E+A GALAXIES WITH BLUE CORES: ACTIVE GALAXIES IN TRANSITION
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ABSTRACT

Hubble Space Telescope (HST) ACS images reveal blue cores in four E+A, or post-starburst, galaxies. Follow-up spectroscopy shows that these cores have LINER spectra. The existence of LINERs, consistent with those in many elliptical galaxies, is yet one more piece of evidence that these postmerger, post-starburst, bulge-dominated galaxies will evolve into normal elliptical galaxies. More interestingly, if LINERs are powered by low-luminosity active galactic nuclei (AGNs), their presence in these E+A’s suggests that any rapid growth phase of the central black hole ended in rough concert with the cessation of star formation. This result emphasizes the importance of E+A’s for exploring how the evolution of black holes and AGNs may be tied to that of galactic bulges.

Subject headings: galaxies: active — galaxies: evolution — galaxies: starburst

1. INTRODUCTION

The strong correlation between black hole mass and galaxy bulge velocity dispersion \((M_\bullet - \sigma)\); Ferrarese & Merritt 2000; Gebhardt et al. 2000) suggests one of two things. Either early-type galaxies do not arise from dissipative mergers, or there is a connection—perhaps causal—between the small-scale physics of black hole (BH) growth and the large-scale physics that organizes the host galaxy morphology, kinematics, and stellar populations during and after the merger. Given the observational evidence that gas-rich mergers do occur and that at least some produce pressure-supported, bulge-dominated remnants, it remains to understand how the processes that drive the evolution of the smallest and largest galactic scales are related.

A key to resolving this question is to identify galaxies undergoing large-scale transitions via mergers and to consider the properties of their cores. Ongoing mergers are too complicated to provide clear answers, while their likely remnants are too far removed from the merger event. E+A galaxies, which have post-starburst spectra, frequent tidal features, and the kinematic and morphological signatures of early-type galaxies (Zabludoff et al. 1996; Norton et al. 2001; Chang et al. 2001; Yang et al. 2004), are true transitional objects and thus plausible test cases. In this Letter, we explore whether there is evidence for a central BH/AGN in nearby E+A’s and, if so, whether the core is consistent with those of early-type galaxies and evolving in concert with the galaxy as a whole.

2. DATA: IMAGING AND SPECTROSCOPY

Our sample is a subset of the 20 nearby \((0.06 < z < 0.12)\) E+A’s (defined to have strong Balmer absorption lines, \(\langle H\beta, H\gamma, H\delta \rangle > 5.5\) Å, but little or no \([O\, II]\) emission, EW([O\, II]) \(< 2.5\) Å) in the Las Campanas Redshift Survey (Zabludoff et al. 1996). Initial inspection of our HST Wide Field Planetary Camera 2 (WFPC2) and Advanced Camera for Surveys (ACS) \(B\) and \(R\) images reveals at least six galaxies with bright, blue, almost stellar-like cores (Y. Yang et al. 2006, in preparation). In Figure 1, we show the color profiles for three of these galaxies (EA 06, EA 16, EA 17) and for another blue-core galaxy (EA 01B) that was observed serendipitously. EA 01B is the disturbed companion galaxy of EA 01A (originally EA 1 in Zabludoff et al. 1996), which we have now determined spectroscopically to lie at the same redshift as EA 01A and also to have an E+A spectrum. The EA 01A-B system is the first known binary E+A system and provides additional evidence that the E+A phase of galaxy evolution is triggered by galaxy-galaxy interactions. The central blue core of each galaxy has \(\Delta(B-R) = 0.3\) with respect to the outer galaxy and a characteristic size of 1 kpc. With the exception of the blue cores, the morphologies of these galaxies are consistent with elliptical/S0 galaxies (EA 01B, EA 06, EA 16) or early spiral galaxies (EA 17).

The blue cores, while too faint to extract independently from models of the underlying galaxy light, raise the possibility of a central AGN (e.g., O’Connell et al. 2005) or of a luminous, compact star cluster (e.g., Colina et al. 2002). We therefore obtained long-slit spectra of the four blue-core E+A’s (and EA 01A) with the Inamori Magellan Areal Camera and Spectrograph (IMACS) on the Magellan 6.5 m Baade Telescope between 2005 April 3 and 5. We used the 300 line mm\(^{-1}\) grism and 0.7 wide slit, which resulted in a dispersion of 1.34 Å pixel\(^{-1}\) and a spectral resolution of \(\sim 4.2\) Å over the wavelength range 4000–8000 Å. We took three 600 s or 900 s exposures for each galaxy to remove the cosmic rays. The frames were processed and flux-calibrated in the standard manner with IRAF. The following analysis uses one-dimensional spectra extracted from a \(0.7' \times 2.7'\) aperture. No X-ray data are yet available for these sources to help discriminate between the possible origins of the blue cores.

3. NEBULAR DIAGNOSTICS OF NUCLEAR ACTIVITY

Optical nebular emission lines provide key diagnostics of the state of the interstellar medium and the source of ionization (AGN or hot stars). Measuring these lines presents a particular challenge in E+A’s because they are weak (by definition) and superposed on a complex stellar continuum. Conventional continuum subtraction techniques are inadequate, especially for the Balmer emission lines, which can be swallowed by 5 Å or more of stellar absorption. Instead, we fit a stellar population model to the continuum following C. Tremonti et al. (2006, in preparation). We use a library of template spectra drawn from the stellar population models of Bruzual & Charlot (2003), which have a spectral resolution of \(\sim 3\) Å. We use templates spanning a range of ages (1, 10, 25, 50, 100, 250, 500, and

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3 \(B\) and \(R\) correspond to F435W and F625W for the ACS imaging (EA 06, EA 16, and EA 17) and to F439W and F702W for the WFPC2 imaging (EA 01), respectively.
750 Myr and 1, 1.5, 3, 6, and 13 Gyr) and metallicities (0.4, 1, and 2.5 Z⊙). To construct the best-fitting model, we perform a nonnegative least-squares fit with dust attenuation modeled as an additional free parameter.

After subtracting the best-fitting stellar population model of the continuum, we fit the nebular emission lines. Because we are interested in recovering very weak nebular features, we adopt a special strategy: we fit all the emission lines with Gaussians simultaneously, requiring that the Balmer lines (Hα, Hβ, Ha) have the same line width and velocity offset, and likewise for the forbidden lines ([O iii] λλ4959, 5007, [N ii] λλ6548, 6584, [S ii] λλ6717, 6731). This procedure minimizes the number of free parameters and allows the stronger lines to constrain the weaker ones. The measured Hα emission-line equivalent widths range from 1 to 5 Å for Hα, and from 0.2 to 1.2 Å for Hβ. Measurements of lines this weak are only possible because of the high signal-to-noise ratio (S/N) of the spectra (10–40 pixel−1) and our continuum subtraction techniques.4 We show examples of our continuum and line fits in Figure 2.

To obtain error estimates for the line fluxes that include errors in the continuum subtraction, we adopt a bootstrap approach. For each spectrum, we take the difference between the continuum and the data as a measure of the error. We randomly resample the errors in bins of 500 Å, add them to the model of the continuum and nebular lines, and fit the resultant spectrum with our code. We do this 1000 times per galaxy and use the spread in the measured emission lines as our estimate of the error. The technique does not address possible systematic errors in the stellar population models. Therefore, we perform an identical fitting procedure, substituting the synthetic spectra of González Delgado et al. (2005) for the empirical ones of

4 The Tremonti et al. code allows the line amplitudes to be negative or positive, and hence there is no overall bias toward detecting lines in emission.

Bruzual & Charlot (2003). The resulting differences in line fluxes are small in EA 01A, EA 01B, and EA 17, but they exceed the random errors in EA 06 and EA 16 (see Fig. 3).

The weak nebular emission lines extracted from our spectra provide a key AGN diagnostic heretofore unavailable for most E+A’s. Following Baldwin et al. (1981) and Veilleux & Osterbrock (1987), we plot the flux ratios, [O iii] λλ5007/Hβ versus [N ii] λ6584/Hα, in Figure 3 (widely referred to as the BPT diagram). For comparison, we plot 254,548 emission-line galaxies from the Sloan Digital Sky Survey (SDSS) Data Release 4. The SDSS data form two distinct and remarkably narrow sequences in this plot, the first corresponding to gas ionized by massive, main-sequence stars (the star-forming sequence), and the second to gas ionized by other means (the Seyfert/LINER sequence). Kewley et al. (2001) theoretically calibrated a limit (Fig. 3, dashed curve) above which galaxies cannot be explained by any possible combination of parameters in a standard star-forming model. Kauffmann et al. (2003) used SDSS data to empirically calibrate a limit that more closely adheres to the star-forming galaxy locus (Fig. 3, solid curve).

Our E+A’s occupy an interesting part of the BPT plot. EA 01A falls squarely on the locus of star-forming galaxies, suggesting that there is minor star formation that was undetected previously because of dilution by light from larger radii. In contrast, the other four sources lie well above the star-forming locus, even considering the uncertainties. Kauffmann et al. (2003) quantify the position of AGNs in the BPT plot using a polar scheme centered at the point where the AGNs leave the star-forming galaxy locus. Galaxies are characterized by their distance D from the origin and by an angle Φ, which is zero along the positive [O iii]/Hβ axis and increases clockwise. Our four blue-core E+A’s have D = 1–1.1 and Φ = 30°–46°. Kauffmann et al. (2003) classify such galaxies as LINERs.
The nature of LINERs (Heckman 1980) remains a puzzle. LINERs may be low-luminosity AGNs (LLAGNs) arising from low-rate or low radiative efficiency accretion onto supermassive black holes (Halpern & Steiner 1983; Ferland & Netzer 1983), or they may be the product of other mechanisms (see Filippenko 2003 and references therein) such as photoionization by young clusters during the Wolf-Rayet phase (Barth & Shields 2000). For example, a 4 Myr old star cluster was identified as the dominant ionizing source of the LINER nucleus in NGC 4303 (Colina et al. 2002), but subsequent Chandra imaging revealed a hard X-ray point source indicative of an AGN (Jiménez-Bailón et al. 2003). In the nuclei of our E+A’s, the Balmer absorption lines constrain the mass fraction of stars less than 10 Myr old to be under 0.1%, ruling out a major contribution from young stars.

A more plausible alternative to ionization by an AGN is ionization by planetary nebula (PN) nuclei that appear in the late-phase evolution of intermediate-mass stars. (Indeed, some LINER galaxies have significant intermediate-age stellar populations [Cid Fernandes et al. 2004; González Delgado et al. 2004].) However, PNe nuclei are inefficient producers of Hα photons (Tanguchi et al. 2000), and the intermediate-age stellar mass required to generate the Hα luminosities of our nuclear spectra (a few times $10^{59}$ erg s$^{-1}$) is large ($\sim 10^8 M_\odot$) in the slit aperture. While such large masses are not ruled out, an LLAGN provides a more natural explanation. Indeed, many LINERs have nuclear activity difficult to explain by means of stellar processes: compact flat-spectrum radio cores or jets, X-ray point sources with power-law spectra, and broad Balmer emission (Ho 2004 and references therein). Maoz et al. (2005) found that 80% of LINERs with compact UV cores show significant variability, strongly linking LINERs to AGNs. Thus, the LINER spectra in our E+A’s are likely signposts of weak AGN activity, but we acknowledge that intermediate-mass stars may provide an alternate or additional source of gas ionization.

4. DISCUSSION

Using spectral diagnostics, we have discovered LINERs in the centers of four E+A galaxies with blue cores. These LINERs have low luminosities similar to those in many nearby early-type galaxies (Ho et al. 1997). The existence of LINERs in E+A’s, which are typically postmerger, post-starburst, and bulge-dominated galaxies, is more evidence that E+A’s will evolve into early-type galaxies.

If these LINERs are low-luminosity AGNs, that is, powered by black holes, a more interesting aspect of our discovery is the apparently simultaneous end of star formation and significant BH growth. If we estimate the AGN bolometric luminosity from the [O III] luminosity (Heckman et al. 2004), and the BH mass and associated Eddington luminosity from the $M_\bullet$-$
alpha$
relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000) and Norton et al.’s (2001) velocity dispersion, the black holes in these E+A’s are currently radiating at only 0.1%–0.5% of their theoretical maximum luminosity. Thus, any period of strong AGN activity and significant BH growth, as might occur during a gas-rich merger (Sanders et al. 1988), has now ended. The same is true for the star formation: after experiencing a burst within the last gigayear, these galaxies are now forming stars at rates of less than 0.01–0.08 $M_\odot$ yr$^{-1}$ (derived from the measured Hα luminosities assuming a star formation rate $SFR(M_\odot$ yr$^{-1}) = L_{H\alpha}/1.27 \times 10^{42}$ ergs s$^{-1}$; Kennicutt 1998).

These results have implications for the intersection of the small-scale physics associated with BH evolution and the large-scale physics that determines the properties of the host galaxy’s bulge. The coherence of the $M_\bullet$-$
alpha$
relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000) requires that these small- and large-scale processes be connected, either causally or through a third process, particularly in systems where $M_\bullet$ or $
alpha$
changes in a factor of a few years.

If the cores of these E+A’s do harbor LLAGNs, are the AGNs really fading? Kauffmann et al. (2003) find that powerful AGNs (Seyfert galaxies with large $D$ and $\Phi < 25^\circ$) lie in massive early-type galaxies with young stellar populations, whereas weak AGNs (pure LINERs with large $D$ and $\Phi > 25^\circ$) inhabit normal early-type galaxies. Given that the blue-core E+A’s are evolving from late- to early-type galaxies through the post-starburst phase, it is quite possible that their AGNs are also in transition (or fading) from the strong (Seyfert) to the weak (LINER) AGNs. Finding Seyfert nuclei among the youngest E+A’s would confirm this conjecture, but our sample is presently too small for this type of search.

Is the apparent relationship between the small-scale (LLAGN-sized) and large-scale (bulge-sized) physics in E+A galaxies causal? Recent numerical simulations including BHs suggest that collisions between galaxies trigger an inflow of gas that causes a strong circumnuclear starburst and fuel BH accretion. A powerful quasar outflow removes the gas from the inner region of the merger remnant, quenching the star formation on a relatively short timescale ($\sim 1$ Gyr; Springel et al.
2005a, 2005b). These models ultimately produce elliptical galaxies within a few gigayears and, unlike past simulations without AGN feedback (Mihos & Hernquist 1994, 1996), effectively predict a true E+A phase in which the merger remnant has no lingering star formation. It is possible, though not proved, that the LINERs in our blue-core E+A’s are the relic (fading) AGNs that once caused the truncation of star formation in these post-starburst galaxies. If so, their presence suggests a path by which early-type galaxies arrive on the M•-σ relation and also solves the long-standing puzzle of what mechanism during the merger ends the star formation in E+A’s.

What is the occurrence of LINER spectra in the general post-starburst galaxy population? In recent work, Yan et al. (2006) investigate the emission-line properties of a large sample of galaxies drawn from the SDSS. They find that AGNs are characterized by large [O iii]/Hα equivalent width (EW) ratios and conclude that post-starburst samples defined with an [O iii] EW cut (such as ours) will be biased against AGNs. However, our high-S/N spectroscopy reveals that even E+A’s with negligible emission (1–5 Å at Hα) have line ratios characteristic of AGNs. Yan et al. (2006) were able to use the BPT diagram (i.e., our Fig. 3) to classify only 40% of their post-starburst sample, owing to the weakness of the emission lines. Of the galaxies they can classify, ~90% harbor AGNs. They suggest that many of the weaker-lined objects may have LINER-like spectra, which is consistent with our results.

A final puzzle is the nature of the blue cores, which first led us to investigate these galaxies. While our ground-based spectral resolution is not ideal for addressing this question, the low emission-line luminosity of our LINERs and the lack of broad emission lines suggest that the blue light is not from an AGN continuum. It may instead arise from a (fading) circumnuclear starburst, which grew in concert with the nuclear activity. Blue cores are common in early-type galaxies at higher redshift (z ≥ 0.5), when field spheroids were assembling. For example, 30% of the morphologically selected elliptical galaxies in the Hubble Deep Field North have color inhomogeneities, mostly due to blue cores (Menanteau et al. 2001). Treu et al. (2005) find that ~15% (2/14) of blue-core spheroids in the Great Observatories Origins Deep Survey North (GOODS-N) field have X-ray detections (LX > 10^40 erg s^-1), suggesting the presence of AGNs. Our blue-core LINER E+A’s may be local examples of a phenomenon common at high redshift.

5. CONCLUSIONS

We identify four E+A galaxies with blue cores, which are revealed by our follow-up spectroscopy to have LINER spectra. The existence of LINERs, similar to those in elliptical galaxies, is more evidence that E+A galaxies, with their post-starburst spectra, postmerger, gas-poor, bulge-dominated morphologies, and pressure-supported kinematics (e.g., Norton et al. 2001; Chang et al. 2001; Yang et al. 2004), evolve into normal early-types. More interestingly, if LINERs are low-luminosity AGNs, their presence in E+A’s suggests that any rapid growth phase of the central AGN has ended in rough concert with the star formation and therefore that the evolution of the black hole is tied to that of the galactic bulge. What is not clear from our work is whether the coupling between AGN and bulge evolution is causal, as is suggested by some theoretical models incorporating AGN feedback (Springel et al. 2005a, 2005b).

The study of a large sample of E+A’s, including an investigation of any correlation between AGN strength and the time elapsed since the starburst, could provide a test of the AGN feedback hypothesis, as those models predict that the black hole accretion rate peaks shortly after the starburst and declines quickly as the merger remnant ages.

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REFERENCES

Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5 (erratum 93, 817)
Barth, A. J., & Shields, J. C. 2000, PASP, 112, 753
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Chang, T.-C., van Gorkom, J. H., Zabludoff, A. I., Zaritsky, D., & Mihos, J. C. 2001, AJ, 121, 1965
Cid Fernandes, R., et al. 2004, ApJ, 605, 105
Colina, L., González Delgado, R., Mas-Hesse, J. M., Leitherer, C., & Jiménez-Bailón, E. 2002, ApJ, 579, 545
Ferland, G. J., & Netzer, H. 1983, ApJ, 264, 105
Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9
Filipenko, A. V. 2003, in ASP Conf. Ser. 290, Active Galactic Nuclei: From Central Engine to Host Galaxy, ed. S. Collin, F. Combes, & I. Shlosman (San Francisco: ASP), 369
Gebhardt, K., et al. 2000, ApJ, 539, L19
González Delgado, R. M., Cid Fernandes, R., Peñarrubia, J., Peñarrubia, J., & Storchi-Bergmann, T. 2004, ApJ, 605, 127
Halpern, J. P., & Steiner, J. E. 1983, ApJ, 269, L37
Heckman, T. M. 1980, A&A, 87, 152
Heckman, T. M., Kauffmann, G., Brinchmann, J., Charlot, S., Tremonti, C., & White, S. D. M. 2004, ApJ, 613, 109
Ho, L. C. 2004, in Coevolution of Black Holes and Galaxies, ed. L. C. Ho (Cambridge: Cambridge Univ. Press), chap. 19
Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1997, ApJ, 487, 568
Jiménez-Bailón, E., Santos-Lleó, M., Mas-Hesse, J. M., Guainazzi, M., Colina, L., Cerviño, M., & González Delgado, R. M. 2003, ApJ, 593, 127
Kauffmann, G., et al. 2003, MNRAS, 346, 1055
Kennicutt, R. C., Jr. 1998, ARA&A, 36, 189
Kewley, L. J., Dopita, M. A., Sutherland, R. S., Heisler, C. A., & Trevena, J. 2001, ApJ, 556, 121
Maoz, D., Nagar, N. M., Falcke, H., & Wilson, A. S. 2005, ApJ, 625, 699
Menanteau, F., Abraham, R. G., & Ellis, R. S. 2001, MNRAS, 322, 1
Mihos, J. C., & Hernquist, L. 1994, ApJ, 425, L13
Mihos, J. C., & Hernquist, L. 1995, ApJ, 464, 641
Norton, S. A., Gebhardt, K., Zabludoff, A. I., & Zaritsky, D. 2001, ApJ, 557, 150
O’Connell, R. W., Martin, J. R., Crane, J. D., Burstein, D., Bohlin, R. C., Landsman, W. B., Freedman, I., & Rood, R. T. 2005, ApJ, 635, 305
Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W. 2002, AJ, 124, 266
Sanders, D. B., Soifer, B. T., Elias, J. H., Madore, B. F., Matthews, K., Neugebauer, G., & Scoville, N. Z. 1988, ApJ, 325, 74
Springel, V., Di Matteo, T., & Hernquist, L. 2005a, MNRAS, 361, 776
Springel, V., Di Matteo, T., & Hernquist, L. 2005b, MNRAS, 361, 776
Taniguchi, Y., Shioya, Y., & Murayama, T. 2000, AJ, 120, 1265
Treu, T., et al. 2005, ApJ, 633, 174
Veilleux, S., & Osterbrock, D. E. 1987, ApJS, 63, 295
Yan, R., Newman, J. A., Faber, S. M., Konidaris, N., Koo, D., & Davis, M. 2006, ApJ, in press (astro-ph/0512446)
Yang, Y., Zabludoff, A. I., Zaritsky, D., Lauer, T. R., & Mihos, J. C. 2004, ApJ, 607, 258
Zabludoff, A. I., Zaritsky, D., Lin, H., Tucker, D., Hashimoto, Y., Shectman, S. A., Oemler, A., & Kirshner, R. P. 1996, ApJ, 466, 104 (erratum 516, 505 [1999])