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Galaxy evolution in clusters since $z \sim 1$

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Abstract

It is now 30 years since Alan Dressler published his seminal paper on the morphology-density relation. Although there is still much to learn on the effect of the environment on galaxy evolution, extensive progress has been made since then both observationally and theoretically. Galaxy clusters provide some of the most extreme environments in which galaxies evolve, making them excellent laboratories to study the age old question of "nature" vs. "nurture" in galaxy evolution. Here I review some of the key observational results obtained during the last decade on the evolution of the morphology, structure, dynamics, star-formation history and stellar populations of cluster galaxies since the time when the universe was half its present age. Many of the results presented here have been obtained within the ESO Distant Cluster Survey (EDisCS) and Space Telescope A901/02 Galaxy Evolution Survey (STAGES) collaborations.

1 Introduction

The precise role that environment plays in shaping galaxy evolution is still hotly debated. Trends to passive and/or more spheroidal populations in dense environments are widely observed: galaxy morphology [17, 18], colour [36, 12, 3], star-formation [23, 38], and stellar age and AGN fraction [35] all correlate with measurements of the local galaxy density. Disentangling the relative importance of internal and external physical mechanisms responsible for these relations is challenging. It is natural to expect that high-density environments will preferentially host older stellar populations. Hierarchical models of galaxy formation (e.g. [14]) suggest that galaxies in the highest density peaks started forming stars and assembling mass earlier. Simultaneously, galaxies forming in high-density environments will have more time to experience the external influence of their local environment. Those processes will also act on infalling galaxies as they are continuously accreted into larger haloes. There are many plausible physical mechanisms by which a galaxy could be transformed by its environment: removal of the hot or cold gas supply through ram-pressure stripping [37, 26]; tidal effects leading to halo truncation [11] or triggered star formation through gas compression [21]; interactions between galaxies themselves via low-speed major mergers [7] or frequent impulsive encounters ("harassment" [43]). Galaxy clusters are excellent laboratories to study all these processes since they provide some of the most extreme environments in which galaxies evolve.

In addition to all these environmental effects, luminosity (or more directly, mass) is also critical in regulating how susceptible a galaxy is to external influences. For example, in low density environments the fraction of passive galaxies is a strong function of luminosity [27]. Understanding these issues in full is further complicated by the relative amounts of obscured and unobscured star formation that may or may not be present. Moreover, changes in morphology are not necessarily equivalent to changes in star formation. There is no guarantee that external processes causing an increase or decrease in the star-formation rate act on the same timescale, to the same degree, or in the same regime as those responsible for structural changes.

Despite all these complications, significant progress has been made. In this contribution I review some of the key observational results obtained during the last decade or so on the evolution of the morphology, structure, dynamics, star-formation history and stellar populations of cluster galaxies since the time when the universe was half its present age. Most of the results presented here have been obtained within the ESO Distant Cluster Survey (EDisCS) and Space Telescope A901/02 Galaxy Evolution Survey (STAGES) collaborations.

2 Results from the ESO Distant Cluster Survey (EDisCS)

The ESO Distant Cluster Survey (EDisCS) [50, 57, 47] is a multiwavelength survey of galaxies in 20 fields containing galaxy clusters at $z = 0.4$–1. Because the were optically selected from the Las Campanas Distant Cluster Survey [24] they span a very broad range of velocity dispersions (and masses), making this the ideal sample to study the high-redshift counterparts of present-day clusters [42]. The available data for these clusters include deep optical and near-IR photometry [57], deep multi-slit spectroscopy [28, 42], and ACS/HST mosaic imaging of 10 of the highest redshift clusters [16]. Photometric redshifts have been derived from the optical and near-IR imaging [49]. Additional follow-up includes XMM-Newton X-Ray observations [34], Spitzer IRAC and MIPS imaging [20], and Hα narrow-band imaging [19]. Our main results are:

(i) The colour and rest-frame K-band luminosity evolution since $z \sim 1$ of the brightest cluster galaxies (BCGs) are in good agreement with population synthesis models of stellar populations which formed at $z > 2$ and evolved passively thereafter. In contrast with some previous results [1], we do not detect any significant change in the stellar mass of the BCGs. These results do not seem to depend on the velocity dispersion of the parent cluster. However, we do find a correlation between the velocity dispersion of the clusters and the stellar mass of the BCGs in the sense that the clusters with large velocity dispersions/masses tend to have more massive BCGs. This dependency, although significant, is relatively weak: the stellar mass of the BCGs changes only by $\sim 70\%$ over a two order of magnitude range in cluster mass. This dependency does not change significantly with redshift [56].

(ii) While the colours of red-sequence galaxies are well described by an old, passively evolving population, there is a significant deficit of faint red galaxies in EDisCS clusters compared with their present-day counterparts. This decrease in the luminous-to-faint ratio of red galaxies since $z \sim 0.8$ is in qualitative agreement with predictions of a model where the blue bright galaxies that populate the colour-magnitude diagram of high-redshift clusters, have their star formation suppressed by the hostile cluster environment. This indicates that the red-sequence population of high-redshift clusters does not contain all progenitors of nearby red-sequence cluster galaxies. A significant fraction of these must have moved on to the red sequence below $z \sim 0.8$ [13, 15, 51].

(iii) The intrinsic colour scatter about the colour-magnitude relation (CMR) for morphologically-selected E and S0 galaxies in all EDisCS clusters is very small. This implies that by the time cluster elliptical and S0 galaxies achieve their morphology, the vast majority have already joined the red sequence. However, there is a small minority of faint early-type galaxies (7%) that are significantly bluer than the CMR. If the colour scatter is due to differences in stellar population ages, the formation redshift $z_{\rm F}$ of the E and S0 galaxies does not depend on the cluster velocity dispersion. However, $z_{\rm F}$ increases weakly with cluster redshift, suggesting that, at any given redshift, in order to have a population of fully formed ellipticals and S0s they needed to have formed most of their stars $\gtrsim$ 2–4 Gyr prior to observation. That does not mean that all early-type galaxies in all clusters formed at these high redshifts. It means that the ones we see already having early-type morphologies also have reasonably old stellar populations. This is partly a manifestation of the "progenitor bias", but also a consequence of the fact that the vast majority of the early-type galaxies in clusters (in particular the massive ones) already had old stellar populations by the time they achieved their morphology. Elliptical and S0 galaxies exhibit very similar colour scatter, implying similar stellar population ages. The scarcity of blue S0s indicates that, if they are the descendants of spirals whose star formation has ceased, the parent galaxies were already red when they became S0s. This suggests the red spirals found preferentially in dense environments [6] could be the progenitors of cluster S0s. We also find that fainter early-type galaxies finished forming their stars later, consistent with the cluster red sequence being built over time and the brightest galaxies reaching the red sequence earlier than fainter ones. Finally, combining the CMR scatter analysis with the observed evolution in the CMR zero-point we find that the early-type cluster galaxy population must have had their star formation truncated/stopped over an extended period $\Delta t \gtrsim 1\,{\rm Gyr}$ [31].

(iv) High S/N VLT spectra reveal that the evolution of the stellar population properties of red-sequence galaxies depend on their mass: while the properties of the most massive are well described by passive evolution and high-redshift formation, those of the less massive galaxies are consistent with a more extended star-formation history [53]. The evolution of the absorption line strengths for the red-sequence galaxies can be reproduced if 40% of the galaxies with $\sigma < 175\,{\rm km\,s^{-1}}$ entered the red-sequence between $z = 0.75$ and $z = 0.45$, in excellent agreement with the evolution of the luminosity functions [13, 15, 51]. Moreover, the fraction of red-sequence galaxies exhibiting early-type morphologies (E and S0) decreases by 20% from $z = 0.75$ to $z = 0.45$. This can be understood if the red-sequence becomes more populated at later times with disc galaxies whose star formation has been quenched. Thus, the processes quenching star formation do not necessarily produce a simultaneous morphological transformation of the galaxies entering the red-sequence [53].

(v) We have also studied the evolution of the fundamental plane (FP) for galaxies in clusters with a very broad range of masses. If we interpret the evolution in the FP as due only to changes in the luminosity of the galaxies, the mass-to-light ratio would evolve as $\Delta \log(M/L_{\rm B}) = (-0.54 \pm 0.01)z = (-1.61 \pm 0.01)\log(1+z)$ for cluster galaxies and as $\Delta \log(M/L_{\rm B}) = (-0.76 \pm 0.01)z = (-2.27 \pm 0.03)\log(1+z)$ in the field. However, that cannot be the whole story since the galaxy sizes and velocity dispersions also evolve. Taken together, the variations in size and velocity dispersion imply that the luminosity evolution with redshift derived from the zero point of the FP is somewhat milder than that derived without taking these variations into account. At fixed dynamical masses, the effects of size and velocity dispersion variations almost cancel out. At fixed stellar masses, the luminosity evolution is reduced to $L_B \propto (1+z)^{1.0}$ for cluster galaxies and $L_B \propto (1+z)^{1.67}$ for field galaxies. This luminosity evolution implies that massive ($> 10^{11}\,{\rm M}_\odot$) cluster galaxies are old ($z_{\rm F} > 1.5$) and lower mass galaxies are $\sim$ 3–4 Gyr younger, confirming the picture of a progressive build-up of the red sequence in clusters. Field galaxies follow the same trend, but are ~ 1 Gyr younger at a given redshift and mass [52].

(vi) Combining previously published data with ACS-based visual morphologies for 10 $0.5 < z < 0.8$ EDisCS clusters we find no significant evolution in the mean fractions of elliptical, S0, and late-type (Sp+Irr) galaxies in clusters over the redshift range $0.5 < z < 1.2$. In contrast, existing studies of lower redshift clusters have revealed a factor of ~ 2 increase in the typical S0 fraction between $z = 0.4$ and 0, accompanied by a commensurate decrease in the Sp+Irr fraction and no evolution in the elliptical fraction. It seems therefore that cluster morphological fractions plateau beyond $z \sim 0.4$ [16]. The evolution in the morphological fractions is accompanied by a parallel evolution in the corresponding stellar mass fractions for the different morphological classes [55]. There seems to be a mild correlation between morphological content and cluster velocity dispersion, highlighting the importance of careful sample selection in evaluating evolution [16]. However, alternative analysis using the galaxies' structural parameters as proxies for morphology do not find such a trend [54].

(vii) We have also explored how the proportion of star-forming galaxies evolves between $z = 0.8$ and 0 as a function of galaxy environment. At high z most systems follow a broad anticorrelation between the fraction of star-forming galaxies and the cluster velocity dispersion $\sigma_{\rm clus}$. At face value, this suggests that at $z =$ 0.4–0.8 the mass of the system largely determines the proportion of galaxies with ongoing star formation. At these redshifts the strength of star formation in star-forming galaxies is also found to vary systematically with environment. In contrast, local SDSS clusters have much lower fractions of star-forming galaxies than clusters at $z =$ 0.4–0.8 and show a plateau for $\sigma_{\rm clus} \geq 550\,{\rm km\,s^{-1}}$, where the fraction of star forming galaxies does not vary systematically with $\sigma_{\rm clus}$. This means that the fraction of star-forming galaxies evolves more strongly in intermediate-mass systems ($\sigma_{\rm clus} \sim$ 500–600 ${\rm km\,s^{-1}}$ at $z \sim 0$) [45]

(viii) We find that the star-formation properties and morphologies of galaxies in clusters and groups at $z =$ 0.4–0.8 depend on projected local galaxy density. In both nearby (SDSS) and distant clusters, higher density regions contain proportionally fewer star-forming galaxies, but the average [OII] equivalent width of star-forming galaxies is independent of local density. In distant clusters the average current star formation rate (SFR) in star-forming galaxies seems to peak at intermediate densities. Unlike at low-z, at high-z the relation between star-forming fraction and local density seems to depend on the cluster mass. The morphology-density relation is already well established in $z = 0.4$–0.8 clusters, but is completely dominated by radial variations in the spiral and elliptical fractions, with the S0s playing no role given their small numbers. The decline of the spiral fraction with density is entirely driven by galaxies of type Sc or later. For galaxies of a given Hubble type, we see no evidence that their star formation properties depend on local environment [46].

(ix) The incidence of post-starburst (E+A or k+a) galaxies, where the star formation ended abruptly in the past Gyr, depends strongly on environment at intermediate redshifts. They reside preferentially in clusters and, unexpectedly, in a subset of the $\sigma_{\rm clus} = 200$–$400\,{\rm km\,s^{-1}}$ groups, those that have a low fraction of [OII] emitters. In these environments, 20%–30% of the star-forming galaxies have had their star formation activity recently truncated. In contrast, there are proportionally fewer k+a galaxies in the field, the poor groups, and groups with a high [OII] fraction. Moreover, the incidence of k+a galaxies correlates with the cluster velocity dispersion: more massive clusters have higher proportions of k+a's. Dusty starbursts present a very different environmental dependence. They are numerous in all environments at $z = 0.4$–0.8, but they are especially numerous in all groups, favouring the hypothesis that dusty starbursts are triggering by mergers. We conclude that cluster k+a galaxies are mainly rather massive S0 and Sa galaxies observed in a transition phase, evolving from star-forming, recently-infallen later types to passively-evolving cluster early-type galaxies. The correlation between k+a fraction and cluster velocity dispersion supports the hypothesis that in clusters these galaxies originate from processes related to the intracluster medium [48].

(x) Using spatially-resolved VLT spectra of EDisCS galaxies with emission lines we find that disturbances in the galaxies' gas kinematics are more frequent in clusters than in the field. This effect is stronger for brighter galaxies. This suggests that gas is being stripped off very efficiently from faint cluster galaxies, removing them from the emission-line sample. Moreover, the fraction of kinematically-disturbed galaxies increases with cluster velocity dispersion and decreases with distance from the cluster centre, but it remains constant with projected galaxy density. This strongly suggest that the effect must be caused by ICM-related processes. The fraction of morphologically-disturbed galaxies (from HST/F814W images) does not depend on luminosity or environment. For the kinematically-undisturbed galaxies, we find that the cluster and field Tully-Fisher relations are remarkably similar (but see also [41, 44, 4]). However, we find some tentative evidence that the specific star-formation rate (SFR per unit stellar mass) is suppressed in the kinematically disturbed galaxies. We also find that cluster galaxies show truncated gas discs as compared with similarly-selected field galaxies (in agreement with [5]). These results suggest that environmental effects are mild enough not to disturb the stellar discs while being able to strongly affect the gas in cluster galaxies [32, 33].

3 Results from the Space Telescope A901/2 Galaxy Evolution Survey (STAGES)

The Space Telescope A901/2 Galaxy Evolution Survey (STAGES) is a multiwavelength project designed to probe physical drivers of galaxy evolution across a wide range of environments and luminosity [25]. This project, targeting the Abell 901(a,b)/902 multiple cluster system (hearafter A901/2) at $z \sim 0.165$, allows us to carry out a comprehensive study of the environmental processes at work in shaping galaxy evolution. The survey design addresses simultaneously several key areas: a wide range of environments; a wide range in galaxy luminosity; and sensitivity to both obscured and unobscured star formation, stellar masses, AGN, and detailed morphologies. Furthermore, STAGES provides several complementary measurements of 'environment' in order to understand directly the relative influences of the local galaxy density, the hot ICM and the dark matter on galaxy transformation. A further advantage is given by examining systems that are not simply massive clusters already in equilibrium. By including systems in the process of formation (when extensive mixing has not yet erased the memory of early timescales), the various environmental proxies listed above might still be disentangled.

The complex multi-cluster A901/2 system at $z \sim 0.165$ has been the subject of an 80-orbit F606W HST/ACS mosaic covering the full $0.5 \times 0.5\,\mathrm{deg}^2$ ($\sim 5 \times 5\,\mathrm{Mpc}^2$) span of the system. Extensive multiwavelength observations with XMM-Newton, GALEX, Spitzer, 2dF, GMRT, Magellan, and the 17-band COMBO-17 photometric redshift survey complement the HST imaging. Our survey goals include simultaneously linking galaxy morphology with other observables such as age, star-formation rate, nuclear activity, and stellar mass. In addition, with the multiwavelength dataset and new high resolution mass maps from gravitational lensing [30], we are able to disentangle the large-scale structure of the system. By examining all aspects of environment we are evaluating the relative importance of the dark matter halos, the local galaxy density, and the hot X-ray gas in driving galaxy transformation.

In summary, STAGES focuses on a single large-scale structure which samples a very broad range of galaxy environments and masses at a single redshift, allowing us to decouple environmental and stellar mass effects from redshift-related ones. I will summarise below some of the results more relevant to this symposium[1].

(i) We have explored the amount of obscured star formation as a function of environment by combining the UV/optical SEDs from COMBO-17 with Spitzer 24 μm photometry. We find that while there is an overall suppression in the fraction of star-forming galaxies with density, the small amount of star formation surviving the cluster environment is to a large extent obscured [22]. Furthermore, we also find that passive spiral and dusty red galaxies in the cluster system are largely the same population. These galaxies form stars at a substantial rate that is only a factor of ~ 4 times lower than blue spirals at fixed mass, but their star formation is more obscured and has weak optical signatures. They constitute over half of the star forming galaxies at masses above $\log M_*/\mathrm{M}_\odot = 10$ and are thus a vital ingredient for

[1]For a more complete and up-to-date description of STAGES-related science see http://www.nottingham.ac.uk/astronomy/stages/.

understanding the overall picture of star-formation quenching in cluster environments [58].

(ii) Only $4.9 \pm 1.3\%$ of intermediate mass ($M_* \geq 1 \times 10^9 \mathrm{M}_\odot$) galaxies in the STAGES field are interacting. The interacting galaxies are found to lie outside the cluster cores and to be concentrated in the region between the cores and virial radii of the clusters. The average star formation rate is enhanced only by a modest factor in interacting galaxies compared to non-interacting galaxies. Interacting galaxies only contribute $\sim 20\%$ of the total SFR density in the A901/2 clusters [29].

(iii) We explored the dependence of the mass-size-relation with environment using a large sample of morphologically-classified galaxies. For elliptical, lenticular and high-mass ($\log M_*/\mathrm{M}_\odot > 10$) spiral galaxies we find no evidence to suggest any such environmental dependence, implying that internal drivers are governing their size evolution. For intermediate-/low-mass spirals ($\log M_*/\mathrm{M}_\odot < 10$) we find tentative evidence for a possible environmental dependence: the mean effective radius for lower mass spirals is $\sim$ 15–20% per cent larger in the field than in the cluster. This is due to a population of low-mass field spirals with relatively extended disks that are largely absent from the cluster environments. These galaxies contain extended stellar discs not present in their cluster counterparts. This suggests that the fragile extended stellar discs of these spiral galaxies may not survive the environmental conditions in the cluster. Internal physical processes seem to be the main drivers governing the size evolution of galaxies, with the environment possibly playing a role affecting only the discs of low-mass spirals [39]. Interestingly, a detailed study of the spiral galaxy population using STAGES ACS images does not find any environmental effects on the detailed structure of their stellar disks such as their scale lengths or the presence or absence of disk truncations/anti-truncations. This implies that the galaxy environment is not affecting the stellar distribution in the outer stellar disk [40].

4 Conclusions

The results quoted above allow us to conclude, among many other things, that spirals transform into S0s in clusters, with the most massive ones completing the process earlier. Star formation ceases quickly in in-falling spirals, leaving a “k+a” signature. Infalling blue spirals become (dusty) red spirals and then S0s. The truncation of star formation proceeds outside-in, helping to grow bulges. The driving mechanism is “gentle” since it preserves disks. All these processes happen in massive clusters first. These conclusions are in excellent agreement with recent independent observations of the properties of nearby S0 galaxies [2, 8, 9, 10].

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