CLUSTER EVOLUTION SINCE $z \sim 1$

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Abstract. We have used the Advanced Camera for Surveys (ACS) on the HST to obtain optical imaging of a sample of 8 galaxy clusters in the redshift range $0.8 < z < 1.3$. The ACS data provides accurate photometry and the ACS high angular resolution makes it possible to obtain crucial morphological information of the cluster galaxy populations. These data are supported by X-ray observations and by ground based imaging and multi-object spectroscopy. We will present results from this multi-wavelength study which is providing a comprehensive view of the evolution of structures in the universe since $z \sim 1$. The structure of the ICM, galaxy and DM components of the clusters are presented and compared. The spectrophotometric properties of cluster galaxies are investigated in the context of galaxy evolution and the formation epoch of massive early-type galaxies in these clusters is estimated to be at $z > 2$. We will also present results from our study of the evolution of the Morphology-Density relation in clusters since $z \sim 1$ down to the present day universe. Our cluster evolution studies are also being complemented by observations of protoclusters at redshift $z \gtrsim 2$.

1 Introduction

A major fraction of the galaxies in the present universe are found isolated in the field. Only about 5% of the galaxies in the local universe belong to gravitationally bound structures such as small groups and clusters of galaxies. Cluster and field environments can affect galaxies in different ways, therefore, a detailed studied of galaxy properties in clusters and in the field is crucial to understand galaxy evolution.

In this respect, clusters of galaxies are ideal laboratories to investigate the influence of high density regions on galaxy properties such as morphology, color and star-forming activity. In addition, the study of the structure of the different components of clusters, baryons and dark matter (DM), allows us to characterize the dynamical state of the cluster and to better understand the assemblage of large scale structures in the universe. In massive clusters, baryons (galaxies and gas) accumulate in the potential well created by the cluster DM halo. In such an environment, galaxy properties can be affected by interactions between galaxies and the surrounding intracluster medium (ICM), however the details of the physical mechanisms operating in such interactions are still not well understood.

Galaxy clusters are hosts of the most massive and oldest early-type galaxies known in the universe. Determining their epoch of formation and understanding their evolution, as well as that of the other cluster galaxy populations, is one of the major tasks in modern cosmology. Such an evolutionary study demands the study of galaxy properties up to redshifts $z \sim 1$. The well defined color-magnitude relation (CMR) in clusters has been investigated to estimate the age and mode of formation of massive cluster early-type galaxies up to $z \sim 1$ [3, 17]. The results drawn from these studies indicate that massive cluster elliptical galaxies are formed at high redshift ($z > 2$), in agreement with studies of red objects in the field at $z > 1$ [5, 6, 24].

However, the major problem in any study of galaxy properties in high density environments at high redshift is to actually find those high density regions. To date, only a few high redshift clusters at $z \gtrsim 1$ have been spectroscopically confirmed (see [21], and references therein). Beyond $z = 1.4$ and below $z \sim 2$ there are no confirmed galaxy clusters. This redshift interval is of great importance since it is in this epoch when aggregations of matter are expected to start virializing to form X-ray luminous ICMs. Some of these regions could be traced by galaxy overdensities physically associated to radio galaxies [2] which are formed at earlier stages in cosmic time. There is clear evidence of the existence of such early structures, the so called proto-clusters [31, 20, 27, 22].

Table 1: ACS intermediate redshift cluster sample.

Cluster	Redshift	$\sigma_v (km/s)$	L_x (10^{44} erg/s)	ACS filters	Total HST orbits
MS1054+03	0.83	1112	23.3	V, i, z	20
RXJ0152-1357	0.84	1300	7.8	r, i, z	40
CL1604+4304	0.90	1200	2.0	V, I	4
CL1604+4321	0.92	935	<1.2	V, I	4
RXJ0910+5422	1.10	-	1.5	i, z	8
RDCSJ1252-2927	1.24	755	2.5	i, z	32
RXJ0848+4452	1.26	-	1.0	i, z	24
RXJ0848+4453	1.27	640	1.5	i, z	24

These structures may thus be the progenitors of the massive galaxy clusters we observe in the local universe. Hence, the study of the physical properties of galaxies in these structures should give us a good idea of how galaxies form and evolve in the peaks of the cosmic matter distribution. In particular, some of those galaxies, including radio galaxies, may be the progenitors of massive cluster early-type galaxies [33].

2 The ACS cluster program

In order to address the above issues, in particular the formation of massive early-type galaxies and the effects of the environment on the galaxy populations, we have carried out an ambitious program with the Advanced Camera for Surveys (ACS; [8]) to study galaxy properties in clusters and proto-clusters at 50% of the current age of the universe. The sample of galaxy clusters in our ACS program is composed of 8 rich clusters in the range $0.8 < z < 1.3$ (corresponding to a lookback time between 7 and 9 Gyr). The proto-clusters under study are galaxy overdensities associated with 3 different powerful radio galaxies at $2.2 < z < 5.2$. Moreover, ACS has been used to observe galaxy clusters with strong lensing features at lower redshift [4] and has also allowed us to discover gravitational arcs in clusters at $z \gtrsim 1$. Together with weak lensing studies from ACS data [14, 18], these strong lensing investigations with the ACS are opening the way to map with high accuracy the mass distribution of some of the most distant clusters of galaxies known to date.

The ACS observations were carried out with the Wide Field Camera (WFC) and included imaging in 2 to 3 different bands with the filters of the Sloan Digital Sky Survey (r [F625W], i [F775W] and z [F850LP]). The high angular resolution and quantum efficiency of the ACS make it possible to obtain accurate photometry and unprecedented morphological details of galaxies at redshifts as high as $z \sim 1.3$. The ACS WFC delivers a field of view of $202'' \times 202''$ with a pixel scale of $0.049''$. In several cases, there are multiple pointings available per cluster, with all pointings overlapping the central $1'$ cluster region.

In addition to the ACS guaranteed time observation (GTO) program, a multi-wavelength data set, from X-rays to infrared (IR), including imaging and spectroscopy, has been built to support the ACS data and to provide one of the most complete and comprehensive studies of distant clusters and proto-clusters so far. Space based observations were carried out with Chandra (imaging), Newton-XMM (imaging and spectroscopy) and Spitzer (imaging) while the ground based data were collected with the ESO NTT (imaging), ESO VLT (imaging and spectroscopy) and Keck (imaging and spectroscopy).

A summary of the ACS data available on the eight galaxy clusters is presented in Table 1. In Figure 1 we show ACS color images of the observed intermediate redshift clusters. A more detailed description of the ACS, X-ray and Spectroscopic data is presented in Postman et al. (2005; [23]).

3 Intermediate redshift clusters of galaxies

The large amount and high quality of data gathered during the ACS cluster program makes it possible to study in detail the assembly and evolution of structures in the universe, from cluster scale down to the scale of massive cluster early-type galaxies, during the last 8.7 Gyrs of cosmic history. Extensive redshift surveys of some of the ACS clusters (e.g., [28, 30, 7]) combined with the available X-ray, optical and near-IR data show clear evidence of massive clusters being assembled through major mergers of smaller clusters or groups at $z \sim 0.8$ (e.g., [14, 10]). At redshift greater than unity, clusters show disturbed morphologies in their gas, galaxy and DM distribution (e.g., [18]; Mei et al., ApJ, submitted) suggestive of large scale mergers occuring at a large lookback time. Most of distant clusters would thus be in an unvirialized state, being formed in a hierarchical way through the accretion of smaller units which may also be part of larger scale filaments ([16];Kodama et al., in prep.). Gas and galaxies, trapped in the potential of DM haloes, follow the dynamics of the merger (with the gas being affected by ram pressure) tracing the spatial distribution of the forming massive structure [25, 14, 15].

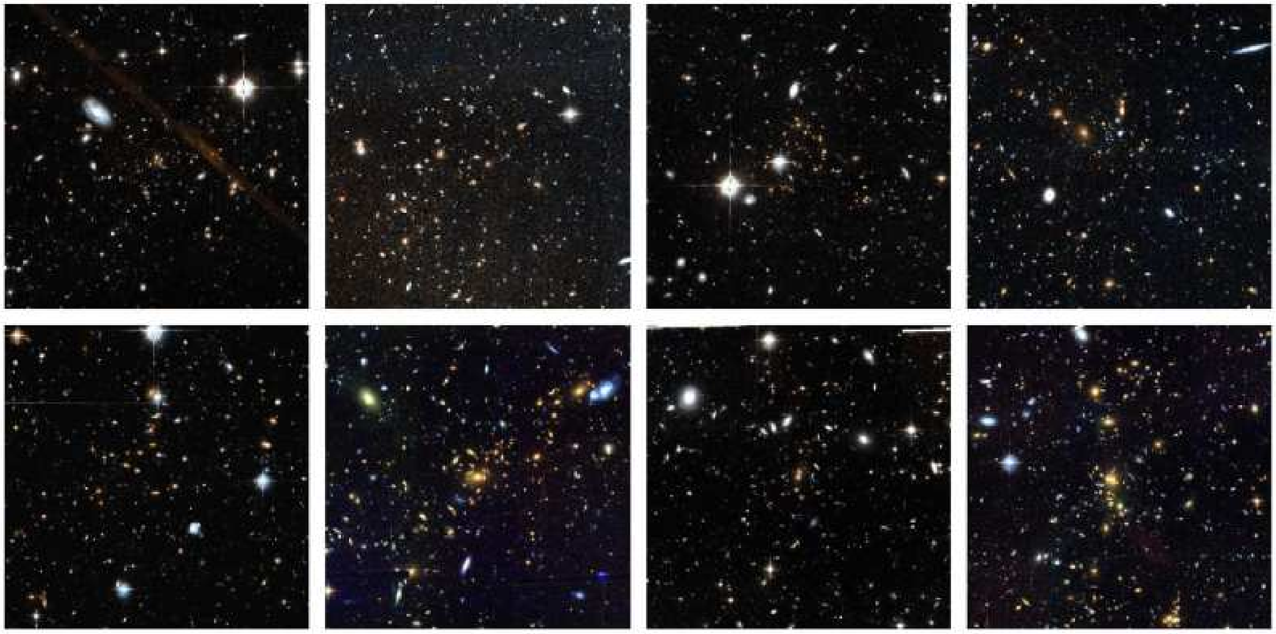

Figure 1: Intermediate redshift clusters observed with the ACS. Top row from left to right: RXJ0848+4452 ($z = 1.26$), RXJ0848+4453 ($z = 1.27$), RXJ0910+5422 ($z = 1.10$) and CL1604+4304 ($z = 0.90$). Bottom row from left to right: CL1604+4321 ($z = 0.92$), MS1054+03 ($z = 0.83$), RDCSJ1252-2927 ($z = 1.24$) and RXJ0152-1357 ($z = 0.84$). All cutouts are $2'$ on a side.

These mergers can continue down to the local universe, as shown by observations of lower redshift and nearby clusters (e.g., [12, 1, 19]).

Identification of the passive and star-forming cluster galaxy populations at $z \sim 1$ shows that the high density regions of clusters are dominated by passive (non star-forming) galaxies, while the star-forming galaxies mostly populate the outer cluster regions. This result, in agreement with the Butcher-Oemler effect, extend to this early epoch the evidence of the existence of such a segregation previously observed in lower redshift clusters (e.g., [9]). In the cluster RXJ0152 ($z = 0.84$) the star-forming galaxy population avoids regions where the X-ray emission is greater than the 3σ level [7]. These observations are consistent with the simple view in which galaxies falling into the central cluster regions get their star-formation activity suppressed due to a galaxy-ICM interaction [13]. However, the details of the physics of such an interaction remain unclear. ACS morphological information shows that while most of the star-forming galaxies are disk or irregular galaxies, there exists a population of compact galaxies with emission ([OII] λ3727) lines ([13]; Rosati et al., in prep.). In RXJ0152, a few star-forming galaxies are as red ($r - i \sim 1.2$; $i - z \sim 0.65$) as massive cluster elliptical galaxies [7, 13], suggesting that these objects (composed of a mixture of old and young stellar populations) may be in a transition stage between late-type and S0 galaxies.

Luminous early-type galaxies are observed to dominate the core of many of these clusters. In some cases, a pair of massive cluster core elliptical galaxies, located close to the X-ray emission centroid, are separated by only a few arcseconds (e.g., [3]). These galaxies are possibly in a pre-merger phase conducive to the formation of a massive cD galaxy. However, RXJ0910 lacks of cD galaxies and any clear evidence of mergers leading to the formation of one ($z \simeq 1.10$; Mei et al., ApJ, submitted). The analysis of the photometric properties of galaxies in the ACS intermediate redshift clusters show that a tight Color-Magnitude Relation (CMR) is already in place at redshift $z = 1.24$ [3]. The slope and scatter of the different CMRs are consistent with passive evolution of early-type galaxies with the bulk of their stars being formed at redshifts $z > 2$. Yet, the spectroscopic data available on the cluster RDCS J1252 ($z = 1.24$; [25]) suggest that most luminous early-type galaxies in this cluster host young (post-starburst) stellar populations [26] produced in recent episodes of star formation at $z \lesssim 2$. A more detailed presentation and an in depth discussion on the CMRs of the ACS clusters is given by Mei et al. (this conference). Different model spectral energy distributions (SED) have also been used to fit the observed colors of cluster early-type galaxies in order to estimate galaxy ages and stellar masses. These results are presented by Rettura et al. (this conference). An extensive morphological classification of galaxies (about 4700) in the ACS cluster sample has been carried out by Postman et al. (2005; [23]). The aim of this effort is to extend previous studies on the evolution of the morphology-density relation from the low redshift universe up to redshift unity. Interesting evolutionary trends are observed suggesting a transformation of late-type galaxies into S0 galaxies from $z \sim 1$ down to $z = 0$ (see [23] and Mei et al. [this conference]).

4 Proto-clusters of galaxies

Distant radio galaxies appear to be good tracers of high density regions in the universe. This is based on the detection of confirmed Ly-α emitter and Lyman break galaxy (LBG) overdensities around radio galaxies at $z > 2$. These candidate overdensities, also called proto-clusters, have also been identified around lower redshift ($z \sim 1.6$) radio galaxies [2]. Our ACS observations concentrated on the fields around three radio galaxies: MRC1138-262 ($z = 2.16$), TNJ1338-1942 ($z = 4.11$) and TNJ0924-2201 ($z = 5.19$). In the case of TNJ1338, the radio galaxy is surrounded by 12 Ly- emitters [31] and an overdensity of ∼50 LBGs (Overzier et al., in prep.) with a significance greater than 4σ. The angular distribution of these objects is highly filamentary with more than half of the objects clustered in a 4.4 arcmin^2 region whose center is occupied by the radio galaxy. The latter itself is a very interesting object. It is the dominant galaxy in the proto-cluster, in terms of size (about 16 kpc in extension) and luminosity, and it is surrounded by an extended (∼ 100 kpc), asymmetric Ly- halo. The ACS optical (rest-frame UV) morphology is characterized by a number of substructures and the observed flux is likely dominated by forming stars. The estimated star-formation rate for the whole radio galaxy is then ∼200 $M_\odot$ yr^{-1} (see [33] for details). These observations strongly suggest that TNJ1338 is destined to evolve into the brightest proto-cluster galaxy and can likely be, therefore, a progenitor of the massive early-type galaxies we observe in local clusters. Likewise, 6 Ly-α emitters have been spectroscopically confirmed to be around TNJ0924 [32], the most distant radio galaxy known to date [29]. Our ACS observations have allowed us to discover 23 LBGs (V_{606}-dropouts at the radio galaxy redshift) around TNJ0924 (Overzier et al., ApJ, submitted). This population, which may be confirmed by future spectroscopic follow-up, may be part of a massive structure in formation already at $z = 5.2$. Compared to TNJ1338, TNJ0924 is about three times smaller and its star formation rate is about 20 times lower (see Overzier et al. [ApJ, submitted] for details).

5 Conclusions

ACS observations are delivering one of the most impressive views of the formation and evolution of structures in the universe since ∼1 Gyr after the Big Bang. Radio galaxies seem to be excellent tracers of forming structures (proto-cluters) in the early ($z > 2$) universe. ACS observations of one of these distant radio galaxies suggest that these objects may be the progenitors of massive early-type galaxies in lower redshift clusters. Giant elliptical galaxies would be formed in major mergers at $z > 2$, with the associated starburst winds producing the ICM. These luminous elliptical galaxies are observed to be anchored in place at $z \sim 1$ in the core of rich galaxy clusters, and their photometric properties indicate a passive evolution of most of their stellar content since their last episode of major star-formation. Late-type galaxies, on the other hand, dominate the outer regions of clusters. There is evidence suggesting that spiral/irregular galaxies in the higer density environment of clusters would be transformed into earlier type galaxies, like S0s, however, the physical mechanisms behind that are still poorly understood. More detailed studies of the evolution of spiral galaxies in clusters are still required. The comparison between such studies and those of spiral galaxies in the field (e.g., [11]; Hammer et al., this conference), together with the present knowledge on early-type galaxies, would provide a comprehensive picture of galaxy evolution as a whole through cosmic time. Finally, the disturbed distribution and kinematics of cluster galaxies, ICM and DM show that massive clusters are assembled in a hierarchical fashion through mergers of multiple clumps since $z \gtrsim 1$. However, more observations are needed in order to bridge the evolutionary gap between the most distant galaxy clusters known and the proto-clusters under study.

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