

“E+A” GALAXIES: ENVIRONMENT AND EVOLUTION

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1. Introduction

One important approach to the study of galaxy evolution is to identify those galaxies whose spectral and/or morphological characteristics suggest that they are in transition. For example, “E+A” galaxies*, which have strong Balmer absorption lines and no significant [OII] emission, are generally interpreted as post-starburst galaxies in which the star formation ceased within the last \sim Gyr (Figure 1). This transition between a star forming and non-star forming state is a critical link in any galaxy evolution model in which a blue, star forming disk galaxy evolves into a S0 or elliptical. Another possible evolutionary track is that the star formation in an “E+A” resumes at some later time, if enough gas remains in the galaxy after its starburst ends. Given this ambiguity, it is important to investigate (1) the environment’s role in “E+A” evolution, (2) the stellar and gas morphologies of “E+A”s, (3) the likely progenitors of “E+A”s, and (4) how common the “E+A” phase is in the evolution of galaxies.

This proceeding summarizes recent results from several inter-related projects designed to address these questions. These projects focus on a sample of 21 nearby “E+A” galaxies ($0.05 < z < 0.15$; Zabludoff et al. 1996) drawn from the Las Campanas Redshift Survey (Schechter et al. 1996). These studies include VLA and HST observations, in addition to comparisons of these data with galaxy-galaxy interaction simulations and stellar population synthesis models. My collaborators are D. Zaritsky (UCO/Lick),

*The term “E+A” is a bit of a misnomer. The Mg, Fe, and Ca lines observed in the spectra of these galaxies are consistent with the stellar populations of ellipticals or “E”s. The additional “A” designation arose from the galaxies’ strong Balmer absorption lines, which are characteristic of A stars. Because the morphologies of “E+A”s now appear to range from spheroidals to disks, a more apt, and exclusively spectroscopic, designation is “K+A” (cf. Franx 1993). Nevertheless, we use “E+A” throughout this paper for historical reasons.

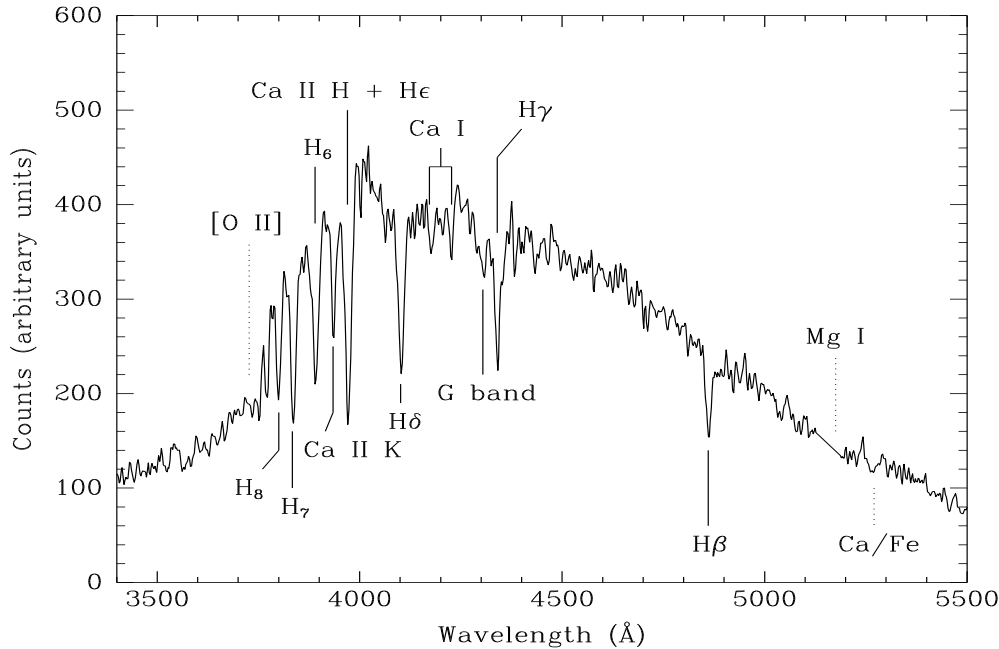


Figure 1. Identification of lines in the rest frame spectrum of an “E+A” galaxy, which is dominated by a young “A” stellar component. The residual sky line at 5577 Å has been excised. Note the absence of [O II] emission.

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2. Environment and “E+A” Evolution

The role of environment in the evolution of “E+A” galaxies, specifically in producing the initial burst of star formation, in ending it, and in allowing it to resume, is unknown. In past work, the detection of “E+A”s almost exclusively in distant clusters led to speculation that these galaxies represent an evolutionary sequence unique to or most efficient in cluster environments. The existence of such a cluster-dependent evolutionary sequence would suggest that the cluster environment, in the form of the intra-cluster medium, galaxy harassment, or the global potential, is responsible for the recent star formation history of “E+A”s and, by extension, for the Butcher-Oemler effect (Butcher & Oemler 1978) in clusters. In contrast to this line of reasoning, Schweizer (1982, 1996) and others find several nearby “E+A”s that appear to lie outside the hot, dense environments of clusters and that have highly disturbed morphologies consistent with the products of galaxy-galaxy mergers. To isolate at least one mechanism that governs

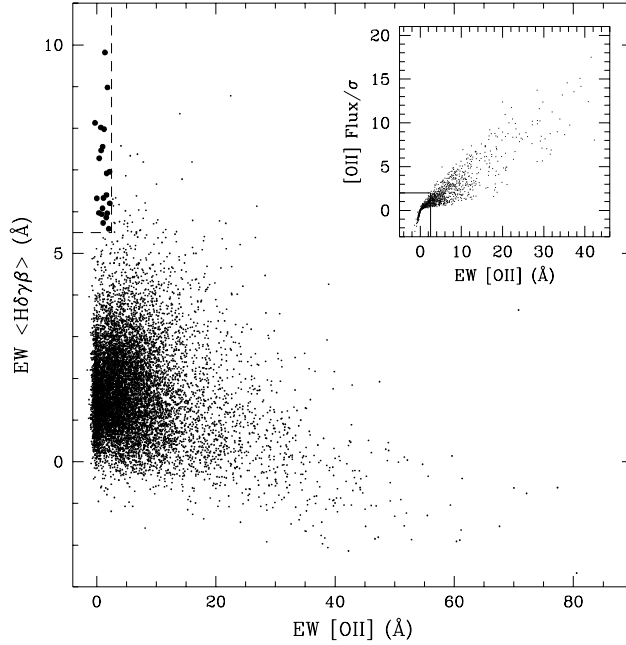


Figure 2. Plot of average Balmer line absorption $\langle H \rangle$ vs. [O II] line emission EW[O II] for the 11113 LCRS galaxies with $S/N > 8$ and $0.05 < z < 0.13$. The dashed line encloses the region, $\langle H \rangle > 5.5 \text{ \AA}$ and $\text{EW}[\text{O II}] < 2.5 \text{ \AA}$, from which the sample of 21 “E+A” galaxies (large points) is drawn. The inset shows that EW[O II] cut excludes galaxies with a more than 2σ detection.

the evolution of “E+A” galaxies requires a statistical inventory of the environments in which “E+A”s form. The Las Campanas Redshift Survey (LCRS), which includes high signal-to-noise spectra for ~ 11000 galaxies with $0.05 < z < 0.15$, is the ideal sample with which to characterize the environments of “E+A”s.

To identify “E+A” galaxies in the LCRS having properties consistent with those of known “E+A”s, we plot the distribution of Balmer absorption line and [O II] emission line strength for the LCRS galaxies (Figure 2; Zabludoff et al. 1996). The “E+A”s are selected to have the strongest Balmer absorption lines (the average of the equivalent widths of $H\beta$, γ , δ is $> 5.5 \text{ \AA}$) and weakest [O II] emission-line equivalent widths ($< 2.5 \text{ \AA}$, which corresponds to a detection of [O II] of less than 2σ significance) of any of the galaxies in the survey. We test whether these 21 “E+A”s lie in rich clusters in several ways, including calculating the local galaxy density around each “E+A” and also checking whether the “E+A” is a member of a rich cluster in the LCRS group catalog (Tucker 1994). Surprisingly, a large fraction ($\sim 75\%$) of nearby “E+A”s lie in the field, well outside of clusters and rich groups of galaxies. We conclude that interactions with the cluster environment are not essential for “E+A” formation and there-

fore that the presence of these galaxies in distant clusters does not provide strong evidence for the effects of cluster environment on galaxy evolution.

If one mechanism is responsible for “E+A” formation, then the observations that “E+A”s exist in the field and that at least five of the 21 in our sample have clear tidal features argue that galaxy-galaxy interactions and mergers are that mechanism. The most likely environments for such mergers are poor groups of galaxies, which have lower velocity dispersions than clusters and higher galaxy densities than the field. Groups are correlated with rich clusters and, in hierarchical models, fall into clusters in greater numbers at intermediate redshifts than they do today (cf. Bower 1991; Lacey & Cole 1993; Kauffmann 1994). When combined with the strong evolution observed in the field population (cf. Broadhurst et al. 1988; Lilly et al. 1995), our work suggests that the Butcher-Oemler effect may reflect the typical evolution of galaxies in groups and in the field rather than the influence of clusters on the star formation history of galaxies.

3. Stellar and HI Morphologies of “E+A”s

Is the transition between galaxy types implied by the post-star formation spectrum of an “E+A” seen in its morphology? The two HST images that we have obtained to date suggest a morphological transition. One “E+A” has an E type morphology, but has extended tidal tails. The other “E+A” is a barred S0. If star formation does not resume in these galaxies, they will look like early types after their blue stars die. One interesting unanswered question is why galaxies of such different morphologies have such similar spectra.

There is substantial evidence that galaxy-galaxy interactions increase star formation rates. While the effects of such interactions are consistent with the starburst history of “E+A”s, the mechanism by which the star formation stops is still a mystery. The HI morphologies of “E+A”s can provide some clues.

In the first LCRS “E+A” for which we have obtained VLA data (Figure 3), there are clear HI tidal tails similar to those of the Antennae (Hibbard & Mihos 1995). These tails support the galaxy-galaxy interaction picture for “E+A” formation. Perhaps even more interesting is the distribution of the gas not in the tails. The gas mass is comparable to that in disk galaxies ($\sim 5 \times 10^9 M_\odot$), but it is extended over $50h^{-1}$ kpc. Thus, the lack of star formation in this “E+A” is not due to an absence of gas, but perhaps to the low density of that gas. It is possible that this gas will someday fall back into the galaxy and generate new star formation.

The rarefied HI gas in this “E+A” suggests that the subsequent evolution of such galaxies could be affected by environment. Extended gas is

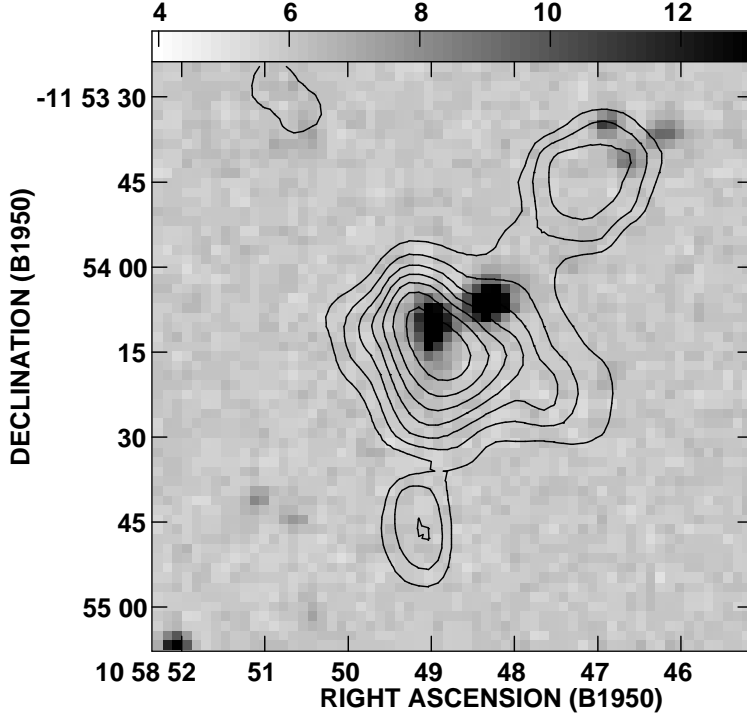


Figure 3. The HI distribution superposed on the Scanned Digitized Sky Survey SERC b_J image of one of the bluest “E+A”s in the sample. The central HI gas has a mass of $\sim 5 \times 10^9 M_\odot$, consistent with that in late type galaxies, but it is extended over more than $50h^{-1}$ kpc.

easier to strip by ram pressure than that in galactic disks. Therefore, if this “E+A” formed in a subcluster, instead of the field, it is likely that the effects of the intracluster medium would preclude subsequent star formation. While derived from only one VLA observation to date, this speculation may illuminate one source of the difference between the galaxy morphologies in clusters and in the field. In this spirit, our current observational program is to compare the gas distributions in cluster and field “E+A”s.

4. “E+A” Progenitors

As discussed above, the clear tidal features in some “E+A”s indicate that these galaxies have evolved morphologically, in addition to spectroscopically. To identify the morphologies of the most likely “E+A” progenitors, we assume that two progenitors merge to form an “E+A” and derive limits on their gas-to-stellar masses from the strength of the “E+A” starburst

(as inferred from a comparison of the Balmer absorption lines and the 4000Å break strengths with stellar population synthesis models; Bruzual & Charlot 1995). If the gas-to-stellar masses of the “E+A” progenitors are consistent with those of gas-rich, disk galaxies, and a particular “E+A” is an S0 or E, then we can conclude that a morphological transformation has occurred.

For most of the 21 LCRS “E+A”s, the (HI+H₂)-to-stellar mass ratios of a pair of Sa-c spirals provide sufficient gas to generate burst strengths corresponding to 10-30% of the total stellar mass in the “E+A”. Note that we assume a standard Scalo IMF and a star formation efficiency (*i.e.*, fraction of gas converted to stars) of 50% or less. However, for the bluest three “E+A”s in the sample (*e.g.*, Figure 1), the burst strengths of $\sim 50\%$ cannot be reproduced without relaxing some of these assumptions. For example, either both merging progenitors are late Sd disks, or at least one is a low surface brightness, Malin I type galaxy, or the star formation efficiency of the resulting burst is an extraordinary 100% (in contrast with the $\sim 50\%$ efficiencies of the brightest IRAS ultra-luminous galaxies). Although based on stellar population synthesis models that are still incomplete, these results support the picture that “E+A”s are a phase of galaxy evolution in which blue, star-forming disk galaxies are transformed via galaxy-galaxy encounters into early type S0 and E galaxies.

5. How Common is the “E+A” Phase?

Are “E+A”s rare objects or do they represent a short-lived phase in the evolution of many galaxies? From a comparison of the 21 “E+A” spectra with stellar population synthesis models, we estimate that the duration of the “E+A” phase is < 0.8 Gyr. The fraction of galaxies that are “E+A”s in the nearby universe is $21/11113 = 0.002$. Therefore, at least 4% of galaxies could have passed through an “E+A” phase within a Hubble time, a fraction which would constitute a significant number of the early types in the field. We plan to improve this estimate by comparing the HST images, HI maps, and follow-up long-slit spectra with simulations of galaxy-galaxy interactions (*cf.* Mihos & Hernquist 1994). The internal kinematics and morphological features on small scales should better constrain the time elapsed since the starburst ended and thus the duration of the “E+A” phase in galaxies.

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