

Ages and evolution of early-type cluster galaxies at $z \sim 1$ from the ACS intermediate redshift cluster survey

S. Mei, J.P. Blakeslee, R. Demarco, H. Ford, N. Homeier
Dept. of Physics & Astronomy, Johns Hopkins University, Baltimore, MD 21218

B.P. Holden, G.D. Illingworth
Lick Observatory, University of California, Santa Cruz, CA 95064

M. Franx
Leiden Observatory, Postbus 9513, 2300 RA Leiden, Netherlands.

M. Postman
Dept. of Physics & Astronomy, Johns Hopkins University, Baltimore, MD 21218

P. Rosati
European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching, Germany

and the ACS IDT team

Abstract. HST permits the study of high- z cluster galaxies in unprecedented detail and offers a unique opportunity to examine the processes driving galaxy formation. As part of our Advanced Camera for Surveys (ACS) intermediate redshift cluster survey, we have observed 8 galaxy clusters with redshift between 0.8 and 1.3. At these redshifts, galaxy clusters are still assembling and galaxies are evolving towards the populations that we observe today. Recent results from the ACS cluster survey have shown that galaxy clusters at redshift around unity show differences but also many similarities with local clusters, in terms of galaxy populations and their distribution. One of the most striking similarities is that the tight relation between galaxy colors and luminosities that applies to local early-type galaxies (the color-magnitude relation; CMR) is already in place at redshifts as high as $z \sim 1.3$. The very precise measurement of the scatter around the CMRs of our cluster sample permits us to constrain the formation ages of the redder early-type populations to be at $z > 2.5$. We will present our most recent results and discuss them as a function of cluster properties at $z \sim 1$.

1 Introduction

The Advanced Camera for Surveys (ACS; Ford et al. 2002), by virtue of its high resolution and sensitivity, permits us to study galaxy clusters in great detail up to redshifts of unity and beyond. At these redshifts, galaxy clusters are still assembling and galaxies are evolving towards the populations that we observe today.

Our ACS Intermediate Redshift Cluster Survey includes eight clusters, X-ray, optical and near-infrared (near-IR) selected, in the redshift range $0.8 < z < 1.3$ (Ford et al. 2004; see also Demarco paper in this proceedings). Recent results from the ACS Intermediate Redshift Cluster Survey (Blakeslee et al. 2003a; Lidman et al. 2004; Demarco et al. 2005; Goto et al. 2005; Holden et al. 2005a; Holden et al. 2005b; Homeier et al. 2005; Postman et al. 2005) have shown that galaxy clusters at redshift around unity show many similarities with local clusters, in terms of galaxy populations and their spatial distribution, but also significant differences in galaxy morphology, ellipticity, and mass-luminosity ratios. The strongest evolution observed in the early-type population is a deficit of a S0 population in this sample when compared to lower redshift samples (Postman et al. 2005). This would give evidence that the formation of the S0 population is still under way in clusters at redshift unity. One of the most striking similarities is that the tight relation between galaxy colors and luminosities that applies to local early-type galaxies (the color-magnitude relation; CMR) is already in place at redshifts as high as $z \sim 1.3$ (e.g. Stanford et al. 1997; Mullis et al. 2005). The CMR in local samples of galaxy clusters presents universal properties, in terms of scatter and zero point (Bower et al. 1992; van Dokkum et al. 1998, Hogg et al. 2004; López-Cruz et al. 2004; Bell et al. 2004; Bernardi et al. 2005; McIntosh et al. 2005) that evolve back in time in agreement with passively evolving models (Ellis et al. 1997; Stanford, Eisenhardt, & Dickinson 1998; van Dokkum et al. 2000, 2001; Blakeslee et al. 2003; Holden et al. 2004; De Lucia et al. 2004).

In this paper, we summarize some recent results on the morphology-density relation and color-magnitude relation.

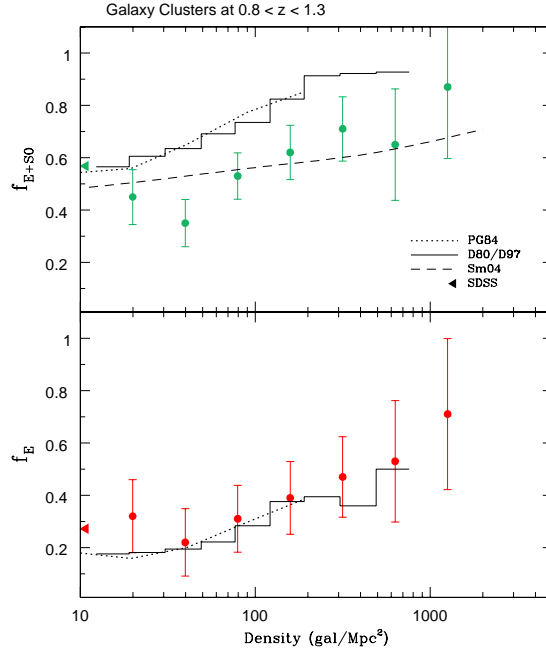


Figure 1: Morphology–density relation from Postman et al. (2005). On the top, we show the total early–type fraction (ellipticals + S0s; top) as a function a galaxy density. Filled circles are data from our ACS Intermediate Redshif Cluster Survey sample at redshift around unity, the dashed line are from Smith et al. (2005) sample at $z \approx 1$. The solid and dotted lines are from local samples, from Dressler (1980) and Dressler et al. (1997) and Postman & Geller 1984, respectively. On the bottom, the elliptical fraction is shown, compared to local samples. While the elliptical fraction remains the same in the local and the redshift around unity samples, the total (E+S0s) fraction decreases with redshift. This implies a deficit of S0s at redshifts around unity.

2 Morphology–density relation

Postman et al. (2005) measured the morphology-density relation (MDR) and morphology-radius relation in seven out of the eight clusters in our ACS Intermediate Cluster Survey (all the them, but RXJ0848+4453). The galaxies were classified according to visual classification using the classical Hubble sequence: ellipticals: E, E/S0; S0s: S0, S0/a; spirals: Sa, Sa/b, Sb, Sb/c, Sc; and irregulars: Irr. The sample was then divided in three broader classes: E, S0s and spirals. Simulations and independent comparisons of our visually derived morphologies indicate that ACS allows one to distinguish between E, S0, and spiral morphologies down to $z_{850}=24$ mag, corresponding to $L = 0.21L^*$ and $L = 0.3L^*$ at $z=0.83$ and 1.24, respectively.

The high ACS resolution and sensitivity permits us to distinguish E from S0s, and compare our sample to local samples to study the MDR evolution. In Fig 1 we show our sample as compared to previous MDR studies at redshift around unity, and to local samples at $z < 0.5$. A clear evolution is observed in the fraction of the S0 and spiral populations as a function of density. When compared to local samples a deficit of S0 and an excess of Sp+Irr galaxies is measured in our sample. The evolution in the MDR is confined to densities of ≈ 40 galaxies Mpc^{-2} , in the external regions of the clusters. The elliptical MDR exhibits no significant evolution between $z=1$ and 0.

This result suggests that: 1) part of the S0 population formed at $z > 1.3$; 2) the formation of the S0 population is still under way in clusters at redshift unity.

3 Color–magnitude relation

ACS enables accurate measurement of the scatter around the color–magnitude relation (CMR), with enough precision to seriously constrain galaxy formation age, which is impossible to obtain from ground–based data (see for example Holden et al. 2004). The measurement of the CMR scatter of the first cluster in our ACS cluster survey, RXJ1252.9-292, permitted us to derive the mean luminosity weighted age of the last epoch of

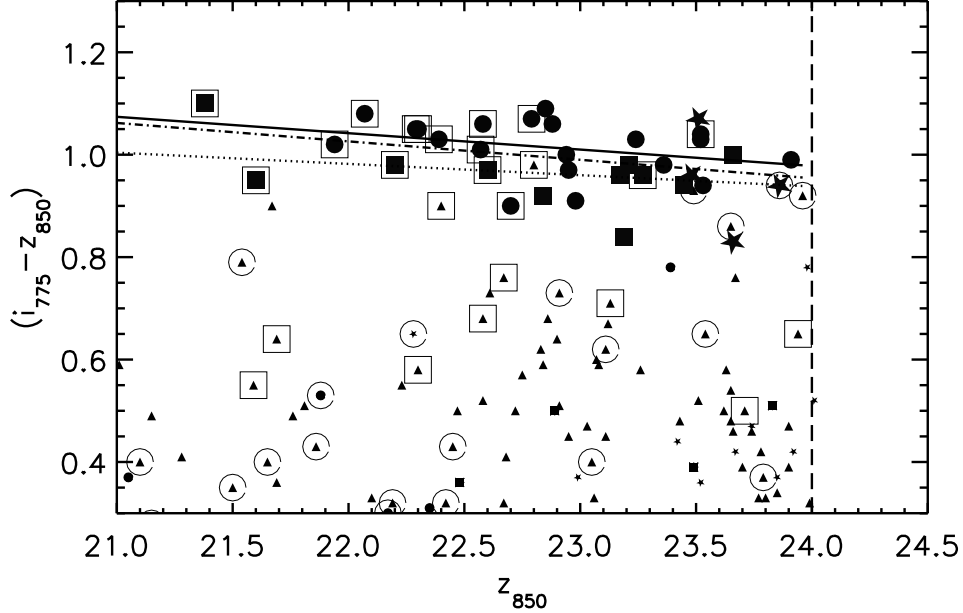


Figure 2: The color-magnitude relations for RXJ J0910+5422. Circles and squares are respectively E and S0 candidates on the red sequence. Stars are S0/a candidates on the sequence. Larger symbols are used for red sequence galaxies. Smaller circles, squares, and stars are used for the corresponding early-type galaxies that do not lie on the red sequence. Small triangles are late-type galaxies. Boxes are plotted around confirmed cluster members. Open circles are plotted around confirmed interlopers. The solid line is the fit to the ellipticals, the dotted line the fit to the S0s, and the dashed-dotted line the fit to the entire sample within $2'$. The green dotted is fitted to the S0s within $1'$. The dashed line is the RXJ1252.9-292 color-magnitude relation scaled to the redshift and colors for RXJ0910+5422. The long-dashed vertical line is the magnitude limit of the morphological classification $z_{850} = 24$ mag. The S0 CMR is bluer than the elliptical CMR by 0.07 ± 0.02 mag.

star formation in the red early-type populations, by using a simple stellar population model (Blakeslee et al. 2003).

To construct the CMR, early-type galaxies with $0.8 < (i_{775} - z_{850}) < 1.2$ mag were selected from the Postman et al. (2005) morphological classification, down to $z_{850} = 24$ mag. Final colors were measured within galaxy effective radii (R_e), to avoid biases due to galaxy internal gradients. R_e values were derived with the program GALFIT (Peng et al. 2002), constraining the *Sersic* index $n \leq 4$. To remove blurring effects (the PSF is 10% broader in the z_{850} band) each galaxy image in both i_{775} and z_{850} was deconvolved using the CLEAN algorithm (Högbom et al. 1974). The $(i_{775} - z_{850})$ colors were measured on the deconvolved images within a circular aperture equal to R_e .

The early-type population in RXJ1252.9-292 shows a small intrinsic scatter in the CMR, with an intrinsic scatter in observed $(i_{775} - z_{850})$ color of 0.029 ± 0.007 mag based on 52 galaxies or 0.024 ± 0.008 mag for 30 elliptical galaxies. Simulations using the latest stellar population models from Bruzual & Charlot (2003) permit us to derive an age scatter for the elliptical galaxies of about 34%, with a mean age of > 2.6 Gyr (corresponding to $z > 2.7$), and the last star formation occurring at $z > 1.5$. Transforming to rest-frame (U-B) color, Blakeslee et al. (2003) concluded that the slope and scatter in the CMR for morphologically selected early-type galaxies show little or no evidence of evolution out to $z \approx 1.2$. Thus, elliptical galaxies were already well established in X-ray-luminous clusters when the universe was a third of its present age. Using deep VLT J and K_s images of this same cluster, Lidman et al. (2004) come to a similar conclusion from the analysis of the near-infrared CMR.

Blakeslee et al. (2003) results were extended to the other clusters of the survey: RXJ0152+1357 and MS1054+03 (Blakeslee et al. 2005); RXJ J0910+5422 (Mei et al. 2005a); RXJ0848+4452 and RXJ0848+4453 (Mei et al. 2005b); CL1604+4304 & CL1604+4321 (Homeier et al., in preparation).

RDCS J0910+5422 does not have a central BCG or cD galaxy, and the X-ray emission center does not correspond to an optical grouping of galaxies; rather a number of luminous confirmed cluster members linearly distributed, at least as projected on the sky. The CMR for the ellipticals in RDCS J0910+5422 is consistent with that found in RDCS 1252.9-292 at $z=1.24$ (Blakeslee et al. 2003). From the scatter about the CMR, a mean luminosity-weighted age $\bar{t} > 2.7$ Gyr ($z \approx 2.3$) is derived for the elliptical galaxies, assuming a simple stellar population modeling (single burst solar metallicity).

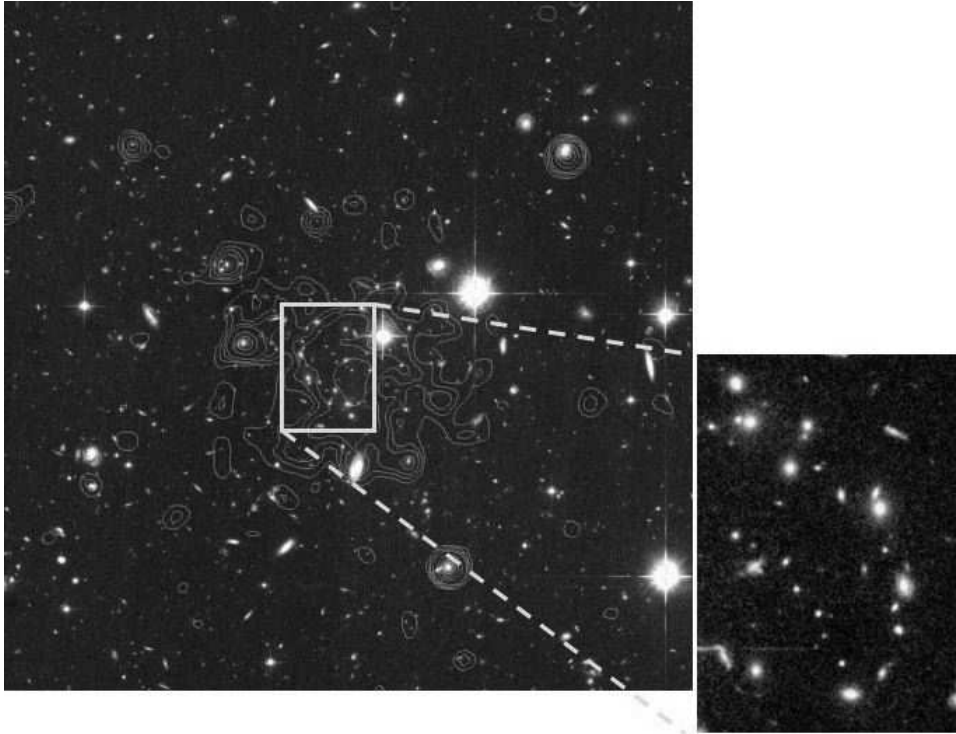


Figure 3: The ACS color image with X-ray contours overlaid. The X-ray observations are from Chandra ACIS-I, over the energy range of 0.5–2KeV, and were smoothed with a 5 arcsec FWHM Gaussian. North is up, East on the left. In the enlargement, galaxy pairs in the central filamentary structure are shown.

However, the CMR for the S0 galaxies in RDCS J0910+5422 is systematically bluer in the observed ($i_{775}-z_{850}$) color by 0.07 ± 0.02 mag, with respect to the elliptical CMR (Fig 2). The color offset between S0 and E corresponds to an age difference of ≈ 1 Gyr, for a single-burst solar metallicity model. Alternatively, it could be the result of a different star formation history; a solar metallicity model with an exponential decay in star formation will reproduce the offset for an age of 3.5 Gyr, i.e. the S0s have evolved gradually from star forming progenitors. The color offset could also be reproduced by a factor of ~ 2 difference in metallicity, but the two populations would each need to have very small scatter in metallicity to reproduce the small scatter in color.

In RDCS J0910+5422, thirteen red galaxy pairs are observed and the galaxies associated in pairs constitute $\sim 40\%$ of the CMR galaxies in this cluster. Nine of the red pairs are found within the cluster central filamentary structure (at radius of $\sim 100h_{70}^{-1}$ kpc from the X-ray center; Fig. 3). The observations of a significant number of red galaxy pairs in a cluster at $z \sim 1$ is interesting in the context of the recent findings by van Dokkum (2005) of red galaxy interactions in $\approx 70\%$ of 86 early-type galaxies in a selected sample of nearby red galaxies from the MUSYC (Multiwavelength Survey by Yale–Chile; Gawiser et al. 2005) and the NOAO Deep Wide-Field Survey. This work concluded that most of the ellipticals in local samples were assembled by red galaxy–galaxy mergers, denominated *dry* mergers because they would involve gas-poor early-type galaxies. At higher redshift, Tran et al. (2005b) confirmed red galaxy mergers first observed by van Dokkum (1999) in MS 1054-03 at $z=0.83$. Tran et al. selected mergers as associated pairs with projected separation less than $10h_{70}^{-1}$ kpc and relative line-of-sight velocities less than 165 km/s. As in RXJ J0910+5422, the red early-type galaxies involved in these mergers are among the brightest cluster members. Their results suggest that most early-type galaxies grew from passive red galaxy–galaxy mergers. In our sample we observe a triplet and three red galaxy pairs with projected distances less than $10h_{70}^{-1}$ kpc. Of those, the triplet and one galaxy pair show zero relative velocity. Of the two other pairs, composed of a bright and a fainter companion, redshifts are not available for the faint companions.

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