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E+A Galaxies in Intermediate-redshift Clusters

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Abstract

Combining HST/WFPC2 mosaics (each to $R_{BCG} \sim 1h^{-1}$ Mpc) with extensive ground-based spectroscopy, we study the nature of E+A galaxies in three intermediate redshift clusters ($z = 0.33,\ 0.58,\ \&\ 0.83$). From a sample of ~ 500 confirmed cluster members, we isolate 44 E+A candidates to determine the E+A fraction and study their physical properties. We find: 1) E+A galaxies are a non-negligible fraction ($\sim 4-14\%$) of the cluster population at these redshifts; 2) While predominantly disk-dominated systems, cluster E+A's span the range in Hubble type and bulge-to-total fraction to include even early-type members; 3) They cover a range in luminosity ($L_B \lesssim 2.5L_B^*$), internal velocity dispersion ($\lesssim 250$ km s^{-1}), and half-light radius ($\lesssim 5h^{-1}$ kpc); and 4) The logical descendents at lower redshift of the high dispersion E+A's at $z = 0.8$ are massive early-type members. We find that while E+A's span the range in luminosity and velocity dispersion at higher redshift, only low mass ones exist in nearby clusters, *e.g.* Coma. This probable evolution in the cluster E+A mass distribution is reminiscent of the galaxy "down-sizing" observed in the field.

1.1 Introduction

Post-starburst ("E+A") galaxies in clusters may provide the crucial link in the morphological transformation of spiral galaxies into the elliptical/S0 systems that dominate the cluster population. Despite the short window of visibility of the post-starburst phase (< 1.5; Couch & Sharples 1987; Barger et al. 1996), E+A members can contribute up to 20% of the total cluster population (Dressler et al. 1999, hereafter D99), and have been found in virtually every spectroscopic cluster survey from $0 < z < 0.8$ (Dressler & Gunn 1983; Couch & Sharples 1987; Wirth, Koo, & Kron 1994, Caldwell et al. 1996; Balogh et al. 1999; D99; Tran 2002) However, the fraction of E+A galaxies in intermediate redshift clusters ($0.2 < z < 0.8$) is contested (D99; Balogh et al. 1999). In addition, fundamental questions such as what the parent population of these systems is and what their descendents can be have yet to be fully answered.

From extensive spectroscopic surveys of CL 1358+62 ($z = 0.33$; Fisher et al. 1998), MS 2053–04 ($z = 0.58$; Tran 2002), and MS 1054–03 ($z = 0.83$; Tran et al. 1999; van Dokkum et al. 2000), we isolate 44 E+A candidates from ~ 500 confirmed cluster members. Using HST/WFPC2 mosaics taken of each cluster (all to $R_{BCG} \sim 1h^{-1}$ Mpc), we measure the colors, magnitudes, half-light radii, bulge-to-total fractions, degree of galaxy asymmetry,

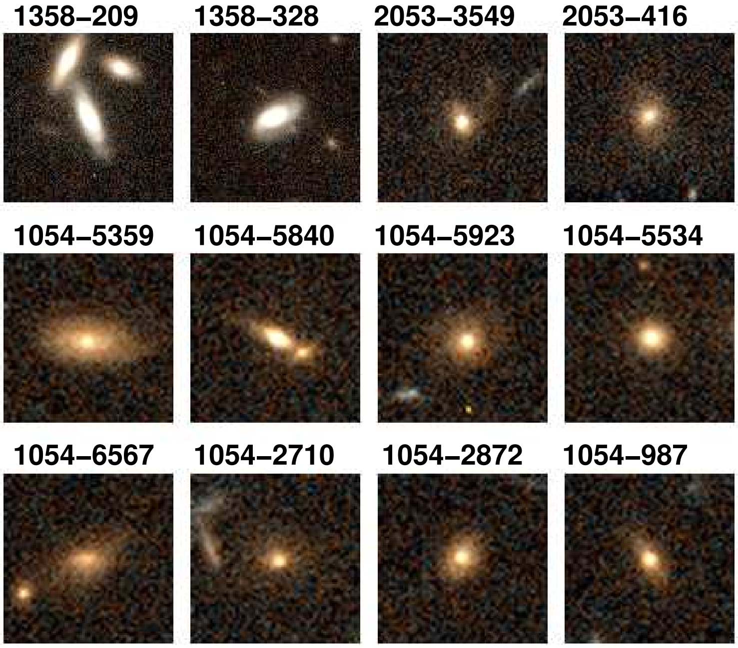

Fig. 1.1. Color thumbnails made with WFPC2 F814W and F606W imaging of the 12 cluster E+A's that satisfy our strict selection criteria ($B_z \leq -19{+}5\log h$, Balmer $S/N > 2$). The images are $10'' \times 10''$ (CL1358, $z = 0.33$), $7'' \times 7''$ (MS2053, $z = 0.58$), and $5'' \times 5''$ (MS1054, $z = 0.83$).

and morphological type of the the cluster members. With LRIS on Keck, we also have obtained internal velocity dispersion for 120 cluster members (Kelson et al. 1997; van Dokkum et al. 1998a; Kelson 2004). With these dispersions and the Fundamental Plane (Faber et al. 1987), we derive pseudo dispersions for the rest of the sample.

Using our robust sample of E+A's, we determine the E+A fraction in intermediate redshift clusters, identify characteristics of their parent population, address what the descendents of these galaxies can be, and discuss the likely down-sizing of this population. Throughout this work, we use $\Omega_M = 0.3, \Omega_\Lambda = 0.7$, and $H_0 = 100$ km s^{-1} Mpc^{-1}.

1.2 Results

We select E+A galaxies from the three clusters in our sample as having strong Balmer absorption [$(\mathrm{H}\delta{+}\mathrm{H}\gamma)/2 \geq 4$ Å] and no [OII] emission (< -5 Å). Because the spectral quality varies for the three clusters, we impose a magnitude limit ($B_z \leq -19{+}5\log h$) set by MS1054, and also apply a signal to noise cut ($S/N \geq 2$) on the Balmer index. Of the 44 E+A candidates in our sample, only 12 satisfy these strict selection criteria (Fig. 1.1). Using members brighter than our imposed magnitude limit ($B_z = -19{+}5\log h$), we obtain E+A fractions of 4%, 8%, and 14% at $z = 0.3$, 0.6, & 0.8 respectively.

In this sample, the cluster E+A's span the range in Hubble type and bulge-to-total fraction. One surprising result is that in the highest redshift cluster, we find even E-S0 galaxies

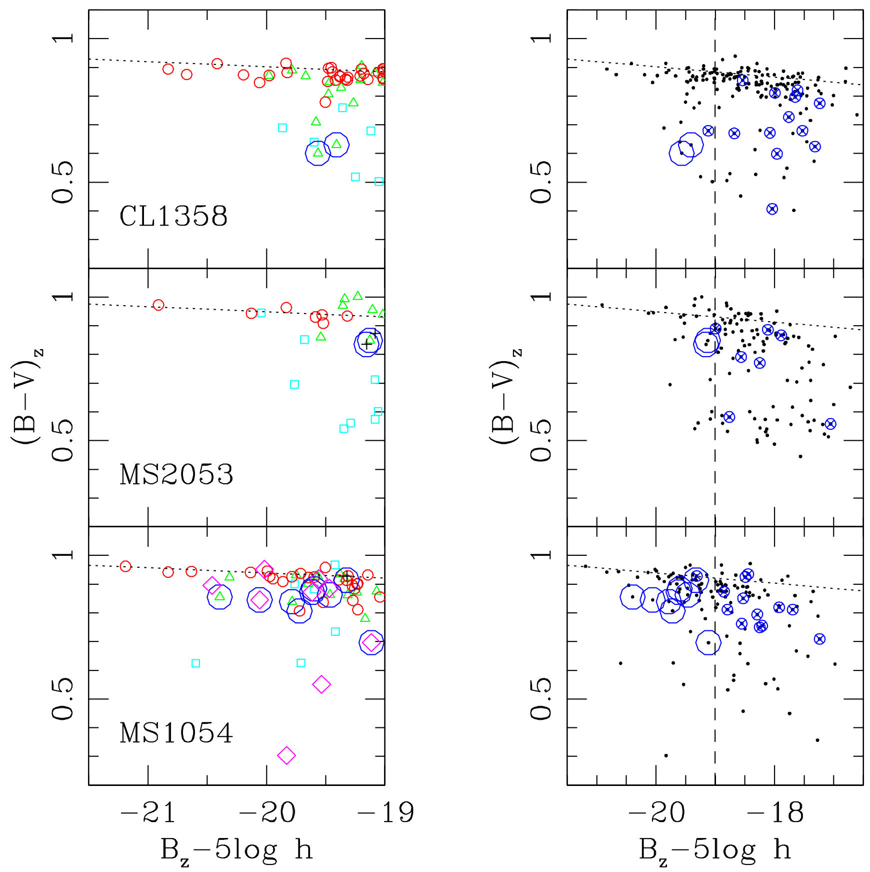

Fig. 1.2. The left panels show the color-magnitude diagram for members above our imposed magnitude limit of $B_z \leq -19{+}5\log h$ while the right panels show all confirmed cluster members. The symbols represent different morphological types: E-S0 (small open circles), S0-a (open triangles), spiral (open squares), no type (plus signs), merger (diamonds), and robust E+A (large open circles); circles with crosses denote E+A candidates that do not satisfy our strict selection criteria . Regardless of magnitude, E+A's tend to be bluer than the CM relation normalized by the E-S0 members. The cluster E+A's in the two lower redshift clusters are faint ($B_z < -19.5{+}5\log h$) but can be up to a magnitude brighter in MS1054.

with the E+A spectral signature. However, the majority of E+A's do have measurable disks, consistent with results from previous cluster E+A studies (Wirth, Koo, & Kron 1994; Caldwell & Rose 1997). Their average bulge-to-total fraction of ~ 0.4 reflects their tendency to be disk-dominated systems.

In Fig. 1.2, we show the color-magnitude (CM) distribution of all cluster members and E+A candidates. In all three clusters, we find bright E+A's ($B_z \gtrsim -19{+}5\log h$); of the 12 robust E+A's, seven are brighter than B_z^* ($-19.5{+}5\log h$; Hoekstra et al. 2000). One unexpected result is that at $z = 0.8$, E+A's are up to a magnitude brighter than their lower redshift

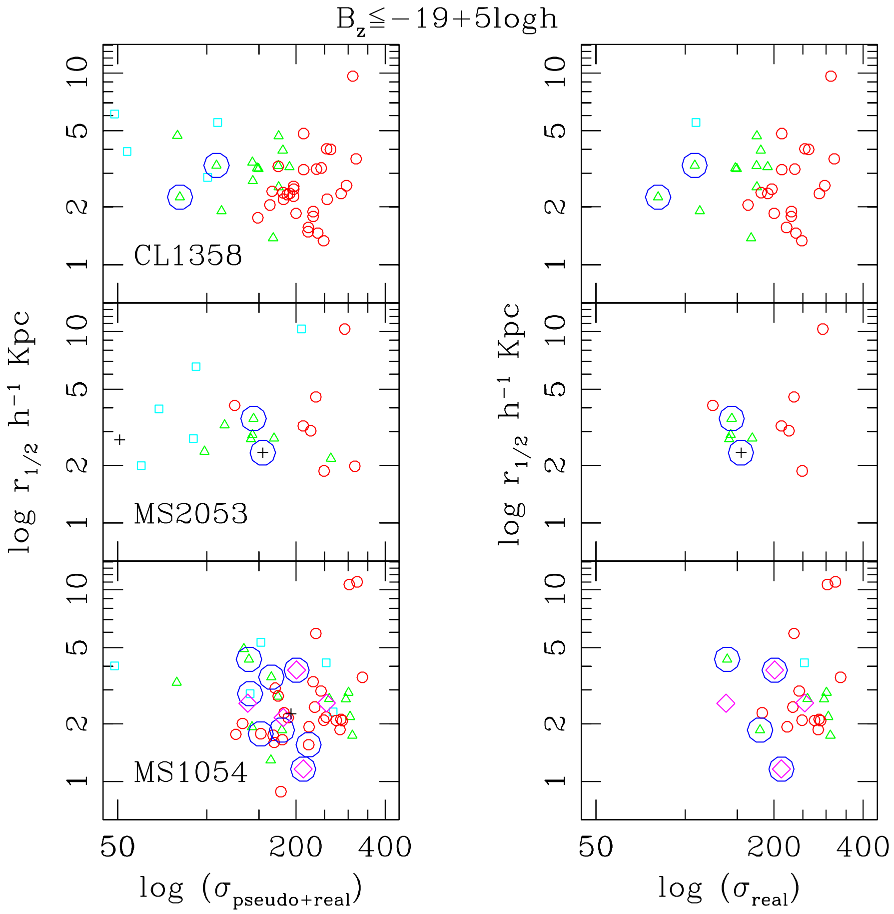

Fig. 1.3. Half-light radius compared to velocity dispersion for $B_z \leq -19{+}5\log h$ members; both these quantities should be relatively constant with redshift. The symbols are as in Fig. 1.2. The left panels utilize pseudo velocity dispersions (except when actually measured) while only members with measured σ are shown in the right panels. The high σ E+A's in MS1054 are very likely to be the progenitors of massive early-types at low redshifts.

counterparts and cover a larger magnitude range. Like the star forming galaxies in the field, the maximum luminosity and mass of cluster E+A's may be decreasing with redshift; this effect is known as galaxy "down-sizing" (Cowie et al. 1996). The wide E+A luminosity range also reinforces the conclusion that they have a heterogeneous parent population.

We observe a similar increase in the range of internal velocity dispersions with redshift. Cluster E+A's at $z = 0.3$ have smaller velocity dispersions ($\sigma \lesssim 150$ km s^{-1}) than at $z = 0.6$ ($\sigma \lesssim 200$ km s^{-1}) and $z = 0.8$ ($\sigma \lesssim 250$ km s^{-1}). The difference between $z = 0.3$ and $z = 0.8$ is most striking. 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*.

To emphasize the disparity between the three clusters, we compare their half-light radii to internal velocity dispersions (Fig. 1.3); neither of these parameters is expected to evolve significantly within the redshift range covered here. The half-light radii and dispersions of E+A's at $z = 0.8$ are comparable to those of the massive early-type members in all three clusters. In contrast, none of the E+A's at $z = 0.3$ 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 $z = 0.8$.

1.3 Conclusions

By examining their physical properties, we confirm the diverse nature of cluster E+A galaxies. Like D99, we find that while they tend to be disk-dominated systems, cluster E+A's span the range in morphology and B/T to include even E-S0 members. They can be significantly more luminous than the ones observed in nearby clusters, and can have large internal velocity dispersions. Only a heterogeneous parent population for the E+A members could reproduce the wide range in physical properties observed here. Considering the high fraction (up to $\sim 14\%$) of cluster E+A's and the short life-time of this phase (~ 1.5 Gyr), this raises the extremely interesting possibility that *all* cluster members may go through an E+A phase at some point in their evolution.

Caldwell et al. (1996) find E+A's in Coma are low luminosity ($L < 0.4L^*$), low dispersion ($\sigma < 150$ km s^{-1}) systems that are unlikely to evolve into massive members. However, this is not the case at $z > 0.3$. From Fig. 1.3, we see that at $z = 0.3$, E-S0's and S0-a's are the only logical descendents of the high dispersion ($\sigma > 150$ km s^{-1}) E+A's at $z = 0.8$. The E+A phase may signify the transformation of early-type spirals into E-S0's, and strongly star-forming spirals into S0-a's.

The E+A's in our most distant cluster ($z = 0.8$) can be luminous ($L \lesssim 2.5L^*$) and can have high internal velocity dispersions ($\sigma > 200$ km s^{-1}). In contrast, the E+A's in our lowest redshift cluster ($z = 0.3$) are sub–L^* and have low dispersions ($\sigma < 150$ km s^{-1}). The data are such that if any bright, high dispersion E+A's existed in our lower redshift clusters, they would have been detected. This observed trend of increasing luminosity and internal velocity dispersion with increasing redshift in the E+A population is similar to the galaxy "down-sizing" observed in the field (Cowie et al. 1996).

References

Balogh, M. L., Schade, D., Morris, S. L., Yee, H. K. C., Carlberg, R. G., & Ellingson, E. 1999, ApJL, 504L, 75
Barger, A. J., Aragon-Salamanca, A., Ellis, R. S., Couch, W. J., Smail, I., & Sharples, R. M. 1996, MNRAS, 279, 1
Caldwell, N., Rose, J. A., Franx, M., & Leonardi, A. J. 1996, AJ, 111, 78+
Caldwell, N. & Rose, J. A. 1997, AJ, 113, 492
Couch, W. J. & Sharples, R. M. 1987, MNRAS, 229, 423
Cowie, L. L., Songaila, A., Hu, E. M., & Cohen, J. G. 1996, AJ, 112, 839
Dressler, A. & Gunn, J. E. 1983, ApJ, 270, 7
Dressler, A., Smail, I., Poggianti, B. M., Butcher, H., Couch, W. J., Ellis, R. S., & Oemler, A. J. 1999, ApJS, 122, 51
Faber, S. M., Dressler, A., Davies, R. L., Burstein, D., & Lynden-Bell, D. 1987, in Nearly Normal Galaxies. From the Planck Time to the Present, 175–183
Fisher, D., Fabricant, D., Franx, M., & van Dokkum, P. 1998, ApJ, 498, 195+
Hoekstra, H., Franx, M., & Kuijken, K. 2000, ApJ, 532, 88
Kelson, D. D., van Dokkum, P. G., Franx, M., Illingworth, G. D., & Fabricant, D. 1997, ApJL, 478, L13
—. 2004, in prep
Tran, K. H. 2002, PhD thesis, , Univ. California at Santa Cruz, (2002)
Tran, K. H., Kelson, D. D., van Dokkum, P., Franx, M., Illingworth, G. D., & Magee, D. 1999, ApJ, 522

van Dokkum, P. G., Franx, M., Fabricant, D., Illingworth, G. D., & Kelson, D. D. 2000, ApJ, 541, 95
van Dokkum, P. G., Franx, M., Kelson, D. D., & Illingworth, G. D. 1998, ApJL, 504, L17
Wirth, G. D., Koo, D. C., & Kron, R. G. 1994, ApJL, 435, L105