Color, spectral and morphological transformations of galaxies in clusters

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Abstract. In this review I focus on the galactic properties in clusters at $z > 0.1-02$. The most salient results regarding the evolution in galaxy colors, spectral features and morphologies are discussed.

1. Blue galaxies: the Butcher-Oemler effect

The Butcher-Oemler effect is the excess of galaxies bluer than the color-magnitude sequence (where most ellipticals/passive galaxies lie) in clusters at $z > 0.1-0.2$ as compared to the richest nearby clusters [1]. Butcher and Oemler were well aware that the fraction of blue galaxies depends on a number of things, including the cluster type, the clustercentric radius considered and the galaxy magnitude limit, as discussed below.

Optical versus X-ray cluster selection – The dependence of the blue fraction on the cluster properties is potentially critical, given that selecting different types of clusters at different redshifts could in principle mimic an evolution. For this reason, it is interesting to ask whether optically and X-ray selected samples of clusters reach similar conclusions regarding the Butcher-Oemler effect [2, 3]. Based on the CNOC (Canadian Network for Observational Cosmology) X-ray-selected cluster sample, an evolution of the blue fraction with redshift, very similar to the original Butcher-Oemler result, has been confirmed [4, 5]. Interestingly, the blue fraction shows no simple trend with cluster X-ray luminosity [2, 3, 6], a point I will discuss later.

Richness – How the blue fraction (f_B) depends on cluster richness has been the subject of an extensive study by [7], who found f_B to be higher in poor clusters and lower in rich clusters, and to increase with redshift for all types of clusters. It would be important to verify how f_B depends on richness using a clustercentric radial limit that varies with the cluster scalelength, instead of the fixed metric radius (0.7 Mpc) adopted by this study, because this choice could induce a spurious trend with richness by sampling different areas in rich and poor clusters [6].

Substructure Possibly the most relevant question of all is how the blue fraction, and the star formation activity in general, depend on cluster substructure, i.e. on the merging/accretion history of the cluster. The exact relation between subcluster merging and blue fraction still needs to be quantified, though there is a tendency for clusters with the highest blue fractions to show signs of recent merging events [8, 9, 2, 10]. Based on spectroscopy, there is of course ample evidence for larger fractions of starforming galaxies in substructured than in relaxed clusters. This trend can originate from a higher average SF activity in the smaller (less massive) systems that make up substructured clusters [11, 12], but can also be amplified by starbursts induced by the merger itself [13, 14, 8, 15] as predicted by several theoretical simulations.

Given the dependence of blue fraction on the cluster characteristics, understanding how f_B evolves at $z > 0.5$ is more problematic with the current cluster samples: a very massive cluster at z=0.8 (MS1054-03) has a blue fraction similar to typical values in clusters at z=0.4-0.5 [16], while in other $z \sim 1$ clusters higher fractions approaching 70-80% have been reported [17, 18].

Two aspects are worth highlighting here. First, we should appreciate that fully understanding (at any given redshift) how the galaxy properties depend upon the cluster properties is very useful in order to uncover how environment affects galaxy evolution. Thus, the dependence of the galactic properties on the cluster characteristics is not a "burden" that is in our way when trying to disclose evolutionary effects. On the contrary, it is in a sense the very thing we are looking for.

Second, the lack of simple correlations between the galaxy properties and the cluster most general (easier to observe) characteristics such as the total X-ray luminosity or the optical richness shows that a single global cluster property of this kind is an insufficient information to characterize the cluster status in a useful way for galaxy evolution studies. More detailed pieces of information are needed, including among others quantitative measurements of the cluster mass, of the ICM local density, the knowledge of the dynamical status of the cluster and its history of accretion of other clusters/groups. In this sense, the wavelength criterion for cluster selection (optical versus X-ray) is not useful on its own, because there is no cluster selection method that is immune from the problem of carefully understanding a posteriori, on a cluster-by-cluster basis, what is the cluster status and history.

Great care is required to compare f_B values of different clusters in a meaningful way also because the blue fraction depends on the magnitude limit adopted, on the passband ([6], see also De Propris in these proceedings) and on the clustercentric radius. [5] have shown that when looking only at the central core region (typically ~ 0.5 Mpc), no trend with redshift is observed, while the Butcher-Oemler effect is conspicuous outside of the core. The radial distribution of the blue galaxies and its evolution with z must be related to the infall of field galaxies onto the cluster. The declining infall rate onto clusters at lower z is likely to play an important role in the Butcher-Oemler effect, together with the evolution of the average star formation rate in the field galaxies and the decline of star formation in cluster galaxies [5, 4]. The Butcher-Oemler effect and the fact that the galaxy populations in clusters evolve significantly during the last Gyrs are confirmed by the spectroscopic and morphological studies described below. This evolution involves luminous giant galaxies, though probably not the most massive early-type galaxies that populate the top end of the magnitude sequence, as discussed in the next section.

2. Red galaxies: the color-magnitude sequence

There is a general consensus regarding the ages of the stellar populations in early-type cluster galaxies, i.e. in ellipticals and S0s as morphologically-classified from HST images. The slope, zero-point and scatter of their color-magnitude (CM) relation at various redshifts indicate passive evolution of stellar populations that formed at $z > 2$-3, and the CM slope is found to be mostly driven by a mass-metallicity relation ([19, 20, 21, 22, 16], see also [23]). Moreover, well defined CM red sequences in higher redshift clusters ($z \geq 1$) are now being observed (e.g. [24, 25, 26, 27]), and there are hints for a flatter CM sequence at high-z [29, 28] that still needs to be comprehended. The old stellar ages in early-type galaxies are confirmed also by their spectroscopic features (see below, e.g. [30, 31]) and by fundamental-plane, mass-to-light ratio and Mg-σ studies (e.g. [32, 33, 34, 35, 36, 37, 38]), though this latter type of works have been necessarily limited to relatively small numbers of the brightest galaxies.

This homogeneity of histories of early-type galaxies in clusters needs to be contrasted with a number of other results and considerations:

a) The population of early-type galaxies observed in distant clusters does not necessarily comprises *all* the early-type galaxies existing at z=0. Morphological transformations might occur in clusters (see below) and change later-type starforming galaxies into some of the early-type galaxies present in clusters today. Due to this “progenitor bias”, in distant clusters we would be observing only those galaxies that were already assembled as early-type and stopped forming stars at high redshift [32, 20, 39].

b) The blue galaxies observed in distant clusters, responsible for the Butcher-Oemler effect, must largely have “disappeared” (= become red) by z=0. [4] (see also [2]) have shown that the color-magnitude diagram observed at intermediate z (rich of blue galaxies) can be reconciled with the CM diagram of the Coma cluster (with very few luminous blue galaxies) if star formation is halted in the blue galaxies at intermediate redshifts.

c) Related to the previous point, some works at $z \sim 1$ argue for a truncation of the CM sequence [40], as only bright galaxies are found to be in place on the sequence and there is a deficit of fainter red galaxies. This is possibly related to the fact that when star formation is halted in blue Butcher-Oemler galaxies they evolve becoming redder *and* fainter, going to populate the red sequence at magnitudes fainter than the top brightest 1 or 2 magnitudes. Furthermore, a UV-excess has been found in the galaxies on the red sequence as compared to passive evolution models [18, 40].

d) On the color-magnitude sequence, there are also passive spirals at all redshifts ([31] at z=0.5, [41] at z=0.3, [42] in Coma, [43] at z=0.25) and some mergers at z=0.8 [44].

All these findings suggest that the color-magnitude sequence of clusters *today* (except the very brightest end of it) must be composed of a variegated population of galaxies that had a variety of star formation histories. Though probably the mass-metallicity relation remains a main driver of the CM relation, intricate age and metallicity effects must be at work, as also shown by the age-metallicity anticorrelation in passive galaxies found by a number of studies based on spectral indices (see [45] and references therein).

3. Spectroscopy: absorption-line spectra

When the first spectra of galaxies in distant clusters were taken, the biggest surprise was the finding of galaxies with strong Balmer lines in absorption and no emission lines. First recognized and named "E+A" by [46], their spectra were first modeled in detail by [47]. Now known also as "k+a" galaxies, they can be explained if star formation was active in the recent past and was halted at some point during the last 1-1.5 Gyr. The strongest cases (equivalent width EW(Hδ) > 5 Å) require a strong starburst before the truncation of the star formation. A large number of works have found and analyzed k+a spectra in distant clusters [46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 11]. The Mass-to-Light ratios of (the few studied) k+a galaxies appear to be much lower than that of early-type galaxies, and are consistent with them having undergone a recent starburst [33, 34].

In 10 clusters at z=0.4-0.5, the MORPHS collaboration has found the k+a fraction to be significantly larger in clusters than in the field at similar redshifts [56, 31]. These cluster k+a's have mostly spiral morphologies and present a radial distribution within the cluster that is intermediate between the passive and the emission-line galaxy populations. In contrast, [57] interpret their results on the CNOC clusters concluding there is no significant excess of k+a's in the clusters at z=0.3 compared to the field. The difference between the MORPHS and the CNOC results cannot be ascribed to the optical vs X-ray cluster selection: the brightest X-ray clusters in both samples have similar X-ray luminosities, the MORPHS clusters spanning a factor of 17 in X-ray luminosities while the CNOC clusters a factor of 4, but the most X-ray luminous MORPHS clusters tend to be those with the highest k+a fractions. A Principal Component Analysis of the CNOC spectra by [5] finds a Post-Starformation component which again is intermediate in dynamical state and stellar age between the old, passive population and the "field-like" starforming component. This component presents a (small) excess in clusters compared to the field, but the PCA cannot be easily translated into galaxy number fractions and thus be compared with the MORPHS results.

An excess of k+a galaxies in clusters as opposed to the field is a strong evidence for a quenching of star formation in galaxies as a consequence of the cluster environment. The implications of k+a spectra regarding the presence of starburts in clusters at high-z will be discussed in the next section. The fact that k+a's mostly have spiral morphologies indicates that spectrophotometric and morphological evolution are largely decoupled, and suggests that the timescale for morphological transformation must be longer than the k+a timescale (> 1.5 Gyr).

3.1. K+A GALAXIES AT LOW REDSHIFT

The occurrence of k+a galaxies at low z is believed to be low, both in the field (0.1%, [58]) and in clusters [59]. In Coma and other nearby clusters, Balmer strong galaxies have been reported at a "reduced frequency and burst strength"(= weaker Balmer lines) compared to distant clusters ([14, 15, 60] and references therein). It has been suggested that in Coma this Balmer strong galaxies are preferentially associated with the NGC4839 group infalling from South-West [14], and the central concentration of the latest star formation activity seems to support the post-starburst scenario [60]. Recently, in a magnitude-limited new spectroscopic survey of Coma galaxies, we find no k+a galaxy *as luminous as those in distant clusters*, but a significant population of faint k+a's (dwarf galaxies, $M_V > -18.5$), with no preference for the NGC4839 group [61]. This work suggests that, while strong-lined k+a spectra in luminous galaxies appear to be an important phenomenon in distant clusters, in the local Universe the k+a incidence is mostly related with dwarf galaxies.

4. Spectroscopy: emission-line spectra

Emission lines are the most widely used indicators of ongoing star formation in the optical, because their flux is roughly proportional to the current star formation rate. Surprisingly, the evolution with redshift

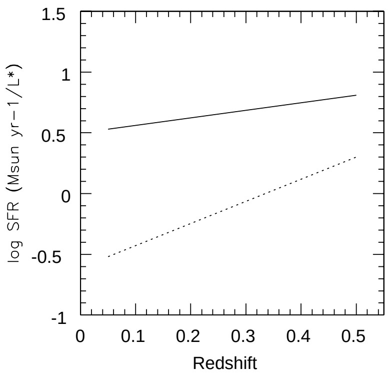

Figure 1. Evolution of the SFR per unit $L_B^\star$ in the field (solid line) and cluster (dotted line).

of the fraction of cluster galaxies with emission lines has not been properly quantified so far, although there is a trend for higher emission line fractions at high z (e.g. [30, 62]). I try to show this graphically in Fig. 1, where I have plotted the SFR per unit $L^\star$ luminosity (as derived from the [OII]3727 line) at z=0.5 and at z=0 for field galaxies (solid line) and cluster galaxies (dotted line). At z=0.5 this is based on the MORPHS cluster and field samples, and at z=0 on the Dressler & Shectman spectroscopic database (Dressler et al. in prep.). The most striking result of this figure is the fact that the evolution in the clusters appears to be *accelerated* with respect to the field, in a similar way as found by [4] on the basis of photometric data. Most works have instead focused on the clustercentric radial behaviour of the emission line properties: the mean EW([OII]) is known to decrease with radius (e.g. [63]). This mean EW is calculated including all galaxies in the clusters (also early-type galaxies) and in principle could be simply explained by the morphology-density relation. However, even *for a given morphological type*, the EW([OII]) distribution appears to be skewed towards lower EWs in the cluster than in the field [56, 64].

A still open and debated question is whether, *before* quenching star formation, the cluster environment produces also a star formation enhancement in the infalling galaxies. Evidence for this enhancement arises from the strong k+a cases, whose spectra can only be explained as post-starburst galaxies. Considering that these strong-lined case must be the youngest (observed relatively soon after truncation), and that soon they will evolve into k+a's with more moderate line strength, the fraction of post-starburst galaxies among k+a spectra is necessarily high. In principle, the starbursting progenitors of these post-starburst galaxies could simply be field starburst galaxies that have infallen into the clusters and had their star formation terminated. Whether the starbursts in the field population are sufficient to account for the k+a population observed in distant clusters is an issue requiring further study (Dressler et al. in prep.). Examples of cluster-induced starbursts have been observed in nearby clusters, where it is easier to study the star formation signatures in great detail.

No need for a star formation enhancement in clusters is found instead by looking at the [OII] or Hα equivalent width distributions in clusters versus field and as a function of radius: no excess of emission line galaxies (as fractions of total number of galaxies) is observed, as well as no tail at high EWs (e.g. [63, 41]). However, eventual cluster-induced starbursts might have gone undetected by this kind of analysis for at least three reasons: a) a possibly short burst timescale; b) if the end-effect of the cluster is to quench star formation, the fraction of emission-line galaxies detected does not say anything about the amount of star formation ongoing in the (still) currently starforming galaxies, and c) dust could moderate the line emission, and it is expected to do so especially in those galaxies with the highest star formation rates.

4.1. The role of dust

There are several lines of evidence indicating the importance of dust extinction in galaxies in distant clusters. In the local Universe, galaxies with very strong emission lines are usually *faint* very late-type galaxies (Sd, Irr), while massive and luminous starburst galaxies in most cases show a combination of strong early Balmer lines in absorption and weak-to-moderate [OII] emission ([65] and references therein). These spectral features are easily understood and reproduced by spectrophotometric models in which younger stars suffer a higher dust extinction than older stellar populations, as can be reasonably expected [31, 66, 67, 68]. Hence, searching for very strong emission lines `is not` an efficient method to identify starbursts with high SFRs.

Spectra resembling those of local massive starbursts with high dust extinction have been found in a significant fraction (~ 10 %) of both cluster and field galaxies at $z = 0.5$ [31]. Furthermore, the Hα line in emission has been detected in some otherwise k+a or passive spectra, again suggesting that the [OII] line in the blue might not have been detected due to dust obscuration [69, 70].

Additional evidence that SFRs can be strongly underestimated in the optical comes from studies at dust-free wavelengths: radio continuum emission has been detected in some of the strongest (=youngest) k+a galaxies at z=0.4 [71] and some optically passive galaxies in low redshift clusters [70], suggesting they are undergoing a current star formation activity that is invisible in the optical. Mid-IR estimates of the SFR in star-forming galaxies in a cluster at z=0.2 lead to values a factor 10 to 100 higher than those based on the [OII] line [72], while standard dust corrections usually adopted only account for a factor 2.5.

5. Morphologies

Before HST, a few ground-based studies provided hints that the galaxies responsible for the Butcher-Oemler effect are prevalently spirals with disturbed morphologies, and/or mergers [73, 74]. Already the first HST images proved that indeed distant clusters contain a large number of spirals, many of which are disturbed [75, 76, 77, 78, 79, 55]. Moreover, in the MORPHS clusters, the high spiral fraction corresponds to a low S0 fraction suggesting that a significant fraction of the spirals evolve into at least some of the S0s that dominate rich clusters today ([78], also [94]). This result has been questioned by other studies [80, 81], but at least part of the discrepancy might be ascribed to the fact that these works have focused on the number ratio of S0 to elliptical galaxies. This latter quantity, more prone to errors than the simple fractions of each morphological type, has been found to be highly dependent on the cluster characteristics, in particular on the central concentration of ellipticals in the clusters [83]. When considering separately the E, S0 and spiral fractions as a function of redshifts, studies at z=0.1-0.25 confirm the trend of evolution of S0s [83]. Also if the overall early-type fraction (E+S0) is examined, a strong evolution with redshift is found [16, 82] with high redshift clusters being composed of a much larger fraction of late type galaxies.

Signatures for quite recent star formation in S0 galaxies consistent with a transformation from spirals have been detected in several clusters, while such activity is found to be absent in ellipticals ([84, 85, 86, 87, 88], see also Katgert in these proceedings). However, not all studies find a difference among the stellar population ages of S0s and ellipticals (e.g. [19, 89, 38]). A possible explanation for the discrepant results are the magnitude limits of the various studies, since most of the S0s with recent star formation avoid the top end of the luminosity function, as expected evolving the luminosities of typical star-forming spirals at intermediate redshifts [86].

Interestingly, cosmological high-resolution simulations are able to account for the morphology-density relation of ellipticals, but they fail to reproduce the properties of the S0s, as if some additional mechanism for S0 formation, not currently included in the models, might be required [90, 91].

Finally, [44] argue for an unexpectedly large fraction of mergers in a cluster at z=0.8. Since most of these pairs have red colors, we might be witnessing the formation of ellipticals through the merging of galaxies whose stars formed at high z, as expected in hierarchical models of structure formation.

Due to space limitations, I am forced to omit in these proceedings the discussion of the morphology-density relation [78, 83, 84, 92], and of the "star formation-density" relation [93, 94].

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