EMISSION LINE GALAXIES IN CLUSTERS

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Abstract   At the present epoch, clusters of galaxies are known to be a hostile environment for emission-line galaxies, which are more commonly found in low density regions outside of clusters. In contrast, going to higher redshifts the population of emission-line galaxies in clusters becomes progressively more conspicuous, and large numbers of star-forming late-type galaxies are observed. I present an overview of the observational findings and the theoretical expectations regarding the evolution of emission-line galaxies in dense environments, discussing the properties of these galaxies and the current evidence for environmental influences on their evolution.

Introduction

This review focuses on galaxies with emission lines in their optical spectra. In the great majority of cases, at least in clusters, an emission-line galaxy can be assumed to be currently forming stars[1], thus the subject of this contribution is essentially the whole population of cluster galaxies with ongoing star formation at any given epoch. One of the major goals of current studies of galaxy formation and evolution is to understand when each galaxy formed or will form its stars, and why. Naturally, star-forming galaxies are at the heart of this investigative effort. Knowing their frequency and their evolution as a function of the environment is fundamental to trace the evolution of the star formation activity with redshift and to start gaining insight on the processes that regulate such activity.

This is an area of research that really encompasses "many scales" of the Universe, from the star formation on the scale of a single star-forming region within a galaxy, to the integrated properties on a galaxy scale, to a galaxy-cluster scale and to the evolution of the global star formation history on a cosmic scale. I will briefly touch upon each of these scales and I will focus on the following main questions: how many emission line galaxies are there in clusters, at different redshifts? What are their properties (star formation rates,

Hubble types, gas content)? What is their fate? How do they evolve and why? And, finally, what can they teach us about galaxy formation and evolution in general?

1.   High redshift

Star formation activity

At any given redshift, the properties of cluster galaxies display a large cluster to cluster variance. The "average galaxy" in the Coma cluster looks quite different from the "average galaxy" in the Virgo cluster, the first cluster being dominated by passively evolving, early-type galaxies, and the second one having a larger population of star-forming spirals. Moreover, clusters of galaxies, far from being closed boxes, continuously "form" and evolve accreting single galaxies, pairs, groups, or merging with other clusters. The galaxy content of a cluster thus changes with redshift. Keeping these two things in mind, it is possible to look for evolutionary trends with redshift.

Historically, the first evidence for a higher incidence of star-forming galaxies in distant clusters compared to nearby clusters came from photometric studies (Butcher & Oemler 1978, 1984, Ellingson et al. 2001, Kodama & Bower 2001). Spectroscopy is of course the most direct way to identify emission–line galaxies. For distant galaxies, the Hα line is redshifted at optical wavelengths that are severely affected by sky or in the near-IR, thus the feature most commonly used is the [OII]$\lambda 3727$ line.

In the MORPHS sample of 10 clusters at $z \sim 0.4 - 0.5$, the fraction of emission–line galaxies is $\sim 30\%$ for galaxies brighter than $M_V = -19 + 5\log \mathrm{h}^{-1}$ (Dressler et al. 1999, Poggianti et al. 1999). In the CNOC cluster sample, at an average redshift $z \sim 0.3$, this fraction is about 25% (Balogh et al. 1999). This incidence is much higher than it is observed in similarly rich clusters at $z = 0$ (Dressler, Thompson & Shectman 1988). Significant numbers of emission-line galaxies have been reported in virtually all spectroscopic surveys of distant clusters (Couch & Sharples 1987, Fisher et al. 1998, Postman et al. 1998, 2001).

The importance of the [OII] emission can also be assessed from cluster composite spectra, that are obtained summing up the light from all galaxies in a given cluster to produce a sort of "cluster integrated spectrum" (Fig. 1, Dressler et al. 2004). As expected, the strength of [OII] in these composite spectra displays a large cluster–to–cluster variation at any redshift, but there is a tendency for the $z = 0.5$ clusters to have on average a stronger composite EW([OII]) than the clusters at $z = 0$.

If numerous observations indicate that emission–line galaxies were more prominent in clusters in the past than today, and if these results are unsurprising given the evolution with z of the star formation activity in the general "field",
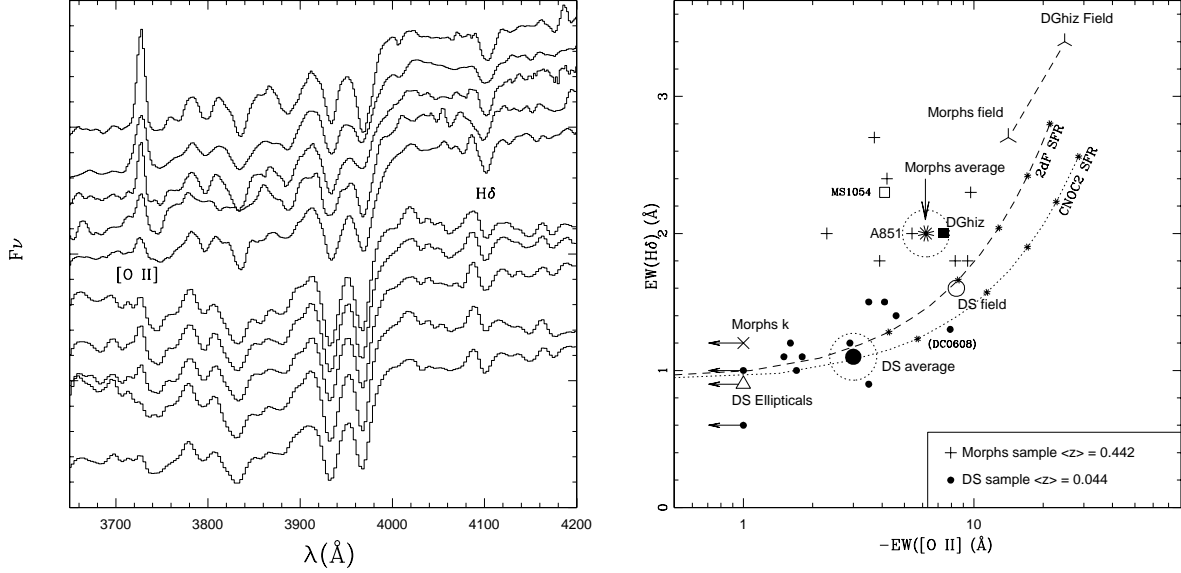
Figure 1. From Dressler et al. (2004). *Left.* Composite spectra of five clusters at $z \sim 0.5$ (top five) and five clusters at $z \sim 0$ (bottom five). The [OII] line is generally more prominent in the high-z spectra. *Right.* Equivalent widths of [OII] versus Hδ as measured from composite spectra of clusters at $z \sim 0.4 - 0.5$ (crosses) and clusters at $z \sim 0$ (filled dots).

quantifying this evolution in clusters has proved to be very hard. The fact that the emission–line incidence varies strongly from a cluster to another at all redshifts, and the relatively small samples of clusters studied in detail at different redshifts, have so far hindered our progress in measuring how the fraction of emission–line galaxies evolves with redshift as a function of the cluster properties.

Discriminating between cosmic evolution and cluster–to–cluster variance is a problem also for Hα cluster–wide studies. Using narrow–band imaging or multiplex multislit capabilities, a handful of clusters have been studied to date at $z \geq 0.2$ (Couch et al. 2001, Balogh et al. 2002a, Finn et al. 2004, and submitted, Kodama et al. 2004, Umeda et al. 2004). These studies have confirmed that the fraction of emission–line (Hα–detected, in this case) galaxies is lower in clusters than in the field at similar redshifts, and have shown that the bright end of the Hα luminosity function does not seem to depend strongly on environment. As shown in Fig. 2, the number of clusters studied is still insufficient to pin down the star formation rate (SFR) per unit of cluster mass as a function of redshift AND of global cluster properties such as the cluster velocity dispersion.
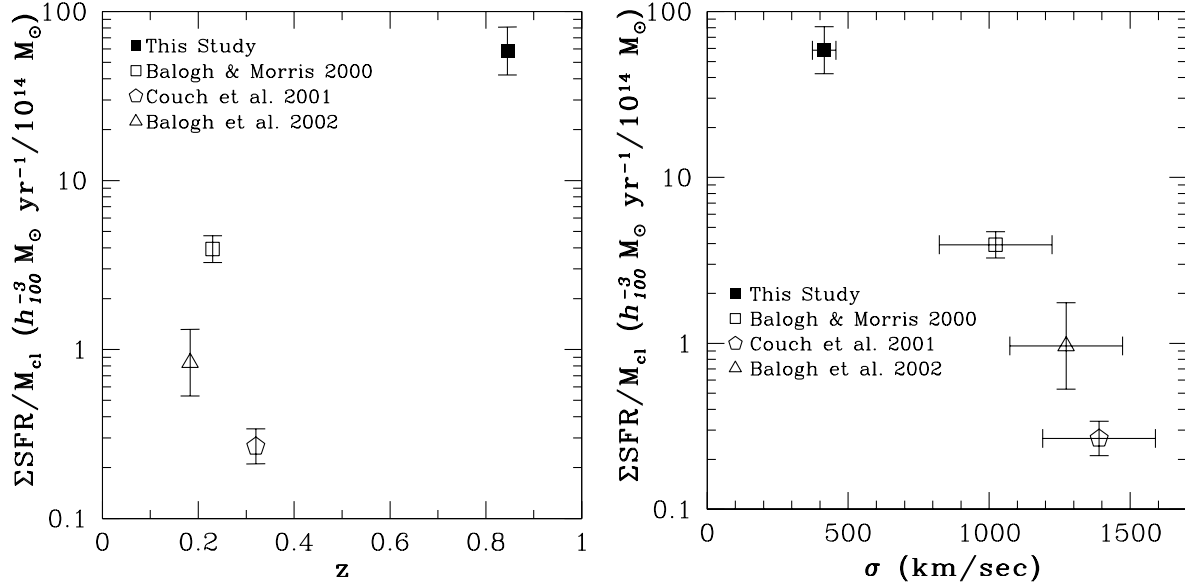
Figure 2. From Finn et al. (2004). Star formation rate per unit of cluster mass, as measured from Hα narrow-band imaging, as a function of redshift (left) and cluster velocity dispersion (right).

A word of caution is compulsory when using emission–lines and assuming they provide an unbiased view of the evolution of the star formation activity in cluster galaxies. There are several indications that dust extinction is in fact important and strongly distorts our view of the star formation activity in at least some cluster galaxies. Evidence for dust arises from optical spectroscopy itself, which finds many dusty starbursting or star–forming galaxies with relatively weak emission–lines both in distant clusters and in the field at similar redshifts (Poggianti et al. 1999, Shioya et al. 2000, Poggianti et al. 2001, Bekki et al. 2001). The radio–continuum detection of galaxies with no optical emission lines (Smail et al. 1999, Miller & Owen 2002) and mid-IR estimates of the star formation rate (Duc et al. 2002, Coia et al. 2004 submitted, Biviano et al. 2004) indicate that even the majority or all of the star formation activity of some cluster galaxies can be obscured at optical wavelengths. Whether taking into account dust obscuration changes significantly the evolutionary picture inferred from emission lines is still a critical open question.

Finally, precious informations about emission–line galaxies can be obtained from absorption–line spectra. In distant clusters, the presence of galaxies with strong Balmer lines in absorption in their spectra, and no emission lines, testifies that these are post-starburst/post-starforming galaxies observed soon after

their star formation activity was interrupted and observed within 1-1.5 Gyr from the halting (Dressler & Gunn 1983, Couch & Sharples 1987, see Poggianti 2004 for a review). These galaxies have been found to be proportionally more numerous in distant clusters than in the field at comparable redshifts (Dressler et al. 1999, Poggianti et al. 1999, Tran et al. 2003, 2004). Their spectral characteristics and their different frequency as a function of the environment are a strong indication for a truncation of the star formation activity related to the dense environment.

Galaxy morphologies

In this section I summarize the results concerning the morphologies of emission-line galaxies in distant clusters obtained with the Wide Field and Planetary Camera 2. At the time of writing, high–quality data of distant clusters have been obtained with the Advanced Camera for Surveys by several groups, and results should appear soon (Desai et al. in prep., Postman et al. in prep.).

The HST images have revealed the presence of large numbers of spiral galaxies in all distant clusters observed. Comparing HST morphologies and spectroscopy, it has been shown that emission–line galaxies in distant clusters are for the great majority *spirals* (Dressler et al. 1999). The viceversa is not always true: several of the cluster spirals, in fact, do not display any emission line in their spectra, and both their spectra and their colors indicate a lack of current star formation activity (Poggianti et al. 1999, Couch et al. 2001, Goto et al. 2003).

These "passive spirals" might be an intermediate stage when star–forming spirals are being transformed into passive S0 galaxies. A strong reason to believe that a significant fraction of the spirals in distant clusters evolve into S0s comes from the evolution of the Morphology-Density (MD) relation. The MD relation is the observed correlation between the frequency of the various Hubble types and the local galaxy density, normally defined as the projected number density of galaxies within an area including its closest neighbours. In clusters in the local Universe, the existence of this relation has been known for a long time: ellipticals are frequent in high density regions, while the fraction of spirals is high in low density regions (Oemler 1974, Dressler et al. 1980). At $z = 0.4 − 0.5$, an MD relation is already present, at least in concentrated clusters, but it is *quantitatively* different from the relation at $z = 0$: the fraction of S0 galaxies at $z = 0.5$ is much lower, at all densities, than in clusters at $z = 0$ (Dressler et al. 1997). The fraction of S0s in clusters appears to increase towards lower redshifts, while the proportion of spirals correspondingly decreases (Dressler et al. 1997, Fasano et al. 2000). Interestingly, ellipticals are already as abundant at $z = 0.5$ as at $z = 0$. Adopting a more conservative distinction between "early-type" (Es+S0s) and late-type (spirals)

galaxies, a similar evolution is found, with the early-type fraction decreasing at higher redshifts (van Dokkum et al. 2000, Lubin et al. 2002). First results at $z \sim 0.7 - 1.3$ seem to indicate that between $z = 0.5$ and $z = 1$ what changes in the MD relation is only the occurrence of early-type galaxies in the very highest density regions (Smith et al. 2004).

Alltogether, the findings described in this and the previous section suggest that many galaxies have stopped forming stars in clusters quite recently, as a consequence of environmental conditions switching off their star formation activity, and that many galaxies have morphologically evolved from late to early type galaxies. What can be the cause/causes for these changes?

2. Physical processes

The physical mechanisms that are usually considered when trying to assess the influence of the environment on galaxy evolution can be grouped in four main families:

1 Mergers and strong galaxy-galaxy interactions (Toomre & Toomre 1972, Hernquist & Barnes 1991, see Mihos 2004 for a review). These are most efficient when the relative velocities between the galaxies are low, thus are expected to be especially efficient in galaxy groups.

2 Tidal forces due to the cumulative effect of many weaker encounters (also known as "harassment") (Richstone 1976, Moore et al. 1998). These are expected to be especially important in clusters, and particularly on smaller / lower mass galaxies.

3 Gas stripping - Interactions between the galaxy and the inter-galactic medium (IGM) (Gunn & Gott 1972, Quilis et al. 2000). The interstellar medium of a galaxy can be stripped via various mechanisms, including viscous stripping, thermal evaporation and – the most famous member of this family – ram pressure stripping. Ram pressure can be efficient when the IGM gas density is high and the relative velocity between the galaxy and the IGM is high, and such conditions are expected to be met especially in the very central regions of cluster cores.

4 Strangulation (also known as starvation, or suffocation) (Larson, Tinsley & Caldwell 1980, Bower & Balogh 2004). Assuming galaxies possess an envelope of hot gas that can cool and feed the disk with fuel for star formation, the removal of such reservoir of gas is destined to inhibit further activity once the disk gas is exhausted. In semi-analytic models, for example, the gas halo is assumed to be removed when a galaxy enters as satellite in a more massive dark matter halo.

Note that while stripping gas from the disk induces a truncation of the star formation activity on a short timescale ($\sim 10^7$ yrs), strangulation is expected to affect a galaxy star formation history on a long timescale (> 1 Gyr) provoking a slowly declining activity which consumes the disk gas after the supply of cooling gas has been removed.

The former two of these families of processes affect the galaxy structure, thus morphology, in a direct way: the merger of two spirals can produce an elliptical galaxy, and repeated tidal encounters can change a late–type into an early-type galaxy. The latter two families, instead, act on the gas content of galaxies, hence their star formation activity, and can modify their morphologies in an indirect way: once star formation is halted in a disk, this can fade significantly, the bulge-to-disk relative importance can change and the galaxy appearance and morphology can appear significantly modified.

3.   Low redshift

Numerous excellent works have been carried out on a single cluster or samples of clusters in the local Universe. Summarizing them is beyond the scope of this paper, and the reader can find a comprehensive review in Gavazzi & Boselli (in prep.). I have chosen to mention two low-redshift results here, to compare and contrast them with the results at higher redshifts: the observed trends of star formation with local environment, and the gas/SF distribution within galaxies.

Trends of star formation with local environment

It has been known for a long time that in the nearby Universe also the average star formation activity correlates with the local density: in higher density regions, the mean star formation rate per galaxy is lower. This is not surprising, given the existence of the MD relation: the highest density regions have proportionally more early-type galaxies devoid of current star formation.

Interestingly, the correlation between mean SF and local density extends to very low local densities, comparable to those found at the virial radius of clusters, and such a correlation exists also outside of clusters (Lewis et al. 2002, Gomez et al. 2003). Again, this seems to parallel the fact that an MD relation is probably existing in all environments, and it has been observed in clusters of all types (Dressler et al. 1980) and groups (Postman & Geller 1984) – though the MD relation is *not the same* in all environments, e.g. in concentrated vs. irregular, high- vs. low- L_X clusters (Dressler et al. 1980, Balogh et al. 2002b).

A variation in the mean SF/galaxy with density can be due either to a difference in the *fraction of star-forming galaxies*, or in the *star formation rates* of the star-forming galaxies, or a combination of both. In a recent paper, Balogh et al. (2004a) have shown that the distribution of Hα equivalent widths (EW)

in star-forming galaxies does not depend strongly on the local density, while the fraction of star-forming galaxies is a steep function of the local density, in all environments. Again, a dependence on the *global environment* is observed, in the sense that, at a given local density, the fraction of emission-line galaxies is slightly lower in environments with high density on large scales (~ 5 Mpc) (but see Kauffmann et al. 2004 for an opposite result).

The fact that a relation between star formation and density is observed also outside of clusters has often been interpreted as a sign that the environment starts affecting the star formation activity of galaxies (provoking a decline in star formation in galaxies that if isolated would continue forming stars) at relatively low densities, when a galaxy becomes part of a group. Personally, I believe the existence of such a correlation is more probably the result of a correlation between initial conditions (galaxy mass and/or local environment very early on, at the time the first stars formed in galaxies) and type of galaxy formed. The exact shape of the correlation, instead, is probably influenced by transformations happening in galaxies when they enter a different environment.

Gas content and gas/SF distribution within galaxies

In order to understand what happens to galaxies in clusters, two crucial pieces of information are 1) the gas content of cluster galaxies and 2) the spatial distribution of the gas and of the star formation activity within each galaxy.

It has been several years since it became evident that many spirals in clusters are deficient in HI gas compared to similar galaxies in the field (Giovanelli & Haynes 1985, Cayatte et al. 1990, see van Gorkom 2004 for a review). Most (but not all) of the HI deficient spirals are found at small distances from the cluster centre. In the central regions of clusters, the sizes of the HI disks are smaller than the optical disks, and a spatial displacement between the HI and the optical occurs in several cases (Bravo-Alfaro et al. 2000). The fraction of HI–deficient spirals increases going towards the cluster centre, and a correlation is observed between deficiency and orbital parameters: more deficient galaxies tend to be on radial orbits (Solanes et al. 2001).

All of these findings strongly suggest that ram pressure stripping, or at least gas stripping in general, plays an important role (see also Bravo-Alfaro and Solanes contributions in these proceedings). On the other hand, the work from Solanes et al. (2001) has unexpectedly shown that the HI deficiency is observed out to 2 Abell radii. This result has raised the question whether the origin of the HI deficiency in the cluster outskirts can be consistent with the ram pressure scenario and whether can be simply due to effects such as large distance errors or rebounding at large clustercentric distances of galaxies that have gone through the cluster center (Balogh, Navarro & Morris 2000, Mamon et al. 2004, Moore et al. 2004, Sanchis et al. 2004).
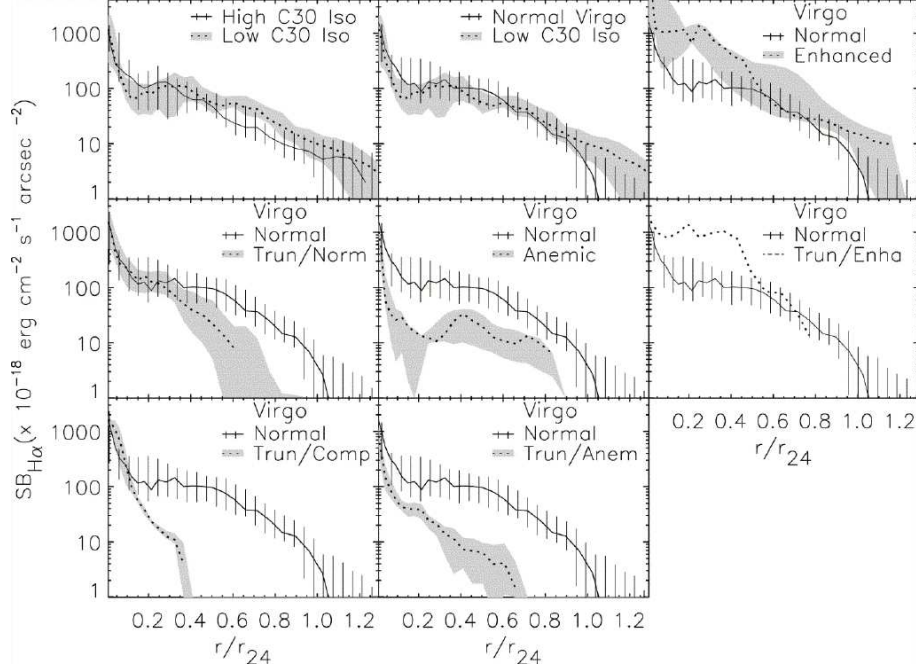
Figure 3. From Koopmann & Kenney 2004. Median Hα radial profiles for galaxies grouped in different classes according to their Hα distribution. The first two panels show profiles that can be considered "normal" (reproduced also in other panels). Truncated, anemic, enhanced classes are shown in all the other panels.

Recent works have yielded a census of the spatial distribution of the star formation (as observed in Hα emission) within cluster galaxies. These works have shown that the majority of the cluster galaxies have peculiar Hα morphologies, compared to field galaxies (Moss & Whittle 1993, 2000, Koopmann & Kenney 2004, Vogt et al. 2004). More than half of the spirals in the Virgo cluster, for example, have Hα radial profiles truncated from a certain radius on, while others have Hα suppressed throughout the disk, and in some cases, enhanced (Fig. 3) (Koopmann & Kenney 2004). On a sample of 18 nearby clusters, similar classes of objects are observed: spirals with truncated Hα emission and HI gas on the leading edge of the disk; spirals stripped of their HI with their star formation confined to the inner regions; and quenched spirals, in which the star formation is suppressed throughout the disk (Vogt et al. 2004). From these works, gas stripping appears a very important factor in determining both the gas content and the star formation activity of cluster spirals, though tidal effects are also found to be significant (Moss & Whittle 2000, Koopmann & Kenney 2004). Spirals in clusters thus appear to be heavily affected by the en-

vironment, and to be observed in different stages of their likely transformation from infalling star-forming spirals to cluster S0s.

It is apparently hard to reconcile the peculiar Hα morphologies of spirals in nearby clusters with the fact that the distribution of Hα equivalent widths (EWs) for blue galaxies in the 2dF and Sloan does not seem to vary significantly in clusters, groups and field (Fig. 9 in Balogh et al. 2004). This apparent contradiction still awaits an explanation.

4.   Trends with galaxy mass and downsizing effect

How do the results described above depend on the galaxy mass? Does the environmental dependence of galaxy properties change with galaxy mass?

It has always been known that fainter, lower mass galaxies on average are bluer than higher mass galaxies, and on average have more active star formation. The references to old and new papers showing this could easily fill this review.

Recently, the interest in this well established observational result has grown, and its implications have been more and more appreciated. In *all* environments, lower mass galaxies have on average a more protracted star formation history. This implies that, on average, going to lower redshifts, the maximum luminosity/mass of galaxies with significant star formation activity progressively decreases. This "downsizing effect", observed in and outside of clusters, indicates an "anti-hierachical" history for the star formation in galaxies, which parallels a similar effect observed for AGNs (Cristiani et al. 2004, Shankar et al. 2004). The downsizing effect is thus another effect *besides* any environmental effect (see e.g. Fig. 4, and Kauffmann et al. 2003, 2004), and the dependence on the galaxy mass/luminosity cannot be ignored when trying to trace evolutionary effects.

In clusters, innumerable results have shown the existence of a downsizing effect (Smail et al. 1998, Gavazzi et al. 2002, De Propris et al. 2003, Tran et al. 2003, De Lucia et al. 2004, Kodama et al. 2004, Poggianti et al. 2004, to name a few). A direct observation of this effect at high redshift is shown in Fig. 5 and illustrates the consequence of downsizing on the characteristics of the color-magnitude red sequence in clusters. A deficiency of faint red galaxies is observed compared to Coma in all four clusters studied, despite of the variety of cluster properties. The red luminous galaxies are already in place on the red sequence at $z \sim 0.8$, while a significant fraction of the faint galaxies must have stopped forming stars and, consequently, moved on to the red sequence at lower redshifts.
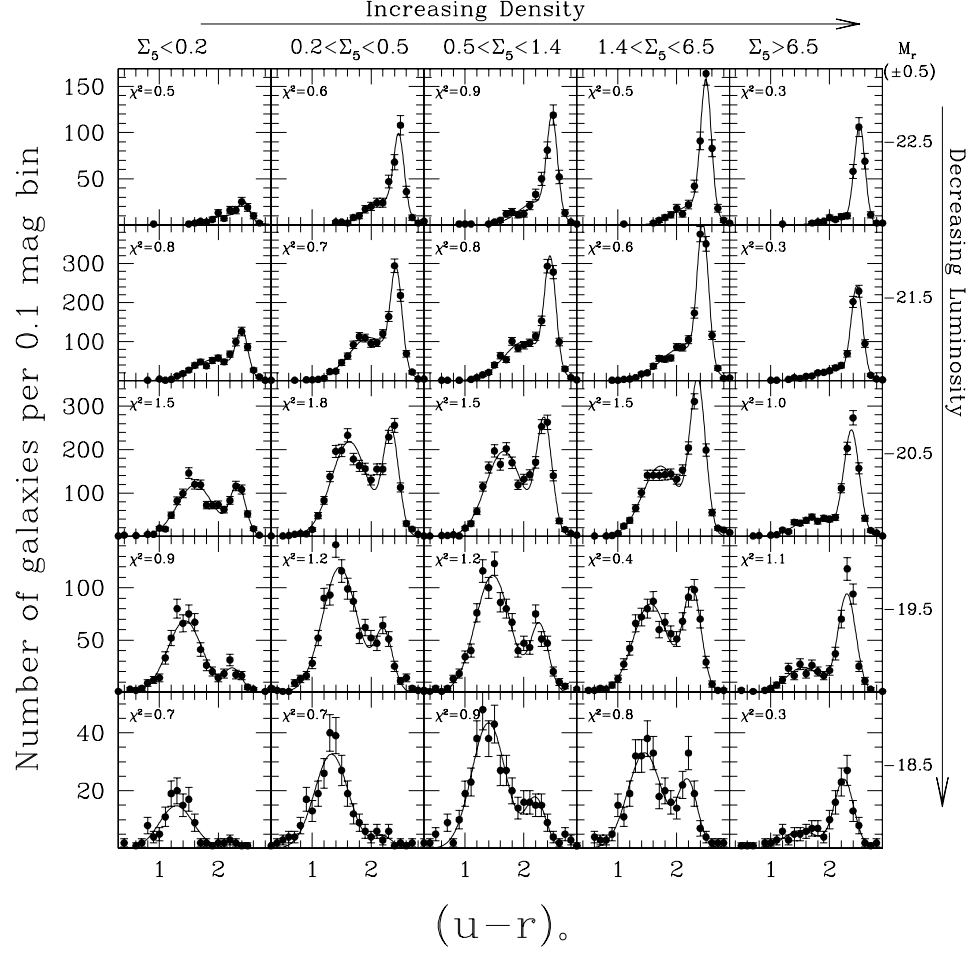
Figure 4. From Balogh et al. 2004b. Galaxy color distribution from Sloan as a function of luminosity and local density.

5. Conclusions and speculations

A number of important issues have not been considered here due to page limits, but should be included in any complete review of emission-line galaxies in clusters, in particular: a description of the IR and radio-continuum studies, the Tully-Fisher relation of cluster versus field spirals, the spatial distribution and kinematics of various types of galaxies, the link between the star-formation activity and cluster substructure, the luminosity function of emission– and
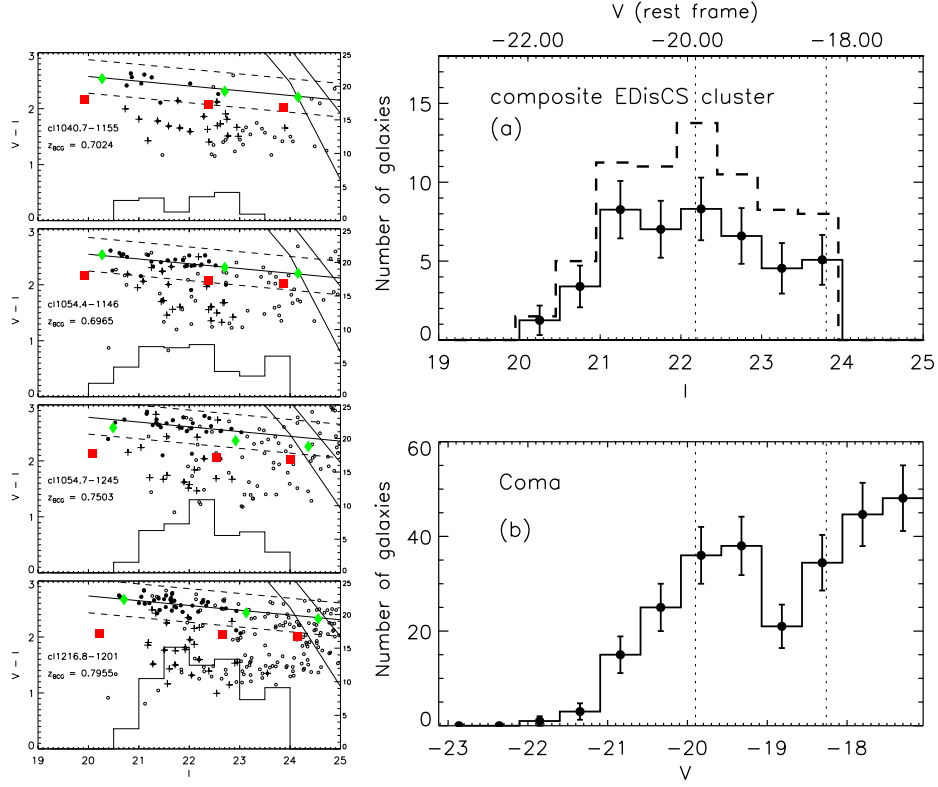
Figure 5. From De Lucia et al. 2004. *Left.* Color-magnitude diagrams of four clusters at $z = 0.7 - 0.8$ from the ESO Distant Cluster Survey. Histograms represent the magnitude distribution of galaxies within 3σ from the red sequence. *Right.* The magnitude distribution of red sequence galaxies at $z \sim 0.75$ (top) is compared with the one of red galaxies in the Coma cluster (bottom). High-z clusters exhibit a clear deficit of low-luminosity passive red galaxies compared to Coma and other nearby clusters.

non–emission line galaxies as a function of the environment, and the line emission from AGNs.

By now, mostly thanks to the scientific debate of the latest years, it is widespread wisdom that we are investigating a three-dimensional space, whose axis are redshift, environment and galaxy mass. In fact, the evolutionary histories and, in particular, the star formation activity of galaxies have similar (increasing) trends as a function of (higher) redshift, (lower) galaxy mass and (lower) density/mass of the environment. While observationally we are beginning to fill this 3-parameter space, the great theoretical challenge is to help comprehend from a physical point of view why this is the history of our Universe.

The results mentioned above do not yet match together into one, coherent picture, and in some cases they might be apparently clashing with each other. The observational results in distant clusters, both those regarding the star formation activity and the morphologies, point to a strong evolution. Many galaxies have stopped forming stars in clusters quite recently, and the morphology of many disk galaxies must have changed. Dense environments seem to accelerate the transformation of star-forming late-type galaxies into passive early-type galaxies. The local large redshift surveys have highlighted the existence of trends of galaxy properties with local density that exist in all environments. This, as well as several other lines of evidence, suggests that whatever induces the existence of a morphology-density and of a star-formation-density relation is not effective *solely* in clusters. On the other hand, there is now solid evidence (and the gas/star formation results in nearby clusters are most convincing in this respect) that gas stripping is at work and affects *most* of the emission-line galaxies in clusters, (or, at least, most of those galaxies in clusters that today still have emission lines).

Twenty years ago, an expression often used in this field was "nature or nurture?". Nowadays, especially within the context of a hierarchically growing Universe, the distinction between nature and nurture has become very subtle, also from a philosophical point of view.

The example of the most massive ellipticals is instructive in this respect. They are found in the cluster cores, and the current cosmological paradigm tells us that they were in the highest density peaks of the primordial fluctuations, thus have always been in the highest density regions, since very high redshifts. Therefore, at least "part" of the morphology-density relation (and of the star-formation density (SFD) relation, since their stars all formed very early on) must have been in place at $z > 3$. Is it more correct to call this a "primordial effect" – because established at very high redshift – or "environmental" – because related to the local density of the environment? but the environment of these ellipticals at $z = 10$ is strongly related to their environment today: can we speak of "galaxy destiny"??

On the other hand, we know that the morphology-density relation in clusters has evolved with redshift, at least as far as the disk galaxies are concerned, and we can directly observe its evolution. Therefore, we know that while the existence of *a* morphology-density relation can be traced back to the first epoch of galaxy formation, its evolution, and thus its exact shape at any time, depends on the subsequent evolution, likely strongly influenced by the environment. Is the *existence* of the MD (and SFD) relation primordial, and its *evolution* environmental?

Perhaps also we, as behavioural psychologists (Ridley, 2003), are coming to realize that nature and nurture are so intertwined that they become, to a certain extent, indistiguishable and unseparable.

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Acknowledgments

Notes

1. In the following, any contribution to the emission originating from an eventual AGN will be disregarded.

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