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ADVANCED CAMERA FOR SURVEYS PHOTOMETRY OF THE CLUSTER RDCS 1252.9−2927: THE COLOR-MAGNITUDE RELATION AT $z = 1.24$

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ABSTRACT

We investigate the color-magnitude (CM) relation of galaxies in the distant X-ray–selected cluster RDCS 1252.9−2927 at $z = 1.24$ using images obtained with the Advanced Camera for Surveys on the *Hubble Space Telescope* in the F775W and F850LP bandpasses. We select galaxies based on morphological classifications extending about 3.5 mag down the galaxy luminosity function, augmented by spectroscopic membership information. At the core of the cluster is an extensive early-type galaxy population surrounding a central pair of galaxies that show signs of dynamical interaction. The early-type population defines a tight sequence in the CM diagram, with an intrinsic scatter in observed $(i_{775}-z_{850})$ 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 indicate an age scatter for the elliptical galaxies of about 34%, with a mean age $\tau_L \gtrsim 2.6$ Gyr (corresponding to $z_L \gtrsim 2.7$), and the last star formation occurring at $z_{\rm end} \gtrsim 1.5$. Transforming to rest-frame $(U-B)$, we conclude that the slope and scatter in the CM relation 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.

Subject headings: cosmology: observations — galaxies: clusters: individual (RDCS 1252−2927) — galaxies: elliptical and lenticular, cD — galaxies: fundamental parameters

1. INTRODUCTION

Present-day cluster elliptical galaxies are a remarkably well-behaved class of objects, with structural and chemical properties obeying simple power-law scaling relations. But this could not always have been the case in a hierarchical universe. While most galaxy formation models can be tuned to reproduce these relations at $z = 0$, a more stringent test lies in reproducing their evolution with redshift. To this end, it is important to study rich clusters out to the highest redshifts, when fractional age differences among the galaxies were proportionately greater. In recent years, deep wide-field optical surveys and deep serendipitous X-ray surveys have uncovered significant numbers of rich galaxy clusters to redshifts of unity and beyond. These most distant, and most massive, of known gravitationally bound structures can then be studied in detail through targeted, high-resolution, follow-up optical and near-infrared observations.

We have undertaken a survey of rich galaxy clusters in the redshift range $0.8 < z < 1.3$ using the Advanced Camera for Surveys (ACS; Ford et al. 2003) on the *Hubble Space Telescope* (*HST*). The aim of this survey is to establish new constraints on the cluster formation epoch and the evolution of early-type galaxies. The first cluster observed, RDCS 1252.9−2927 (hereafter RDCS 1252) at $z = 1.237$ (Rosati et al. 2003), was discovered as part of the *ROSAT* Deep Cluster Survey (Rosati et al. 1998) and is among the highest redshift galaxy clusters with spectroscopic confirmation. This Letter presents the first results from our ACS cluster survey, focusing on the color-magnitude (CM) relation of the early-type galaxies in RDCS 1252. We adopt the best-fit *Wilkinson Microwave Anisotropy Probe* (*WMAP*) cosmology: $(h, \Omega_m, \Omega_L) = (0.71, 0.27, 0.73)$ (Bennett et al. 2003), giving 8.4 kpc arcsec^{-1} at $z = 1.237$.

2. OBSERVATIONS AND IMAGE REDUCTIONS

RDCS 1252 was observed in the F775W and F850LP bandpasses (hereafter i_{775} and z_{850}, respectively) with the ACS Wide Field Camera (WFC) as part of the guaranteed time observation program (proposal 9290) during 2002 May and June. The observations were done in a 2×2 mosaic pattern, with three and five orbits of integration in i_{775} and z_{850}, respectively, at each of the four pointings. There was nearly 1′ of overlap between pointings; thus, the core of the cluster was imaged for a total of 12 orbits in i_{775} and 20 orbits in z_{850}.

The data were processed with the "*Apsis*" pipeline described by Blakeslee et al. (2003), with some recent updates. In particular, we used a version of the *drizzle* software (Fruchter & Hook 2002) supplied by R. Hook that implements the "*Lanczos3*" interpolation kernel (a damped sinc function). This kernel produces a sharper point-spread function (PSF) and greatly reduces the noise correlation of adjacent pixels and the resulting "moire" patterns. *Apsis* also now removes discontinuities in the residual bias level at the amplifier boundaries, producing a more uniform background. We calibrate our photometry to the AB system using photometric zero points of 25.640 (i_{775}) and 24.843 (z_{850}). These are uncertain at the ∼0.02 mag level, which has no effect on our conclusions. We

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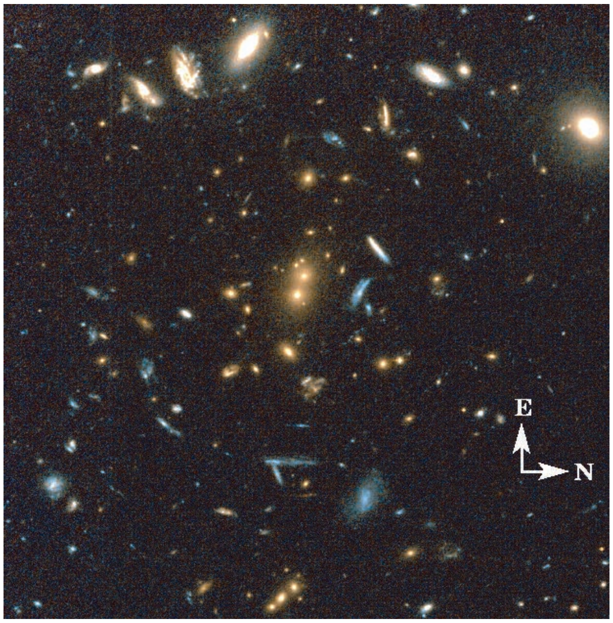

FIG. 1.—Color composite of the core region of RDCS 1252, constructed from our ACS/WFC F775W and F850LP images, shown in the observed orientation. The displayed field size is roughly 1′ across or less than 4% of the full mosaic.

adopt a Galactic reddening for this field of $E(i-z) = 0.041$ mag based on the Schlegel, Finkbeiner, & Davis (1998) dust maps.

3. OBJECT SELECTION AND PHOTOMETRY

Figure 1 shows the central ∼1′ region of a color composite made from our reduced i_{775} and z_{850} images. A red galaxy population is clearly visible. The central pair of galaxies are separated by 1″.8 (15 kpc) and are each of magnitude $z_{850} \approx 21$. We used SExtractor (Bertin & Arnouts 1996) in "dual-image mode" with low threshold and deblending settings to find objects in the reduced images and to perform the initial photometry. SExtractor "MAG_AUTO" values were used for the total magnitudes. The isophotoal $(i_{775}-z_{850})$ color effectively separates out evolved galaxies at $z \gtrsim 1$, and the cluster is obvious as a central concentration of galaxies with $0.80 < (i_{775}-z_{850}) < 1.05$. We selected an initial sample of 312 nonstellar objects with $z_{850} < 24.8$, in the broad isophotal color range $0.5 < (i_{775}-z_{850}) < 1.2$, and inside a radius of 1′.92. Our goal is to study the early-type galaxy population in RDCS 1252, for which we have limited spectroscopic data, and these cuts are designed to select the vast majority of our target sample while reasonably limiting foreground/background contamination. The color selection is roughly 7 times broader than the full width of the red sequence we find below. The radial cutoff corresponds to about 1.0 Mpc for both our adopted *WMAP* cosmology and an Einstein–de Sitter cosmology with $h = 0.5$.

Our final colors are measured within galaxy effective radii R_e to avoid biasing the CM slope due to color gradients. We follow the basic approach outlined by van Dokkum et al. (1998, 2000). We derive the R_e-values using the program "GALFIT" (Peng et al. 2002) by fitting each galaxy to a Sersic model (convolved with the PSF) but constraining the n-parameter such that $1 \le n \le 4$. Bright neighboring galaxies were fitted simultaneously. We note that the subtraction of the model for the two central galaxies reveals evidence of interaction in the form of an S-shaped residual.

Next, we deconvolve i_{775} and z_{850} postage-stamp images of each galaxy using the CLEAN algorithm (Högborn 1974) in order to remove the differential blurring effects of the PSF, which is ∼10% broader in the z_{850} band. To reduce noise, the CLEAN maps are smoothed with a Gaussian of FWHM = 1.5 pixels before adding the residual images to the maps to ensure flux conservation. We then measure the i_{775} and z_{850} magnitudes of each galaxy within a circular aperture of radius R_e, typically about 6 pixels or 0″.3. We did not allow the radius to drop below 3 pixels. Photometric errors were determined empirically from the pointing overlap regions. We reprocessed the four pointings separately and measured the color differences within R_e for 202 pairs of measurements for 74 different early-type galaxies (classifications described below) in the overlap regions. We then median-filtered to obtain the errors as a smooth function of magnitude. The error thus determined for single-pointing $(i_{775}-z_{850})$ measurements at $z_{850} = 23$ was 0.025 mag, rising to ∼0.05 mag at $z_{850} = 24.5$.

Each galaxy in our initial sample was examined and morphologically classified, following a procedure similar to that in Fabricant, Franx, & van Dokkum (2000). This was done independently of the profile fitting, but the types show a good correlation with the Sersic index n. Here, we simply distinguish between E, S0, and later types, in which the intermediate S0 class indicates the apparent presence of a disk without spiral or other structure. Full details on the classifications for a much larger sample, including the spatial distribution of the various types, will be presented by M. Postman et al. (2003, in preparation). About 180 galaxies in this field have measured redshifts, obtained with VLT/FORS (P. Rosati et al. 2003, in preparation), with 31 being cluster members. All galaxies in our initial sample classified as early-type and not known to be interlopers from their spectra are included in our CM analysis in the following section. Of the 31 known members, 22 are classified as early-type, and we include all of these in our analysis even though one (an S0 galaxy) happened to lie beyond our 1 Mpc cutoff.

4. THE COLOR-MAGNITUDE RELATION AT $z = 1.24$

We fitted the early-type galaxy CM relations using simple linear least squares; other methods gave very similar results. We estimate the scatter from both the standard rms and the biweight scale estimator (Beers, Flynn, & Gebhardt 1990). No rejection was done in fitting subsamples composed of known members, the faintest of which has $z_{850} = 23.48$ or $\sim 0.5L_B^*$. We also performed fits to samples with unconfirmed members, allowing us to go 1 mag further down the galaxy luminosity function. However, here we iterate to reject the 3 σ outliers, as these are likely to be interlopers: none of the 22 confirmed early-type members are more than 2.3 σ discordant. After the iterative rejection process, we find concordant scatters for those samples, and the rms and biweight estimator are the same to within ± 0.001 mag.

Figure 2 presents the CM relation for the RDCS 1252 galaxies. The fit to the full sample of early-type galaxies with $z_{850} < 24.5$ gives

$$(i-z) = (0.958 \pm 0.006) - (0.025 \pm 0.006)(z - 23). \quad (1)$$

Other results are listed in Table 1. The mean locations of the CM relations for the elliptical and S0 subsamples agree to well within the errors, while the slopes are consistent at the 1.5 σ level. Eight known late-type members from P. Rosati et al. (2003, in preparation) for which we have photometry are bluer than the early-type galaxies by 0.25 mag, with a scatter of 0.14 mag about this offset, indicating young stellar populations. We find an intrinsic scatter $\sigma_{\rm int} = 0.023 \pm 0.007$ mag for the 15 confirmed elliptical members. For a limit of $z_{850} < 24.5$, we derive $\sigma_{\rm int} = 0.026$ mag for the clipped sample of 31 elliptical galaxies and $\sigma_{\rm int} = 0.029$ for the 52 E+S0 galaxies. At this limit, the observational errors become dominant, and classification is difficult, which could bias our $\sigma_{\rm int}$ estimates. For $z_{850} < 24.0$, still 3 mag down the luminosity function to about 0.3 L^*, we find $\sigma_{\rm int} = 0.024$ for 25 elliptical galaxies (with no outliers).

We estimate $M_B^* \approx -21.7$ AB for RDCS 1252, based on local surveys (Norberg et al. 2002), *WMAP* cosmology, and -1.4 mag of luminosity evolution (Postman, Lubin, & Oke 2001; van Dokkum & Stanford 2003). The correction from z_{850} to rest-frame B is $+0.3$ mag for an early-type spectrum. Thus, the brightest cluster member at $z_{850} = 21.0$ corresponds to $\sim 4.8 L_B^*$. The cluster red sequence is about 0.1 mag bluer than predicted for nonevolving elliptical templates (Coleman, Wu, & Weedman 1980; Schneider, Gunn, & Hoessel 1983). For comparison, a Bruzual & Charlot (2003, hereafter BC03) solar metallicity model reddens by 0.11 mag and fades by 1.5 mag in aging from $\sim$3 to $\sim$11.5 Gyr. The present-day relation for the Coma Cluster (transformed according to the relations given below) is also shown in Figure 2.

The tight CM relation allows us to constrain the scatter in early-type galaxy ages, subject to model uncertainties. The evolution in $(i_{775}-z_{850})$ at this redshift is complicated at young ages because z_{850} straddles the 4000 Å break and has its blue end near the Balmer jump at 3700 Å. The Balmer jump reaches a maximum at 0.5–1 Gyr, when the relative contribution from A stars is greatest, resulting in a red color at these ages. It is interesting that several of the S0 galaxies lie *above* the CM relation, possibly indicating ages less than 1 Gyr. As the A star contribution lessens, the color quickly evolves toward the blue, reaching a local minimum near $\sim$1.5 Gyr, before commencing a roughly monotonic reddening with age.

We have simulated the $(i_{775}-z_{850})$ colors of galaxies formed under two simple star formation models, similar to those used by van Dokkum et al. (1998). In model 1, the galaxies form in single bursts randomly distributed over the interval $(t_0, t_{\rm end})$, where t_0 is set to the recombination epoch and $t_{\rm end} < t_z \equiv 5.1$ Gyr, the age of the universe at $z = 1.24$. In model 2, galaxies form stars at constant rates between randomly selected times (t_1, t_2), where $t_0 < t_1 < t_2 < t_{\rm end}$. We vary $t_{\rm end}$ and at each step calculate colors and luminosities for 10,000 "galaxies" by interpolation and integration of the BC03 solar metallicity models. Assuming $\sigma_{\rm int} = 0.024$ mag for the elliptical galaxies, model 1 implies a minimum age $t_z - t_{\rm end} = 1.6$ Gyr; i.e., all galaxies finish forming at redshifts $z > z_{\rm end} = 1.9$; the mean luminosity-weighted age is $\tau_L = 3.3$ Gyr (corresponding to $z_L = 3.6$) with a scatter of 30%. Model 2 gives $t_z - t_{\rm end} = 0.53$ Gyr, $z_{\rm end} = 1.4$, and $\tau_L = 2.6$ Gyr (corresponding to $z_L = 2.7$) with 38% scatter. Thus, although some galaxies in model 2 have formed stars recently, the mean ages are still high. Both models give a mean color $\langle i_{775}-z_{850}\rangle = 0.94$, similar to that observed.

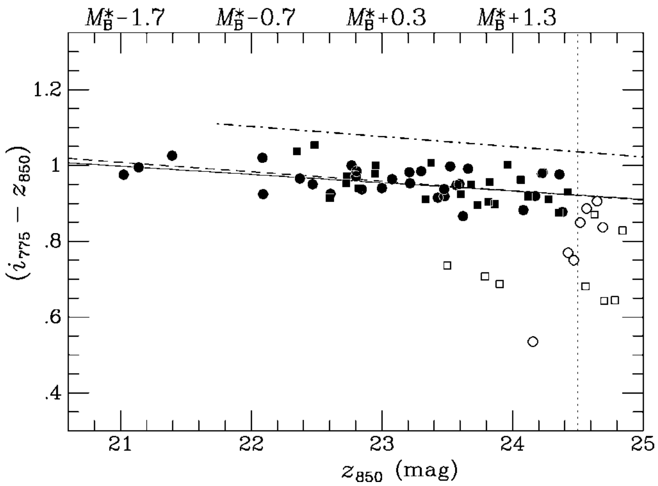

FIG. 2.—Color-magnitude diagram for early-type galaxies inside 1′.9 with $(i_{775}-z_{850}) > 0.5$, excluding spectroscopically known interlopers. The circles and squares represent elliptical and S0 galaxies, respectively; the filled symbols are used in the CM relation fits, while the open symbols (all of which lack spectroscopic information) are rejected as outliers or as below the faint cutoff (indicated by the dotted line). Two representative fits are shown: the fit to the 15 elliptical members (*solid line*) and the fit to the 52 early-type red-sequence galaxies. The approximate luminosity conversion for RDCS 1252 is shown at the top, assuming the *WMAP* cosmology and -1.4 mag of luminosity evolution as described in the text, such that $M_B^* = -21.7$ (AB). The relation for the Coma Cluster, transformed to these bandpasses at $z = 1.24$ (no evolution correction), is indicated by the dot-dashed line.

For the S0 galaxies, we find $z_{\rm end} = 1.5$ for model 1 and $z_{\rm end} = 1.3$, indicating recent star formation, and age scatters of 44%–47%. Finally, we note that the 1996 version of the BC03 models would have predicted higher formation epochs, e.g., $z_{\rm end} > 2.5$ and $z_{\rm end} > 2.0$ for the elliptical galaxies in models 1 and 2, respectively, and an age scatter of only 20%, although the predicted color is then redder by 0.1 mag. Overall, we conclude that the elliptical galaxies are an evolved population, with a mean age $\tau_L \gtrsim 2.6$, a minimum age $\sim 1 \pm 0.5$ Gyr, and an age scatter of 34% ± 15%, where the error reflects uncertainty in $\sigma_{\rm int}$ and scatter in the models.

5. DISCUSSION

To enable comparison with previous work, we convert observed $(i_{775}-z_{850})$ quantities to rest-frame $(U-B)_z$ at $z = 1.24$. The models (BC03; Kodama et al. 1998) and empirical templates indicate $\Delta(U-B)_z = (1.8 \pm 0.4) \times \Delta(i_{775}-z_{850})$, where the error bar reflects the scatter in the models at the

TABLE 1

RDCS 1252−2927 COLOR-MAGNITUDE RELATIONS

Sample	$z_{850}^{\rm (lim)}$	N_r	N_c	Slope	$\sigma_{\rm bwt}$ [a]	$\sigma_{\rm bwt}$ [b]	$\sigma_{\rm int}$
E[c]	...	15	15	−0.022 ± 0.011	0.029	0.029 ± 0.005	0.023 ± 0.007
E+S0[c]	...	22	22	−0.018 ± 0.013	0.038	0.038 ± 0.006	0.033 ± 0.007
E[d]	24.0	25	25	−0.020 ± 0.009	0.033	0.033 ± 0.005	0.024 ± 0.008
E+S0[d]	24.0	44	41	−0.025 ± 0.008	0.045	0.038 ± 0.004	0.029 ± 0.007
E[d]	24.5	34	31	−0.019 ± 0.007	0.053	0.036 ± 0.005	0.026 ± 0.008
E+S0[d]	24.5	58	52	−0.025 ± 0.006	0.054	0.039 ± 0.004	0.029 ± 0.007
S0[d]	24.5	24	21	−0.042 ± 0.013	0.058	0.039 ± 0.006	0.032 ± 0.008

[a] Biweight scatter based on raw number of galaxies N_r.
[b] Biweight scatter based on N_c galaxies after 3 σ clipping.
[c] Spectroscopically confirmed members of specified type only.
[d] All red-sequence objects (known interlopers omitted) of specified type, $z_{850} < z_{850}^{\rm (lim)}$, and within the area of analysis.

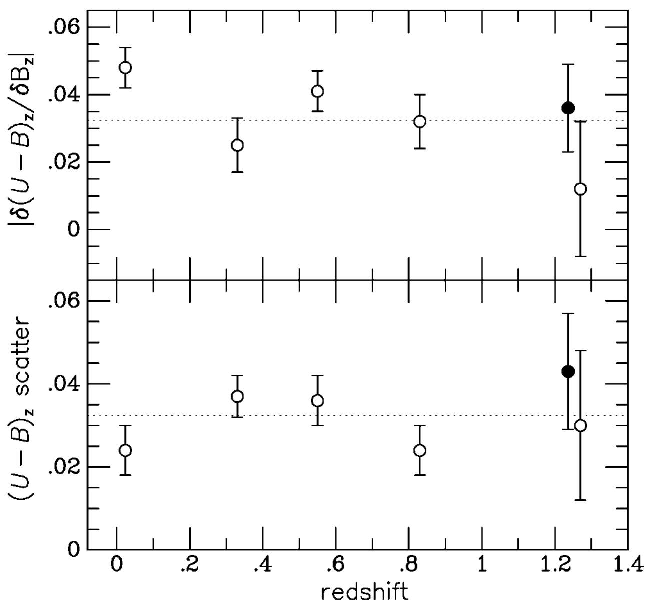

FIG. 3.—Slope (*top*) and scatter (*bottom*) of the rest-frame ($U-B$) CM relation as a function of redshift. The filled circle is from the present work; the open circles show results from, in order of increasing redshift, Bower, Lucey, & Ellis (1992); van Dokkum et al. (1998); Ellis et al. (1997); van Dokkum et al. (2000); and van Dokkum et al. (2001). The dotted lines indicate the average values.

relevant ages and adds about 20% uncertainty to our transformed slope and scatter. Figure 3 uses this conversion, and other transformations from van Dokkum et al. (2000), to compare our results with some previous studies of the CM relation in intermediate-redshift clusters with *HST* as well as the results of van Dokkum et al. 2001 on RX J0848+4453, the only cluster of comparable redshift to have its CM relation measured.

Linear fits to the data shown in Figure 3 yield slopes of -0.014 ± 0.010 and 0.003 ± 0.008 for the evolution in the absolute slope and the scatter, respectively. Thus, the scatter is constant, and there is at best marginal evidence of slope evolution, which indicates that the slope is due to a variation in metallicity, not age. Previous studies of cluster samples out to $z \sim 1$ have come to similar conclusions (e.g., Stanford, Eisenhardt, & Dickinson 1998; Kodama et al. 1998; van Dokkum et al. 2000). Van Dokkum et al. (2001) concluded that the slope at $z = 1.27$ was shallower than in the Coma Cluster. However, as shown in the figure, our slope measurement is consistent within the errors with both Coma and RX J0848+4453. Further studies of a diversity of clusters at similar redshifts are needed to explore this issue.

The lack of evolution in the CM relation scatter can be explained by progenitor bias (e.g., van Dokkum & Franx 2001): galaxies selected as early-type at any epoch will have old stellar populations, while the later-type progenitors of the youngest elliptical galaxies today will not be selected. The result is an underestimate in the color scatter for the progenitors of modern elliptical galaxies and thus overestimated ages. An upper limit on the scatter for elliptical progenitors may be estimated from a fit to all confirmed RDCS 1252 members; the result is 3–4 times larger than for the early-type galaxies. A detailed study of the morphological fractions in RDCS 1252 (M. Postman et al. 2003, in preparation) should help illuminate the magnitude of this bias. We also note that the two central galaxies themselves, based on their proximity and irregular isophotes, appear likely to undergo a dissipationless merger to form a single $\sim 9L_B^*$ galaxy, similar to local cD galaxies.

We conclude that massive, evolved early-type galaxies were already present in rich clusters at $z = 1.24$. Our simple models imply mean luminosity-weighted ages of 2.6–3.3 Gyr, corresponding to formation at $z = 2.7$–3.6. However, the ($i_{775}-z_{850}$) color is not ideal for the redshift of RDCS 1252, being better suited to measuring the 4000 Å break at $z \approx 1.1$. Combining our ACS data with deep, high-resolution near-IR imaging of this field (Lidman et al. 2003) will enable a more robust assessment of early-type galaxy ages. In addition, further studies of the CM relations and morphologies of galaxies in other $z \gtrsim 1$ clusters are needed to improve the constraints on the formation epoch of cluster galaxies and on the evolution of their stellar populations and structural properties.

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