THE GALAXY POPULATION OF CLUSTER RX J0848+4453 AT Z = 1.27

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Accepted for publication in The Astrophysical Journal Letters

ABSTRACT

We present a study of the galaxy population in the IR-selected cluster RX J0848+4453 at z = 1.27, using deep Hubble Space Telescope (HST) NICMOS H$\text{F}_{160}$W and WFPC2 I$_{F814W}$ images of the cluster core. We morphologically classify all galaxies to $K_s = 20.6$ that are covered by the HST imaging, and determine photometric redshifts using deep ground based BRIJ$K_s$ photometry. Of 22 likely cluster members with morphological classifications, eleven (50%) are classified as early-type galaxies, nine (41%) as spiral galaxies, and two (9%) as “merger/peculiar”. At HST resolution the second brightest cluster galaxy is resolved into a spectacular merger between three red galaxies of similar luminosity, separated from each other by $\approx 6h_{50}^{-1}$ kpc, with an integrated magnitude $K = 17.6$ ($\approx 3L_*, z = 1.27$). The two most luminous early-type galaxies also show evidence for recent or ongoing interactions. Mergers and interactions between galaxies are possible because RX J0848+4453 is not yet relaxed. The fraction of early-type galaxies in our sample is similar to that in clusters at $0.5 < z < 1$, and consistent with a gradual decrease of the number of early-type galaxies in clusters from $z = 0$ to $z \approx 1.3$. We find evidence that the color-magnitude relation of the early-type galaxies is less steep than in the nearby Coma cluster. This may indicate that the brightest early-type galaxies have young stellar populations at $z = 1.27$, but is also consistent with predictions of single age “monolithic” models with a galactic wind. The scatter in the color-magnitude relation is $\approx 0.04$ in rest frame $U-V$, similar to that in clusters at $0 < z < 1$. Taken together, these results show that luminous early-type galaxies exist in clusters at $z \approx 1.3$, but that their number density may be smaller than in the local Universe. Additional observations are needed to determine whether the brightest early-type galaxies harbor young stellar populations.

Subject headings: galaxies: clusters: individual (RX J0848+4453) — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: fundamental parameters — galaxies: interactions

1. INTRODUCTION

Studies of nearby and distant clusters have provided strong constraints on the evolution and formation of their galaxy population. Approximately 80% of galaxies in the central regions of nearby clusters are elliptical and S0 galaxies (Dressler 1980). Studies of clusters at $0 < z < 1$ have shown that the luminosities and colors of these early-type galaxies evolve slowly with time, and have very small scatter (e.g., Schade et al. 1996, Ellis et al. 1997, Stanford, Eisenhardt, & Dickinson 1998, van Dokkum et al. 1998, De Propris et al. 1999), indicating that the stars in early-type galaxies were formed at $z > 2$.

On the other hand, there is growing evidence for morphological evolution among cluster galaxies. Dressler et al. (1997) reported a high fraction of spiral galaxies in clusters at $0.3 < z < 0.5$. Other studies have confirmed this trend, and extended it to $z = 0.8$ (Couch et al. 1998; van Dokkum et al. 2000). These spiral galaxies may be the progenitors of S0 galaxies in nearby clusters (e.g., Butcher & Oemler 1984, Dressler et al. 1997). Furthermore, rich clusters at $0.3 < z < 0.9$ show enhanced rates of interactions and mergers (e.g., Couch et al. 1998, van Dokkum et al. 1999), which may lead to the formation of young elliptical galaxies at late times. As a result of these processes, early-type galaxies in distant clusters may form a subset of all progenitors of early-type galaxies in nearby clusters (e.g., van Dokkum & Franx 2001).

The strongest constraints on the formation and evolution of cluster galaxies come from the highest redshift data. Here, we present a study using NICMOS and WFPC2 on HST of the galaxy population in RX J0848+4453 at $z = 1.27$. The cluster was discovered by Stanford et al. (1997), as part of a deep BRIJ$K_s$ field survey (Eisenhardt et al. 2001). Its redshift corresponds to a time when the Universe was only 35% of its present age, and the properties of its galaxy population provide direct information on the early stages of the formation of cluster galaxies. We assume $\Omega_m = 0.3$, $\Omega_\Lambda = 0$, and $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$.

2. DATA

On 1 March 1999 the cluster was observed by WFPC2 on HST. Ten exposures were obtained in the I$_{F814W}$ band for a total of 27.8 ks. The exposures were reduced using standard procedures and combined with “drizzle” (Fruchter & Hook 1997). A mosaic of three NIC3 pointings in H$\text{F}_{160W}$ was obtained on

1Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5–26555.

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5 and 6 June 1998 during a campaign when the HST secondary was moved to ensure optimal focus for Camera 3. Each pointing consisted of 8 dithered exposures each lasting $\sim$1400 s. The data were processed using a combination of STScI pipeline routines and custom software, and were combined into a single mosaic using drizzle by registering to the WFPC2 reduced image. The PSF of the drizzled NICMOS data has FWHM $\sim 0.22\arcsec$. The overlap of the two datasets is good but not complete; results presented below will make use of objects for which we have either WFPC2 or NIC3 data, or both.

Ground-based imaging data obtained as previously reported in Stanford et al. (1997) were used in calculating photometric redshifts as described below. To summarize: deep imaging was obtained at the KPNO 4 m using PFCCD in the $BRI_z$ bands and IRIM in the $JK_s$ bands over a $\sim 5' \times 5'$ area in Lynx (Eisenhardt et al. 2001). Within this area, deep $JHK_s$ band data which cover $\sim 2.5' \times 2.5'$ were also obtained reaching e.g. a 4$\sigma$ limit of $K_s \sim 21.7$.

3. PHOTOMETRIC REDSHIFTS

Ideally, the galaxy population of clusters is studied using magnitude limited samples of spectroscopically confirmed members (e.g., Lubin et al. 1998). However, even using the Keck Telescopes only 10 member redshifts have been obtained within the HST field, due to the faintness of the galaxies (Stanford et al. 1997 and in preparation). Therefore we chose to determine photometric redshifts for all galaxies in the fields covered by NIC3 and/or WFPC2 to a limiting magnitude of $K_s = 20.6$. This approach has the advantage of a uniform selection in a red filter, at the expense of having a small amount of contamination by field galaxies.

We used the publically available “hyperz” code by Bolzonella, Miralles, & Pello (2000) to determine photometric redshifts, using the $BRIJK_s$ ground based photometry. Empirical templates from Coleman, Wu, & Weedman (1980) were used in the SED fitting. The assigned redshifts are weighted averages of fits to four spectral types ranging from E/S0 to a star burst spectrum. Figure 1 shows the resulting photometric redshift distribution of galaxies in the HST field.

![Photometric redshift distribution in the HST field](image)

Based on the photometric redshift distribution of confirmed members we assume that galaxies with $1.14 < z_{\text{phot}} < 1.40$ are cluster members. One of these is a luminous AGN at $z_{\text{spec}} = 0.889$ which we discard. The final sample of 25 likely cluster galaxies includes the ten confirmed members.

4. MORPHOLOGIES

Morphological classifications of all galaxies in the WFPC2 and/or NIC3 field to $K_s = 20.6$ were performed by P. G. v. D., S. A. S., and B. P. H., following the method outlined in Fabricant, Franx, & van Dokkum (2000). We preferentially used the deeper $H_{F160W}$ images for galaxies that were observed with both WFPC2 and NIC3. The reliability of such visual classifications has been discussed extensively (e.g., Smail et al. 1998, Fabricant et al. 2000). In general, when comparing independent sets of classifications the early-type galaxy fraction is robust, but there is large scatter in the relative numbers of elliptical and S0 galaxies (e.g., Fabricant et al. 2000, van Dokkum et al. 2000). In the present study we do not discuss the fractions of elliptical galaxies and S0 galaxies separately.

Three of the 25 likely cluster members could not be classified: they were discarded from the sample to leave 22 probable cluster members with morphological classifications. Eleven of the 22 (50%) are E or S0 galaxies, nine (41%) are spirals, and two (9%) are classified as “merger/peculiar”. Both “merger/peculiar” galaxies are spectroscopically confirmed cluster members. In nearby clusters, the morphological fractions are a strong function of the local galaxy density (Dressler 1980). Following the prescription of Dressler (1980) we find that the logarithm of the galaxy density log $\rho_{\text{proj}} \sim 1.3 h_{50}^{-2} \text{Mpc}^{-2}$ for RX J0848+4453. The predicted early-type fraction from the local morphology-density relation is 70%, higher than the observed fraction of 50$^{+12}_{-17}$%, although the difference is not significant. Color images of the ten brightest galaxies in RX J0848+4453 are shown in Fig. 2 along with their morphological classification.

5. A LUMINOUS TRIPLE MERGER AT $z = 1.27$

The second brightest cluster galaxy is a single object in ground based images, but is resolved into three individual galaxies in the HST images (cf. Fig. 2). The three objects have very similar luminosities, morphologies, and colors, and are separated from each other by only 0.6$''$ ($\approx 6 h_{50}^{-1}$ kpc). The probability of finding three unrelated objects with such a small separation and high luminosity in our sample is $\sim 10^{-7}$. The probability that two are physically associated and one is unrelated is $\sim 10^{-4}$. Hence we conclude that the three objects are bound, and are in the late stages of a triple merger. This interpretation is confirmed by the presence of tidal tails. The three galaxies will probably evolve into a $\sim 3L_\star$ elliptical galaxy in $< 500$ Myr (e.g., Rix & White 1989). Note that we have counted the three merging galaxies as one object in determining the fraction of “merger/peculiar” galaxies in RX J0848+4453.

The integrated spectrum of the three objects shows no evidence for significant star formation (Stanford et al. 1997). Such apparently dissipationless mergers were previously observed in the outskirts of the cluster MS 1054–03 at $z = 0.83$ (van Dokkum et al. 1999). Similar to MS 1054–03, RX J0848+4453 is not relaxed (Stanford et al. 2000). The triple merger may occur in a subclump, where the relative velocities of galaxies are sufficiently low. If the merging galaxies were accreted from the field a major question is how and when they lost their gas.
Interestingly, the brightest and third brightest cluster galaxy also show evidence for interactions. The brightest cluster galaxy has an extended, asymmetric envelope. Such features can be explained by a recent merger or accretion event (e.g., Statler, Smecker-Hane, & Cecil 1996). The third brightest galaxy has a close companion, at a distance of 1.27\,″. The probability of finding two unrelated galaxies within this distance in our sample is 8\%, and the colors of the companion object suggest that it is a cluster member. Spectroscopy of the companion galaxy is needed to confirm that the galaxies are physically associated.

6. COLOR-MAGNITUDE RELATION

The color-magnitude (CM) relation of probable members of RXJ0848+4453 is shown in Fig. 3. Rest frame $U-V$ colors and absolute $V$ magnitudes were calculated from the observed (ground based) $I$ and $J$ band magnitudes (see, e.g., van Dokkum et al. 2000). Colors were measured in 3″ apertures. The broken line indicates the CM relation of early-type galaxies in Coma (Bower, Lucey, & Ellis 1992).

Early-type galaxies in RXJ0848+4453 follow a narrow CM relation, with the exception of a few faint outliers. The CM relation is noticeably flatter than in the Coma cluster; a fit to the early-type galaxies with $M_V^I < -22.5$ gives a slope of $-0.02 \pm 0.03$, compared to $-0.08 \pm 0.01$ for Coma (Bower et al. 1992). This flat slope is probably not caused by the effects of color gradients, since these are expected to steepen the slope of the CM relation (Scodellaggio 2001).

As a result of the difference in slope, the offset of the CM relation from that of the Coma cluster depends on magnitude. At $M_V^I = -23$ the offset is $0.3 \pm 0.1$ magnitudes, consistent with predictions of stellar population synthesis models for populations formed at $z \geq 2$ (e.g., Worthey 1994). The constraints are not very strong because of the relatively large uncertainty in the offset. The corresponding rest frame $V$ band luminosity evolution is $\sim 1$ magnitude, consistent with the evolution of the $M/L_V$ and the luminosity function to $z \sim 1$ (van Dokkum et al. 1998; De Propris et al. 1999).

The scatter was determined using the biweight statistic (Beers, Flynn, & Gebhardt 1990). The observed scatter among the early-type galaxies is only $0.06^{+0.04}_{-0.03}$ in (ground based) rest frame $U-V$ color, identical to the expected scatter from measurement errors alone. Ten of the early-type galaxies are observed with NIC3 and WFPC2, allowing us to obtain an independent measurement of the scatter. The observed scatter is $0.10^{+0.07}_{-0.05}$ in $[F814W]_0 - [F160W]_0$. After correcting for a measurement error of 0.07 magnitudes this gives an intrinsic scatter of $\approx 0.07$ in rest frame $U-R$, or $\approx 0.04$ in $U-V$. This scatter is very similar to that in the nearby Coma cluster ($0.047 \pm 0.005$ in $U-V$; De Propris et al. 2000). This result extends to $z \sim 1.3$ the results of Stanford et al. (1998) on the CM relation at $z < 1$.
type galaxies, but a few are very red. The triple merger is only $0.12 \pm 0.02$ magnitudes bluer in rest frame $U-V$ than early-type galaxies of the same luminosity. This system resembles the red mergers seen in the cluster MS 1054–03 at $z = 0.83$ (van Dokkum et al. 1999).

7. DISCUSSION

The presence of red mergers in high redshift clusters is direct evidence against formation of all massive elliptical galaxies in a “monolithic collapse” at very high redshift, and in qualitative agreement with hierarchical galaxy formation models. The triple merger in RX J0848+4453 shares many of its characteristics with the luminous red mergers seen in MS 1054–03 at $z = 0.83$ (van Dokkum et al. 1999). Despite its higher redshift, the merger fraction in RX J0848+4453 may not be as high as in MS 1054–03. The mergers in MS 1054–03 occur preferentially in the outskirts of the cluster, and it would be interesting to extend the study of RX J0848+4453 to larger radii. The merger fraction may be correlated with the dynamical state of clusters; this may be tested by studying a sample of clusters in different stages of collapse.

![Fig. 4.— Evolution of the early-type galaxy fraction in clusters. Data points at $z < 1$ are taken from the literature (see text). Solid symbols are clusters with $L_x > 10^{44.5}$ ergs s$^{-1}$, and open symbols indicate $L_x < 10^{44.5}$ ergs s$^{-1}$. The large symbol at $z = 1.27$ is RX J0848+4453 which has $L_x = 0.7 \times 10^{44}$ ergs s$^{-1}$ (Stanford et al. 2000). The early-type galaxy fraction in RX J0848+4453 is similar to that of clusters at $0.5 < z < 1$.](image)

The fraction of early-type galaxies provides a complementary measurement of morphological evolution. Figure 4 shows the evolution of the early-type galaxy fraction from $z = 0$ to $z = 1.3$. Data points at $z < 1$ are taken from Dressler et al. (1997), Andreon et al. (1997), Fabricant et al. (2000), Lubin et al. (1998), and van Dokkum et al. (2000). The early-type fraction in RX J0848+4453 is similar to that in clusters at $0.5 < z < 1$. The interpretation is complicated by the effects of infall of field galaxies onto clusters between $z = 1.27$ and $z = 0$ (e.g., Ellingson et al. 2001). Furthermore, clusters at $z \approx 1.3$ may be rare and not representative of the progenitors of nearby clusters such as Coma (e.g., Kauffmann 1995). As a result of these effects the observed evolution of the early-type galaxy fraction may underestimate the true evolution.

The low and constant scatter in the CM relation from $z = 0$ to $z = 1.3$ can be interpreted as evidence that early-type galaxies formed at very high redshift (e.g., Ellis et al. 1997). However, it is also consistent with models in which early-type galaxies are continuously transformed from spiral galaxies (van Dokkum & Franx 2001). In that case, the low scatter implies that the morphological transformations are probably not accompanied by strong star bursts. The red colors of the triple merger in RX J0848+4453, and of spiral galaxies and mergers in clusters at lower redshift (e.g., Poggianti et al. 1999, van Dokkum et al. 2000), are consistent with this scenario.

The flattening of the slope of the CM relation with redshift, if confirmed for other clusters, may indicate that the most massive early-type galaxies harbor young stellar populations at $z \sim 1.3$, consistent with predictions of semi-analytical models for galaxy formation (e.g., Kauffmann & Charlot 1998). However, a similar effect is expected in single age formation models with a galactic wind (Arimoto & Yoshii 1987). In these models the colors of massive galaxies evolve more rapidly because they have higher metallicities. Measurements of line indexes and $M/L$ ratios of the most massive early-type galaxies in RX J0848+4453 may help to determine the ages of the stars in these galaxies.

We thank Chris Hanley for help with the WFPC2 and NIC-MOS image reductions. P. G. v. D. acknowledges support by NASA through Hubble Fellowship grant HF-01126.01-99A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA under contract NAS 5-26555. Support for S. A. S. came from NASA/LTS grant NAG5-8430, and STScI grants GO-06812.02 and GO-07872.01. B. H. acknowledges support from NASA/Chandra grant GO-1082A. Portions of this research were carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

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