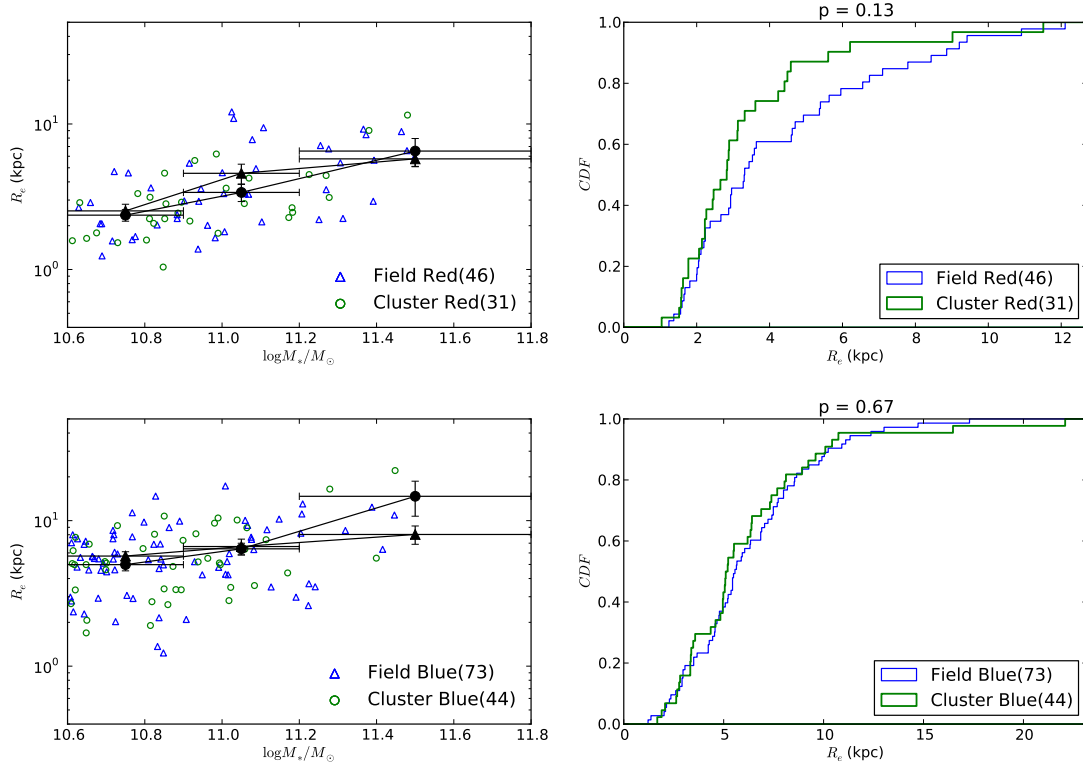


Figure A.3: Stellar mass–size relation for the spectroscopic colour-selected samples from low-mass clusters (Section 3.3.3). *Left:* The stellar mass–size relations for blue and red field (blue triangles) and cluster (red circles) galaxies. The larger black triangles and circles show average values in arbitrary mass bins for the field and cluster galaxies respectively. The horizontal error bars span the size of each bin, and the vertical error bars correspond to 1σ -errors in the mean R_e of each bin. *Right:* The corresponding R_e cumulative distribution function (CDF) for the red and blue samples. The dashed blue and red lines correspond to the field and cluster samples respectively. The numbers above each CDF plot correspond to the p -value derived from the K–S tests discussed in the text. The numbers in the boxes denote sample sizes.

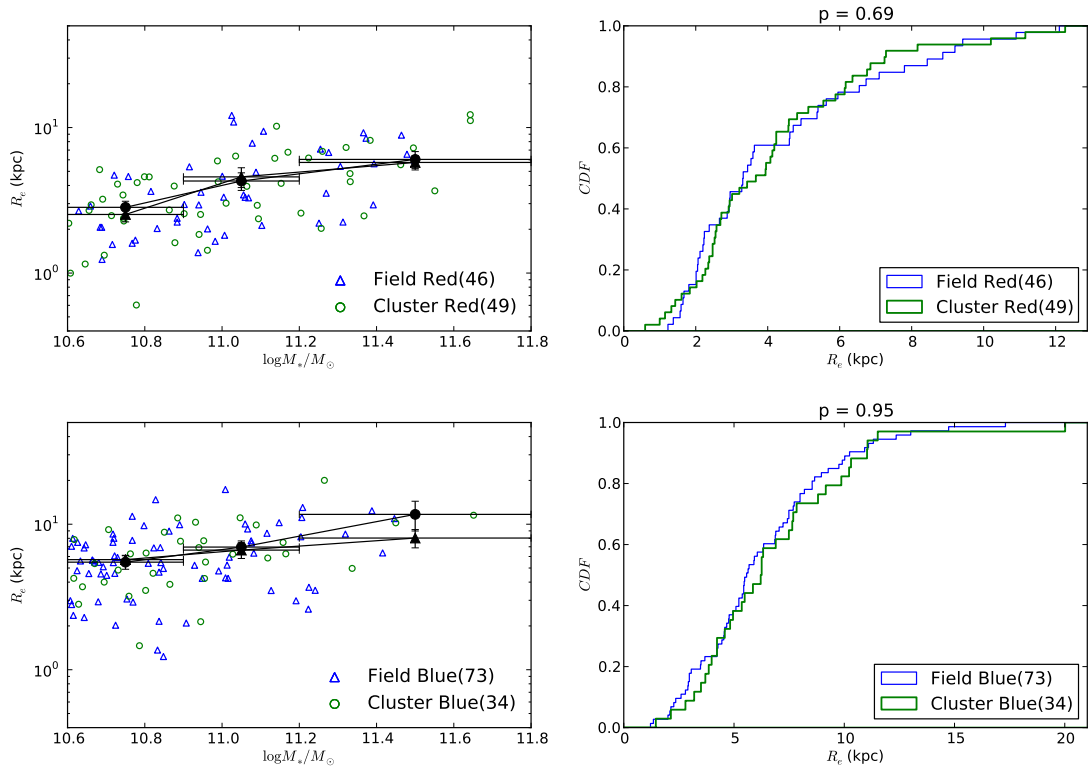


Figure A.4: As Figure A.3, but for the galaxies from high-mass cluster sample.

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