Environment Shaping Galaxies: Star Formation Histories of Cluster Galaxies

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Abstract. In this paper I present some recent and new results regarding the effects of the cluster environment on the star formation history of galaxies. Three main aspects are discussed: the differences in the stellar population ages of cluster ellipticals and S0 galaxies; the comparison of the spectroscopic properties of galaxies in distant clusters and in Coma; and the incidence and properties of faint post-starburst/post-starforming galaxies in the Coma cluster.

1. Introduction

In the quest for understanding how galaxy evolution is affected by environmental processes, galaxy optical spectra provide precious informations regarding the evolutionary histories and stellar population content of galaxies. Here I summarize some of the latest results obtained from spectroscopy of cluster galaxies, both at low and high redshift.

2. Lenticular galaxies

Lenticular (S0) galaxies are a key component in clusters, being very numerous and sometimes the most numerous of all Hubble types in rich clusters today. Already more than 20 years ago it was suggested that S0 galaxies could evolve from spirals that lost their gas supply. The hypothesis of a spiral origin for a significant fraction of the cluster S0’s has received strong support from HST studies of clusters at z=0.4-0.5 (Dressler et al. 1997) and ground-based studies at z=0.1-0.2 (Fasano et al. 2000): these works find the proportion of spirals to increase and the incidence of S0s to decrease at higher redshifts.

Based on this, one might expect to observe in cluster S0’s some (weak) residual signs of their past history as spirals. Perhaps the most obvious evidence to seek is the presence of relatively young (as compared to ellipticals) stellar populations. We have investigated the ages of stars in ellipticals and S0 galaxies in the Coma cluster (Poggianti et al. 2001b), deriving luminosity-weighted ages and metallicities from spectroscopic index-index diagrams (Fig. 1). The main result is that more than 40% of the S0s have undergone star formation during the last ~ 5 Gyr, while such activity is absent in the ellipticals.

A similar conclusion was reached in the Fornax cluster (Kuntschner & Davies 1998) and in Abell 2218 (Smail et al. 2001), but other studies had failed
to detect any difference between the ages of Es and S0s. A possible explanation for the discordant results of different studies could be the galaxy luminosity range explored. In our Coma sample the fraction of S0 galaxies with recent star formation is higher at fainter magnitudes, and their quite faint luminosities are consistent with them being the descendants of typical star-forming spirals at intermediate redshifts. In contrast, the brightest S0's seem to have had their latest star formation episode at higher redshifts, and possibly have formed by some other mechanism, therefore any study limited to very luminous galaxies might have missed the bulk of the population with spiral-origins. The most straightforward way to test this would be to study the S0 luminosity function in the field and in the clusters, at low and high-z.

3. Galaxy spectra: distant clusters versus Coma

Additional evidence that starforming galaxies are progressively transformed into passive ones in clusters comes from the spectra of distant cluster galaxies. When the first spectra of distant cluster galaxies were taken (e.g. Dressler & Gunn 1983, Couch & Sharples 1987, Fabricant et al. 1991), it came as a surprise that many of these spectra displayed unusually strong Balmer lines in absorption, and no emission lines. This type of spectra, named “k+a” or “E+A” spectra, indicate that star formation has recently ceased in these galaxies (during the last 1-1.5 Gyr). Those with the strongest Balmer lines require a starburst before the quenching of star formation, and therefore are usually referred to as “post-starburst galaxies”. The incidence of k+a spectra among cluster galaxies at z=0.4 appears to be much higher than in field galaxies at similar redshifts (Dressler et al. 1999) and the majority of k+a spectra belong to galaxies classified as spirals on the basis of their morphology in HST images (Poggianti et al. 1999). The differences in the strength of the Hδ and of the other Balmer lines in k+a spectra as opposed to spectra of passive galaxies are shown in Fig. 2, where cluster galaxy spectra at z=0.5 with 3 < Hδ < 8 Å and Hδ < 3 Å have been separately coadded (Dressler et al. 2002).

In the following I am going to show a comparison between the spectral types of distant cluster galaxies and those of Coma galaxies of similar absolute magnitudes. The Coma dataset is a spectroscopic survey of a magnitude limited sample with essentially no additional color or morphological selection criteria (Mobasher et al. 2001, Poggianti et al. 2002). The distant dataset is the spectroscopic catalog of the MORPHS collaboration (Dressler et al. 1999), that includes 10 rich clusters at z=0.4-0.5 with a wide range of properties, such as concentration, optical and X-ray luminosity. In Table 1 we present the spectral properties of Coma galaxies, of the whole MORPHS sample and, separately, of the two MORPHS clusters whose X-ray luminosities more closely resemble Coma.

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1 The X-ray luminosity of Coma (corresponding to $L_X \sim 9.5 \times 10^{44}$ erg s$^{-1}$ when observed at $z=0.5$ at 0.3-3.5 keV) lies in between that of Cl0016+16 ($L_X \sim 11.8 \times 10^{44}$ erg s$^{-1}$, 0.3-3.5 keV) and that of 3C 295 ($L_X \sim 6.4 \times 10^{44}$ erg s$^{-1}$, 0.3-3.5 keV)
Figure 1. $\text{H} \beta$ versus $\text{Mg}_2$ index strength for ellipticals (empty circles) and S0 galaxies (filled circles) in Coma (Poggianti et al. 2001b). Overplotted are spectrophotometric models of single stellar populations of different ages and metallicities as labelled (see paper for details).
Figure 2. Coadded spectra of cluster galaxies at $z=0.5$: passive galaxies (top, $EW(H\delta) < 3\, \text{Å}$) and k+a galaxies (bottom, $3 < EW(H\delta) < 8\, \text{Å}$. The Balmer lines (from left $H\theta$, $H\eta$, $H\zeta$, $H\epsilon$, $H\delta$, $H\gamma$, $H\beta$) are highlighted by the dashed lines.
The most striking difference in Table 1 is the lack of bright k+a galaxies in Coma. Moreover, there is a tendency for emission-line galaxies to be less common in Coma. Choosing to compare only with clusters of similar X-ray luminosities enhances the difference between the k+a population at \( z = 0.5 \) and at \( z = 0 \), and attenuates the difference in the emission-line population.

Table 1. Comparison between Coma1 and clusters at \( z = 0.5 \)^a

| Class          | MORPHS^b | Cl 0016+16 | 3C 295 | Coma1 |
|----------------|----------|------------|--------|-------|
| passive (k)    | 51.1%    | 56.2%      | 55.8%  | 90.6% |
| k+a/a+k        | 22.4%    | 32.7%      | 29.5%  | 0%    |
| emission       | 26.5%    | 11.1%      | 14.7%  | 9.4%  |
| \( N \)        | 390      | 29         | 25     | 32    |

^a The data refer to the inner 1.4 Mpc and to \( M_V < -19.8 \) in all clusters.

^b All MORPHS clusters.

3.1. Emission lines: an interesting but incomplete view

For distant galaxies the most commonly used indicator of current star formation activity is the [O\textsc{ii}]3727 line, whose flux is expected to be roughly proportional to the present star formation rate of a galaxy.

Based on the [O\textsc{ii}]3727 line of clusters and field galaxies in the MORPHS spectroscopic catalog, complemented by a sample of nearby galaxies (Dressler et al. 2002), we have computed the SFR per unit B-band luminosity at \( z = 0.5 \) and \( z = 0 \), in clusters and in the field, with the following results:

\[
\begin{align*}
  z = 0.5 & \quad \frac{SFR}{L_B}(field) = 3 \times \frac{SFR}{L_B}(clusters) \\
  z = 0.0 & \quad \frac{SFR}{L_B}(field) = 10 \times \frac{SFR}{L_B}(clusters)
\end{align*}
\]

Thus, the difference between the field and the clusters is a factor of 3 more pronounced in the local Universe than at \( z = 0.5 \). Furthermore,

\[
\begin{align*}
  \text{clusters} & \quad \frac{SFR}{L_B}(z = 0.5) = 6 \times \frac{SFR}{L_B}(z = 0.0) \\
  \text{field} & \quad \frac{SFR}{L_B}(z = 0.5) = 2 \times \frac{SFR}{L_B}(z = 0.0)
\end{align*}
\]

i.e., the evolution of the SFR per unit luminosity, as derived from the [O\textsc{ii}] line, has been steeper in clusters than in the field during the last 5 Gyrs, as if the cluster environment has somehow “accelerated” the evolution towards more passive, earlier-type galaxies. These results should be always considered remembering that:

a) a lower SFR ([O\textsc{ii}] flux) per unit luminosity in the clusters does not rule out that a SF enhancement could take place in some or all cluster galaxies prior to the final quenching of star formation;
b) dust effects are ignored in these calculations, and the amount of star formation hidden by dust is unknown. It is important to keep in mind that starburst galaxies with very high SFR in the local Universe are characterized by spectra with weak to moderate emission lines, because generally the higher the SFR, the higher the dust extinction and the fraction of SF hidden.

If dust affected cluster galaxies differently than field galaxies, for example due to an environmentally-induced star formation enhancement, then the comparison field-cluster shown above would be misleading. If, instead, dust effects played the same role in all environments at a given redshift, the relative comparison field-cluster would be meaningful. The evidence of important dust effects in distant cluster galaxies has been highlighted by the first radio continuum (Smail et al. 1999) and mid-IR (Duc et al. 2002) studies.

4. Fainter galaxies

Any comparison with the distant cluster data is inevitably limited to the brightest end of the galaxy luminosity function, while in nearby clusters it is possible to study also fainter galaxies. In Coma, our spectroscopic survey extends over more than 6 magnitudes down to $M_B \sim -14$.

In the previous section I have discussed the fact that Coma lacks the population of luminous k+a galaxies that is present in clusters at $z=0.4$. Strikingly, very clear examples of k+a spectra are found instead among the faint Coma galaxies, as shown in Fig. 3 (Poggianti et al. 2002). We show here a sample of k+a’s with a range of Hβ strengths, from very strong, post-starburst galaxies (#1 and #4) to weaker cases (#6 and #7). Balmer-strong spectra of Coma galaxies have been previously reported in a number of works by Caldwell, Rose and collaborators (e.g. Rose et al. 2001 and references therein).

Coma k+a’s in our sample are typically fainter than $M_V \sim -18.5$ (Fig. 4) and constitute a significant fraction (10-15 %) of the dwarf galaxy population at $M_B > -17$. Why are k+a’s in clusters a luminous phenomenon at $z=0.5$, and a faint phenomenon at $z=0$? Is this due to a “cosmic evolution” (i.e. the changes in field galaxies + the hierarchical history of clusters), or to an evolution with z of the processes affecting galaxies in clusters? The former possibility is probably more likely. In fact, when studying the luminosity-weighted ages of all Coma galaxies with no emission lines in our sample we find systematic trends of age with galaxy luminosity. Fig. 5 shows what proportion of currently-passive Coma galaxies of a given magnitude experienced the latest star formation during the last 3 Gyr, between 3 and 9 Gyr ago and more than 9 Gyr ago. The age of the latest star formation episode was derived from index-index diagrams similar to Fig. 1, as described in Poggianti et al. 2001a.

About half of all galaxies of any luminosity do not show signs of significant star formation activity in the last 9 Gyr, i.e. since $z=1.4$ in a Λ cosmology. Among the bright, currently passive galaxies, the fraction that experienced a star formation activity between 3 and 9 Gyr ago $(0.25 < z < 1.4)$ is much higher than the fraction with SF during the last 3 Gyr (since $z = 0.25$), while the opposite is true for the faint galaxy population. This seems to point to a “downsizing effect” suggesting that the last star formation activity (possibly related to the epoch of accretion onto the cluster) occurs on average at lower redshifts for progressively
fainter galaxies. In this scenario, the galactic properties become a probe of the cluster accretion history of field starforming galaxies.

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Figure 3. Spectra of faint k+a galaxies in Coma. The Balmer lines (from left Hθ, Hη, Hζ, Hε, Hδ, Hγ, Hβ) are highlighted by the dashed lines.
Figure 4. Magnitude distribution (top) and color-magnitude diagram (bottom) of galaxies in the center (Coma1) and South-West region (Coma3) of Coma. The dotted line shows the magnitude limit corresponding to the MORPHS limit. The dashed line is the adopted magnitude division between “giants” and “dwarfs”. Total histogram = all. Dashed histogram = k+a’s. Shaded histogram = emission-line galaxies. The corresponding absolute V band magnitude scale is shown on top of the plot.
Figure 5. Fraction of young (filled dots, age < 3 Gyr), intermediate-age (crosses, 3 to 9 Gyr) and old (empty dots, age > 9 Gyr) Coma1 galaxies within each R magnitude bin as derived from the Hβ/Mg2 diagram (left) and the HγF/<Fe> diagram (right). The errorbars are Poissonian.