Outskirts of Galaxy Clusters: Intense Life in the Suburbs
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E+A galaxies in intermediate redshift clusters

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Abstract. Using extensive ground-based spectroscopy, we isolate the E+A population in three intermediate redshift clusters ($z = 0.33$, 0.58 and 0.83) and study their physical properties using HST/WFPC2 imaging. Our analysis includes galaxy colors, luminosities, Hubble types, and quantitative structural parameters as well as measured and estimated internal velocity dispersions. We find E+A galaxies make up a non-negligible fraction ($\sim 7-13\%$) of cluster members at these redshifts, and their diverse nature indicates a heterogeneous parent population. From their velocity dispersions and half-light radii, we infer that the descendants of the E+A's in our highest redshift clusters are massive early-type galaxies, and we estimate that $\gtrsim 30\%$ of the E-S0 members have undergone an E+A phase. We also find the characteristic E+A mass decreases with decreasing redshift; this is similar to the decrease in luminosity of rapidly star-forming field galaxies since $z \sim 1$, i.e. galaxy "down-sizing".

1. Introduction

Post-starburst galaxies ("E+A"; Dressler & Gunn 1983) in clusters may provide the crucial link in the morphological transformation of spiral galaxies into the elliptical/S0 systems that dominate the cluster population at the current epoch (see Butcher & Oemler 1978). Characterized by strong Balmer absorption and little or no [OII]λ3727 emission, E+A's also are referred to as k+a/a+k (Franx 1993; Dressler et al. 1999, hereafter D99) or Hδ-strong galaxies (Couch & Sharples 1987). Despite the short window of visibility of the post-starburst phase (< 1.5 Gyr; Couch & Sharples 1987; Barger et al. 1996), E+A members can contribute up to 20% of the total cluster population (D99), and have been found in virtually every spectroscopic cluster survey from $0 < z < 1.3$.

Here we summarize results presented in Tran et al. (2003b) on the E+A population in three intermediate redshift clusters: CL 1358+62 ($z = 0.33$), MS 2053–04 ($z = 0.59$), and MS 1054–03 ($z = 0.83$). We have completed extensive spectroscopic surveys (> 130 confirmed members in *each* field) and obtained HST/WFPC2 mosaics of the three clusters ($R \sim 1h^{-1}$ Mpc) to characterize their galaxy populations. By pairing wide-field HST/WFPC2 imaging with deep ground-based spectroscopy, we can study in detail the nature of E+A galaxies in clusters at $z > 0.3$.

First we isolate the E+A galaxies in the three clusters to measure the fraction of members that are also E+A's. This has important ramifications on whether the *majority* of cluster members undergo an E+A phase or if only a small fraction do. Because our analysis includes colors, magnitudes, half-light radii, bulge-to-total fractions, degree of galaxy

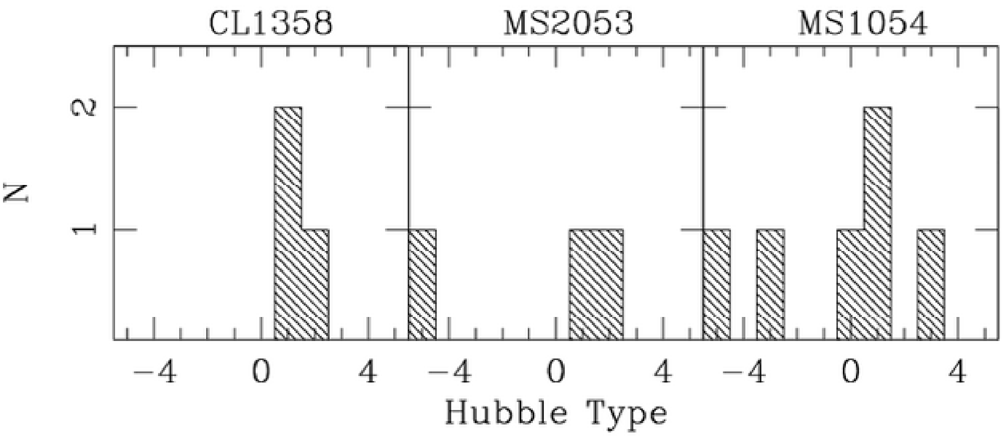

Figure 1. The Hubble types of the E+A galaxies in each cluster; we consider only the E+A's brighter than $M_{Be} = -19.1 + 5\log h$. The morphological types of {E, E/S0, S0, S0/Sa, Sa, Sb, Sc} are assigned values of $\{-5, -4, -2, 0, 1, 3, 5\}$; intermediate values are also used. We do not show the two E+A mergers in MS1054. The E+A galaxies span the range in morphological type to include even early-type members (Type< -2). However, cluster E+A's tend to be systems with disks (Type$\geqslant 1$).

asymmetry, Hubble types, and internal velocity dispersions (measured and estimated), we can determine whether E+A galaxies can include even the most massive members, and if they have a heterogeneous parent population. In addition, we can use their sizes and internal velocity dispersions (σ) to determine what their descendants will be. By analyzing clusters at three different redshifts, we can also determine whether the luminosity and internal velocity dispersion distributions of the cluster E+A's evolves with redshift. We use $H_0 = 100$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, and $\Lambda = 0.7$.

2. Results

From over 1200 redshifts obtained in the three cluster fields, we isolate ~ 500 members. We select E+A galaxies from our cluster sample as members having strong Balmer absorption [(Hδ+Hγ)/2 $\geqslant$ 4Å] and no [OII]λ3727 emission (> -5 Å). We also apply a signal to noise cut ($S/N \geqslant 20$) on the Hδ and Hγ fluxes and use a magnitude limit ($M_{Be} \leqslant -19.1 + \log h$) to ensure we are not including any passive galaxies that are scattered into the E+A regime due to observational errors. For uniformity, we consider only members brighter than this cut when comparing the E+A population between the clusters. We find 14 cluster galaxies that satisfy our strict E+A selection criteria.

2.1. *E+A fraction*

For members brighter than $M_{Be} = -19.1 + 5\log h$, we obtain E+A fractions of 7 ± 4%, 10 ± 6%, and 13 ± 5% at $z = 0.33,\ 0.58,\ \&\ 0.83$ respectively; errors are determined by assuming a Poisson distribution for the E+A galaxies. Considering the low E+A fraction in Coma (Caldwell et al. 1993), these results show the E+A fraction evolves strongly with redshift. They also suggest the E+A fraction continues to increase at $z > 0.5$. However, larger samples at $z > 0.3$ are needed to determine if this increase is real or if the trend flattens at $z > 0.3$.

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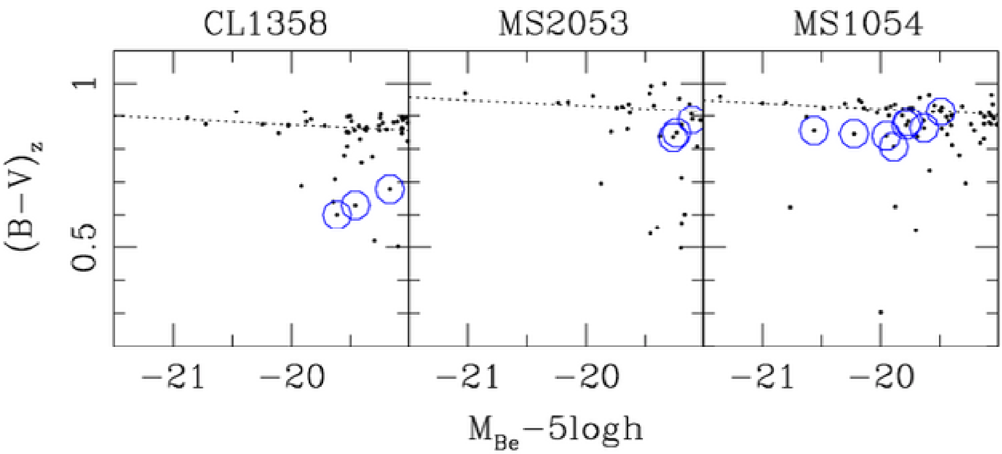

Figure 2. The color-magnitude diagram for all cluster members brighter than $M_{Be} = -19.1 + 5\log h$; the cluster members that are E+A's are circled. The color-magnitude relation (dotted line) is normalized to the E/S0 members and its slope is from van Dokkum et al. (2000). E+A galaxies in the two lower redshift clusters are faint ($M_{Be} \gtrsim -19.5 + 5\log h$) but they can be up to a magnitude brighter in MS1054 ($z = 0.83$).

2.2. *Morphology*

The cluster E+A's in our sample span the range in Hubble type (Fig. 1) and bulge-to-total fraction (B/T; see Tran et al. 2001, 2003a) to include both spirals and E/S0's. However, the majority of E+A's have measurable disks, consistent with results from previous cluster E+A studies (Wirth & Koo 1994; Couch et al. 1994, 1998; Caldwell et al. 1999; D99). Their average bulge-to-total fraction of ~ 0.4 reflects their tendency to be disk-dominated systems.

The observed range in B/T and Hubble type of the E+A population is similar to the heterogeneous morphologies found in studies of lower redshift cluster E+A's ($z \lesssim 0.3$). It also confirms suggestions in earlier studies that E+A's must have a wide variety of progenitors (Zabludoff et al. 1996; D99). We also note that the earliest-type E+A's are in our most distant cluster; it may be that more massive cluster members, i.e. early-types, had their E+A phase at higher redshift.

2.3. *Color-magnitude diagram*

In Fig. 2, we show the color-magnitude (CM) distribution of all cluster galaxies and E+A candidates brighter than our magnitude limit of $M_{Be} = -19.1 + 5\log h$; all members, including the E+A candidates, have been corrected for simple passive evolution (see van Dokkum et al. 1998). In all three clusters, we find bright E+A galaxies ($M_{Be} \lesssim -19.1 + 5\log h$). Even more striking are the very luminous E+A's at $z = 0.83$: these E+A's are up to a magnitude brighter than their lower redshift counterparts and cover a larger magnitude range. Note the cluster E+A's tend to be bluer than the red sequence. The E+A luminosity range, particularly at $z = 0.83$, indicates that they have a heterogeneous parent population. The fact that the brightest E+A's in this sample are in our most distant cluster suggests that the cluster E+A population evolves with redshift.

2.4. *Internal velocity dispersions*

Having demonstrated that E+A's at higher redshift can be as luminous as the brightest cluster members, we now determine if these brighter E+A's are also *massive* galaxies,

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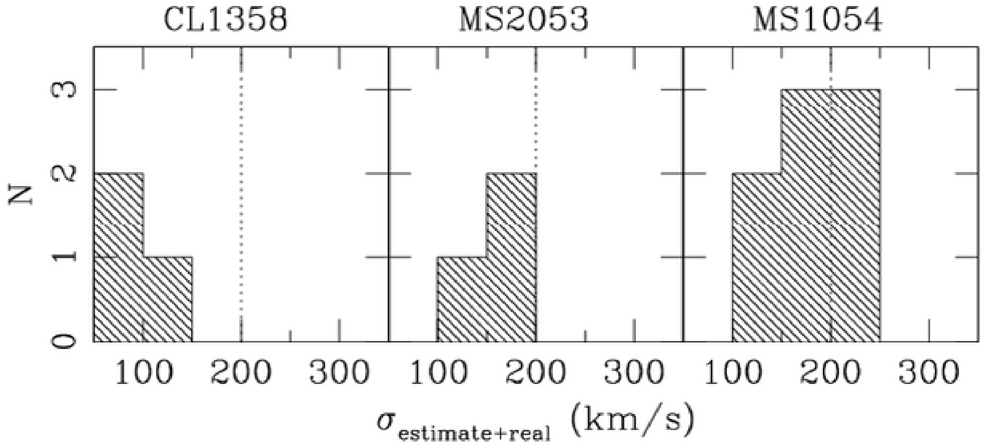

Figure 3. Histogram of internal velocity dispersions (measured and estimated) for E+A members brighter than $M_{Be} = -19.1 + 5 \log h$. The characteristic E+A mass (as traced by σ) increases with redshift to include even E+A galaxies with $\sigma > 200$ km s^{-1} in MS1054 ($z = 0.83$). This trend is similar to the observed decrease, since $z \sim 1$, in the maximum luminosity of field galaxies undergoing rapid star formation ("down-sizing"; Cowie et al. 1996).

or whether they are simply low luminosity/mass members that are temporarily brightened. By determining the E+A mass distribution, we can characterize what the E+A progenitors are and also constrain what their descendants at lower redshift can be. We use internal velocity dispersion as a tracer of the mass where we have obtained direct σ measurements for 120 cluster members (Kelson et al. 2000a, 2001; van Dokkum et al. 1998), and we estimate σ for the rest of the sample using the Fundamental Plane (see Kelson et al. 2000b).

Figure 3 shows the distribution of internal velocity dispersions (measured and estimated σ) for cluster members brighter than $M_{Be} = -19.1 + 5 \log h$. The range in velocity dispersion for E+A galaxies increases at higher redshift: E+A's at $z = 0.33$ have smaller velocity dispersions ($\sigma \leqslant 150$ km s^{-1}) than at $z = 0.58$ ($\sigma \leqslant 200$ km s^{-1}) and $z = 0.83$ ($\sigma \leqslant 250$ km s^{-1}). Considering the robustness of the spectroscopic data and high quality of the WFPC2 imaging, any E+A's with $\sigma > 200$ km s^{-1} (measured or estimated) in the two lower redshift clusters would have been easily detected *if they existed*.

We find that the half-light radii (∼sizes) and dispersions of E+A's at $z = 0.83$ are comparable to those of the massive early-type members in all three clusters. In contrast, none of the E+A's at $z = 0.33$ could be considered a cluster giant. It is apparent that the progenitors of the lower redshift E+A's are very different from those at $z = 0.83$. The observed trend of decreasing internal velocity dispersion with decreasing redshift is consistent with the "down-sizing" of the E+A population.

3. Conclusions

From a sample of ~ 500 spectroscopically confirmed cluster members in three clusters at $z = 0.33$, 0.59 and 0.83, we isolate 14 E+A galaxies and find E+A's make up a non-negligible component of the cluster population ($\sim 7 - 13\%$) at intermediate redshifts. Although most of them are disk-dominated systems, E+A's span the range in morphological type to include even early-type members. They can be more luminous than L^* and can have internal velocity dispersions in excess of 200 km s^{-1}. We find the E+A's

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with the highest internal velocity dispersions and luminosities are in our most distant cluster. This galaxy "down-sizing" is similar to the observed decrease in luminosity of rapidly star-forming field galaxies since $z \sim 1$ (Cowie et al. 1996).

Our study indicates the high dispersion ($\sigma > 200$ km s^{-1}) E+A's at $z = 0.83$ are the logical progenitors of massive early-types at lower redshift. We estimate $\geqslant 30\%$ of cluster E-S0's at $z = 0.83$ have had an E+A phase. We consider this a lower limit as evolution in the E+A fraction and characteristic mass as well as the conversion of spirals into early-types can increase the true fraction to 100%. These results show that the E+A phase can play an important role in the transformation of star-forming galaxies into early-type members.

Acknowledgements

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