A CENSUS OF BROAD-LINE ACTIVE GALACTIC NUCLEI IN NEARBY GALAXIES: COEVAL STAR FORMATION AND RAPID BLACK HOLE GROWTH

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Received 2012 May 9; accepted 2012 December 2; published 2013 January 17

ABSTRACT

We present the first quantified, statistical map of broad-line active galactic nucleus (AGN) frequency with host galaxy color and stellar mass in nearby (0.01 < z < 0.11) galaxies. Aperture photometry and z-band concentration measurements from the Sloan Digital Sky Survey are used to disentangle AGN and galaxy emission, resulting in estimates of uncontaminated galaxy rest-frame color, luminosity, and stellar mass. Broad-line AGNs are distributed throughout the blue cloud and green valley at a given stellar mass, and are much rarer in quiescent (red sequence) galaxies. This is in contrast to the published host galaxy properties of weaker narrow-line AGNs, indicating that broad-line AGNs occur during a different phase in galaxy evolution. More luminous broad-line AGNs have bluer host galaxies, even at fixed mass, suggesting that the same processes that fuel nuclear activity also efficiently form stars. The data favor processes that simultaneously fuel both star formation activity and rapid supermassive black hole accretion. If AGNs cause feedback on their host galaxies in the nearby universe, the evidence of galaxy-wide quenching must be delayed until after the broad-line AGN phase.

Key words: galaxies: active – galaxies: evolution – galaxies: nuclei – quasars: general

Online-only material: color figures, machine-readable table

1. INTRODUCTION

The well-studied correlations between supermassive black hole (SMBH) mass and properties of the host galaxy bulge (e.g., Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merrit 2000; Marconi & Hunt 2003) indicate that SMBH growth may be intimately tied to galaxy evolution. However, the causal physics behind the SMBH-galaxy link remains mysterious. Theoretical simulations suggest that rapidly accreting SMBHs in the active galactic nucleus (AGN) phase correspond to periods of recent massive star formation in their host galaxies (e.g., Hopkins et al. 2006, 2008). Powerful AGNs may also cause “feedback” on their host galaxies, shutting down star formation by blowing out the star-forming gas either via radiative winds (Silk & Rees 1998; Fabian 2002; Di Matteo et al. 2005) or radio jets (Croton et al. 2006). Observational evidence for star formation or feedback coevolving with black hole growth can be found in the star formation histories of AGN host galaxies (e.g., Heckman & Kauffmann 2006).

Of particular interest are the hosts of the most luminous AGNs, which are readily identified by broad emission lines in their optical spectra (e.g., Vanden Berk et al. 2001). These broad-line AGNs rapidly accrete material at rates of 1%–100% of the Eddington limit (Kollmeier et al. 2006; Trump et al. 2009), and so require plentiful gas in their hosts, with the possibility of accompanying star formation activity. There is also evidence that broad-line AGNs universally have high velocity optical and X-ray outflows (Ganguly & Brotherton 2008; Winter 2010), indicative of powerful winds and the potential for effective feedback in shutting down star formation. Studying the mass and rest-frame color of the host galaxy can reveal its recent star formation history: at a given stellar mass, galaxies that are very blue in rest-frame u – z have recently experienced a great deal of star formation, while red galaxies are quiescent and dominated by old stars. However, the brightness of many broad-line AGNs complicates observations of their host galaxies, since the AGN often outshines the galaxy’s starlight.

Most authors simply avoid the problem of AGN contamination by studying host-dominated AGN. “Host-dominated” means that the accreting black hole is either obscured or weakly accreting (Eddington ratios of <1%), and the photometry is dominated by the host galaxy. Studies of such host-dominated AGNs suggest a preference for massive (log(M*/M⊙) > 10.5) host galaxies (Kauffmann et al. 2003a; Haggard et al. 2010), although Aird et al. (2012) suggest this is a relic of selection effects and AGNs are instead equally likely to be in hosts of any stellar mass. Several observations suggest that host-dominated AGNs are most often found in “green valley” galaxies, so called because they have colors intermediate between the more densely populated star-forming blue cloud and the passive red sequence of galaxies (Nandra et al. 2007; Salim et al. 2007; Georgakakis et al. 2008; Silverman et al. 2008; Gabor et al. 2009; Schawinski et al. 2009; Hickox et al. 2009; Kocevski et al. 2009). Other studies, however, argue that active galaxies have the same color distribution as inactive galaxies of similar mass and the apparent green valley peak for AGN hosts is caused only because AGNs prefer massive galaxies (Silverman et al. 2009; Xue et al. 2010). Cardamone et al. (2010) additionally argue that the apparent green valley hosts of AGNs are just dust-reddened star-forming (and intrinsically blue) galaxies, and dust-corrected AGN hosts have the same color distribution as inactive galaxies.

Besides the difficulties in the differing interpretations, the above studies include only obscured or weakly accreting AGNs with very different fueling and outflow properties from luminous broad-line AGNs (Ho 2008; Trump et al. 2011). By definition, host-dominated AGNs do not dominate the energetics of their hosts, and probably have minimal influence on the current star formation in their galaxies. Studying the impact of AGNs on galaxy evolution requires observing galaxies during the most rapid period of SMBH growth.

Studies of broad-line AGN host galaxies have generally used structural decomposition of high spatial resolution Hubble Space Telescope (HST) images (e.g., Peng et al. 2002). By modeling the luminous point-source AGN and subtracting
it from the extended host galaxy light, the intrinsic galaxy properties can be disentangled from the contaminating AGN. The first high-resolution studies of quasar hosts suggested that these luminous AGNs prefer massive and luminous hosts (Bahcall et al. 1997). The host galaxies of luminous AGNs were also found to have younger stellar populations than inactive galaxies of the same mass, with colors spanning the blue cloud and green valley (Jahnke et al. 2004a, 2004b). However, the need for high-resolution HST imaging limited these studies to small numbers (~20) of AGNs. Recent Herschel far-infrared studies, also limited to small samples, similarly suggest that more luminous AGNs have higher star formation rates than their inactive counterparts (Santini et al. 2012; Rovilos et al. 2012; but see also Mullaney et al. 2012).

In this work we expand host galaxy studies of rapidly accreting AGNs using 561 broad-line AGNs at 0.01 < z < 0.11 from the Sloan Digital Sky Survey (SDSS). The large number of AGNs, with a set of matched inactive galaxies, allows for the first statistical map of broad-line AGN frequency across the nearby galaxy color–mass diagram. The selection and properties of the data are described in Section 2. Our AGN/host decomposition method is described in Section 3, which introduces a novel aperture photometry method for separating point-source AGNs and extended inactive galaxies. Section 4 reveals that the broad-line AGNs have a strong preference for star-forming galaxies, and demonstrates that this preference is not a function of selection effects. We discuss what these results mean for the relationship between nuclear activity and star formation, and the efficacy of AGN feedback, in Section 5.

Throughout this work we assume a cosmology with $h = 0.70$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$.

2. OBSERVATIONAL DATA

We select samples of broad-line AGNs and inactive galaxies from the SDSS (York et al. 2000). Each type is selected using the spectroscopic classification provided by the SDSS DR7: broad-line AGNs are identified by $SpecClass = 3$, while galaxies without broad emission lines have $SpecClass = 2$. We visually inspected the spectra of all broad emission line AGNs to ensure that they are correctly classified (removing the misclassified ~1% of objects). Note that we refer to all galaxies without broad lines as inactive, while some of these “inactive” galaxies may actually have emission line ratios that suggest weak or obscured AGNs (Baldwin et al. 1997; Kewley et al. 2006).

Given the parent sample of broad-line AGNs and inactive (non-broad-line) galaxies in the SDSS, we make the following cuts.

1. Face-on systems only, with $b/a > 0.5$ (where $b/a$ is the ratio between the minor and major axes of the $r$-band image). This constraint is designed to eliminate dusty systems and removes a significant number (36%) of inactive galaxies but only 15% of the initial broad-line AGNs.

2. $0.01 < z < 0.11$. The sample is further sub-divided into $\Delta z = 0.01$ bins (i.e., $0.01 < z < 0.02$, $0.02 < z < 0.03$, etc.) for the AGN light correction, as described in Section 3.

$3. r < 17.77$. This is the spectroscopy limit for inactive galaxies in the SDSS. Although the SDSS spectroscopy includes broad-line AGNs to fainter magnitudes ($i < 19.1$ or $i < 20.2$), we require $r < 17.77$ for both samples to ensure a complete control sample.

The SDSS spectroscopy is >95% complete to both galaxies and quasars in these redshift and magnitude ranges (Strauss et al. 2002; Richards et al. 2002). These initial selection criteria result in a total of 192,946 inactive galaxies and 972 broad-line AGNs. Beyond the redshift and magnitude limits, the sample is divided into luminosity-limited “faint” and “luminous” samples, each complete to a given $r$-band absolute magnitude.

1. Luminous sample. This is limited to all $0.01 < z < 0.11$ sources with $M_r < -20.8$, which corresponds to the $r < 17.77$ spectroscopy limit at $z = 0.11$. The luminous sample probes the full redshift range of the sample, and includes 506 broad-line AGNs and 119,022 inactive galaxies.

2. Faint sample. This is limited to all $0.01 < z < 0.05$ sources with $M_r < -19$, which similarly corresponds to the $r < 17.77$ limit at $z = 0.05$. The faint sample is designed to probe a large range of luminosities and stellar masses, with 120 broad-line AGNs and 34,164 inactive galaxies.

Note that galaxies in the faint sample with $M_r < -20.8$ are also in the luminous sample, and there are a total of 561 unique broad-line AGNs in the two samples.

2.1. Photometry

The SDSS provides magnitudes in five $ugriz$ filters for all broad-line AGNs and inactive galaxies. We use both the total magnitude $m$ integrated across the entire galaxy, and the inner aperture magnitude $m_{in}$ measured within a $3''$ diameter of the galaxy center. An outer aperture magnitude $m_{out}$ is calculated from the light outside the $3''$ diameter, given by

$$m_{out} = -2.5\log(10^{-0.4m} - 10^{-0.4m_{in}}).$$

Note that $m_{in}$ is calculated after convolving the image to 2'', which ensures uniform seeing for all objects. While convolving to lower resolution slightly worsens AGN contamination, it actually helps our AGN/galaxy decomposition by ensuring that all active galaxies have the same 2'' resolution as the point-source stars and inactive galaxies used to calibrate the method.

We $K$-correct the observed photometry in both samples to the $z = 0.05$ frame using the public $k$correct IDL software (Blanton & Roweis 2007). The prime (′) notation is used to denote colors and magnitudes $K$-corrected to $z = 0.05$. Figure 1 shows the $K$-corrected outer $(u - z)'$ color with the outer $M'$ absolute magnitude for inactive galaxies and broad-line AGNs in the faint sample, and Figure 2 similarly shows the luminous sample. Naively one might assume that the outer magnitudes do not contain any light from the AGN point source. However, both figures show that many broad-line AGNs have brighter and bluer outer magnitudes than the inactive galaxy population. Light from the SDSS point-spread function (PSF) extends beyond the inner 3'' aperture, and a more sophisticated process is necessary to recover the uncontaminated galaxy properties. This technique is derived and applied in Section 3.

The high $b/a$ preference for broad-line AGNs could be a selection bias, such that a point source is biasing the axis ratio measurement. However, several studies also suggest a genuine preference for broad-line AGNs to lie in spheroid-dominated (Bahcall et al. 1997) or face-on (Rigby et al. 2006) galaxies.
Figure 1. Outer \((u - z)'\) color with outer \(M_z'\) absolute magnitude, each \(K\)-corrected to \(z = 0.05\), for both inactive galaxies (contours and points) and broad-line AGNs (filled red circles) in the faint sample. Outer magnitudes represent the light outside a 3" diameter aperture. Broad-line AGNs lie all over the color–magnitude diagram but tend to appear brighter and bluer than inactive galaxies because the AGN light contaminates even the outer magnitude measurements. Section 3 outlines the derivation and application of a correction that recovers the uncontaminated host galaxy light for broad-line AGNs.

(A color version of this figure is available in the online journal.)

Figure 2. \(K\)-corrected outer \((u - z)'\) color with outer \(M_z'\) absolute magnitude for the luminous sample, where outer magnitudes are defined as the light outside a 3" diameter aperture. As in Figure 1, light from the AGN causes their hosts to appear brighter and bluer than inactive galaxies. The contaminating blue AGN light is particularly evident in the many AGNs with total \(M_r < -20.8\) but outer \(M_z > -20.8\) (in contrast to the typically redder inactive galaxy population).

(A color version of this figure is available in the online journal.)

2.2. Stellar Masses

Galaxy stellar masses come from the MPA-JHU value-added catalog, derived according to Kauffmann et al. (2003b). Derived masses for the inactive galaxies have 1\(\sigma\) errors of \(\sim 0.05\) dex, with no error dependence on mass or magnitude. However, most of the broad-line AGN hosts are absent from this catalog, and those included in the catalog probably have inaccurate stellar masses due to the AGN contamination. To estimate masses for AGN hosts, we first calculate the mass-to-light ratios of inactive galaxies as a function of color and luminosity.

Figure 3 shows the median \(z'\)-band mass-to-light ratio in bins across the color–magnitude diagram. We use this figure to estimate masses for broad-line AGN hosts, applying the mass-to-light ratio from the bin corresponding to their corrected (AGN-subtracted) host galaxy color and absolute magnitude.

3. DISENTANGLING AGN AND GALAXY LIGHT

Broad-line AGNs dominate the light in the inner (<3") aperture but also contribute light in the outer (>3") aperture (as shown by Figures 1 and 2). We seek to remove the AGN emission to obtain uncontaminated measurements of host galaxy light. It turns out that inactive galaxies, uncontaminated by AGN light, have fairly tight relationships between \(z\)-band concentration and inner and outer magnitudes in each filter: we exploit
Figure 3. Median mass-to-light ratio, in the $z'$-band, for all inactive galaxies with $r < 17.77$ at $0.01 < z < 0.11$. Mass-to-light ratio is computed in bins of color $(u - z')$ and luminosity ($M'_z$), with no data shown for bins containing fewer than five galaxies. Mass-to-light ratio is a strong function of color and a weak function of luminosity. This figure is used to estimate masses for broad-line AGN hosts, using their corrected (AGN-subtracted) galaxy colors and luminosities to determine the appropriate mass-to-light ratio.

(A color version of this figure is available in the online journal.)

These relationships to predict the galaxy-only magnitudes of AGN hosts. Likewise the relationship between inner and outer magnitudes of stars can predict the magnitudes of the AGN-only point-source component.

3.1. Galaxy Inner and Outer Aperture Magnitudes

We begin by comparing the inner ($< 3''$) and outer ($> 3''$) aperture magnitudes of inactive galaxies and broad-line AGNs. Figure 4 shows inner and outer magnitudes in three different filters ($u$, $r$, $z$) and redshift ranges ($0.02 < z < 0.03$, $0.04 < z < 0.05$, $0.08 < z < 0.09$). Light from broad-line AGNs has the strongest contaminating effect in blue light and inner magnitudes, but also affects outer magnitudes. For each of the five filters and in 10 bins of redshift ($0.01 < z < 0.11$ in $\Delta z = 0.01$ intervals), we find the best-fit line describing outer ($m_{\text{out}, \text{GAL}}$) and inner magnitude ($m_{\text{in}, \text{GAL}}$) for inactive galaxies (shown by the dashed lines for the filters and redshift ranges in Figure 4). The offset above this line is defined by

$$\Delta m = A + Bm_{\text{out, GAL}} - m_{\text{in, GAL}}. \quad (2)$$

The best-fit line is given by $\Delta m = 0$, and broad-line AGNs typically have $\Delta m > 0$. However, even inactive galaxies have a large scatter in $\Delta m$, presumably because there is significant structural variation in galaxies of a given outer apparent magnitude. Adding a structural measurement could better describe the typical relationship for inner and outer magnitudes in inactive galaxies and explain their scatter about $\Delta m = 0$. In particular we use $z$-band concentration, defined as the ratio between the radius containing 90% of the $z$-band light and the radius containing 50% of the light, $C_z = R_{90,z}/R_{50,z}$.

Figure 5 shows $\Delta m$ from Equation (2) versus $z$-band concentration $C_z$. Galaxies with $\Delta m < 0$ (from fainter inner magnitudes...
Figure 5. Offset from the best-fit line describing inner and outer magnitudes in Figure 4 (Δm, given by Equation (2)) vs. z-band concentration (Cz) for inactive galaxies (black contours and points) and broad-line AGNs (filled red circles). The panels show the same three filters and redshift ranges as in Figure 4. The dashed blue line shows the best-fit cubic line to the inactive galaxy population. Broad-line AGNs have the same range in Cz as inactive galaxies, but tend to have significantly higher Δm (especially in blue light). The offset from the best-fit line is the residual δm in Equation (3).

(A color version of this figure is available in the online journal.)

than the average given their outer magnitude) have low concentration, while galaxies with Δm > 0 (and brighter inner magnitudes) are more concentrated. The inactive population shows a tighter relation after using Cz to describe the structural variation, and broad-line AGNs scatter to brighter inner magnitudes and higher Δm.

A cubic line is fit to the inactive galaxies in Figure 5 (shown by the dashed line), with the offset from this line given by

$$\delta m = \Delta m - C - DC_z - EC_z^2 - FC_z^3.$$  \hspace{1cm} (3)

Figure 6 shows δm with Cz for inactive galaxies and AGNs. Broad-line AGN hosts tend to have δm > 0, as the AGN light causes the inner aperture magnitude to be brighter than expected given the galaxy’s z concentration. Inactive galaxies have δm ~ 0 with small scatter: the standard deviation is typically only $\sigma_{\delta m} = 0.3$ mag, with slightly larger $\sigma_{\delta m} = 0.5$ mag scatter for low-concentration (Cz < 2.5) galaxies in the u band. We use δm as an estimate of the brightness excess in the inner aperture due to AGN light.

Using Equation (3) for AGN/host decomposition has two important assumptions. First, we assume that Cz is not contaminated by the broad-line AGN. We originally chose Cz with this in mind: z-band light is the least affected by the (typically blue) AGN, and $R_{50}$ and $R_{90}$ are large radii well beyond the point-source AGN. Figure 7 directly tests if the AGN affects Cz by plotting AGN luminosity against z-band concentration and comparing the distributions of Cz among broad-line AGNs and inactive galaxies. In general, both the faint and luminous AGN samples span a wide range of concentrations. However, the most luminous ($M'_{u,AGN} < -20$) AGNs are typically more concentrated: this may be evidence that very luminous AGNs contaminate the concentration measurement, or it may be that more luminous AGNs prefer more bulge-like hosts (Bahcall et al. 1997; Cisternas et al. 2011; Kocevski et al. 2012). In case it is the result of a bias, we flag these high-luminosity AGNs when discussing any connections between AGN strength and host galaxy properties. Meanwhile we conclude that our assumption that Cz is unaffected by the AGN remains valid for the bulk of broad-line AGNs with $M'_{u,AGN} > -20$.

The second assumption is that all inactive galaxies have δm ~ 0 with some random scatter $\sigma_{\delta m}$, independent of the presence of an AGN. There is evidence that this scatter is not due to measurement error: as Figure 8 shows, inactive galaxies have values of δm that are correlated across the ugriz filters. In other words, an inactive galaxy with δm ~ 1 in the u band will also tend to have δm ~ 1 in g, r, i, z. (This effectively means that the δm = 0 assumption causes a much smaller scatter in color than in luminosity or stellar mass: see Section 3.4.) We tested if, in addition to Cz, δm was connected to galaxy properties like color or Sérsic (1968) index. However, we found no additional correlation and were unable to find the physical basis for the small scatter of inactive galaxies about δm = 0. Defining δm using color and Sérsic index instead of Cz also proved ineffective at reducing the scatter. Instead $\sigma_{\delta m}$ is treated as a random error, and we investigate its effects in Section 3.4.

Inactive galaxies with Δz > 1 (in the upper left of the right panels in Figure 6) are potentially interesting because they have...
Figure 6. Offset from the best-fit cubic describing galaxy structure in Figure 5 ($\delta m$, given by Equation (3)) vs. $z$-band concentration ($C_z$) in the same filters and redshift ranges as in Figures 4 and 5. Inactive galaxies are shown by black contours and points and broad-line AGN hosts are given by filled red circles. The dashed blue line shows $\delta m = 0$, and the solid blue lines show the scatter of the inactive galaxies about $\delta m = 0$.

(A color version of this figure is available in the online journal.)

Figure 7. At top, the host-subtracted AGN $u$-band absolute magnitude with $z$-band concentration for both the faint ($M'_{r} < -19, 0.01 < z < 0.05$) and luminous ($M'_{r} < -20.8, 0.01 < z < 0.11$) samples. The bottom panels show histograms of the $C_z$ distributions for both inactive galaxies and broad-line AGNs in both samples. The distribution of concentration among the most luminous ($M'_{r,AGN} < -20$) AGNs peaks at higher values: we flag these high-luminosity AGNs in the subsequent discussion because their concentration might be biased by AGN contamination. Note that the different concentration distributions between the two inactive galaxy samples is caused by the luminous sample containing a higher proportion of high-mass spheroids than the faint sample.

(A color version of this figure is available in the online journal.)
Figure 8. Comparisons of measured $\delta m$ (from Equation (3)) for inactive galaxies in $ugrz$ filters. Values of $\delta m$ in different filters are strongly correlated near the dashed one-to-one line.

similar relationships between inner and outer magnitudes to bright AGNs. However, after visually inspecting their images and spectra we determined that these galaxies probably have nuclear starbursts and are not some class of misclassified broad-line AGNs.

3.2. Point Source Inner and Outer Aperture Magnitudes

Most of the light from a point source is detected in the inner aperture, but the PSF of the SDSS causes light from point sources to “leak” into the outer aperture as well. Stars can be used to model the relationship between inner and outer aperture magnitudes for AGN-only light ($m_{\text{in,AGN}}$ and $m_{\text{out,AGN}}$), since both are point sources. We select a sample of 362 stars with $r < 16$ and $-0.2 < r - z < -0.1$. The brightness ensures their photometry is well measured, and the color cut makes them similar to the colors of bright AGNs.

Figure 9 shows the inner and outer magnitudes for the sample of 362 stars. These point sources have a well-defined relationship between inner and outer aperture magnitude, and the best-fit line in each filter describes the relationship between inner and outer magnitude for the AGN-only light:

$$m_{\text{in,AGN}} = G + H m_{\text{out,AGN}}.$$ (4)

Figure 9 shows that the brightest AGNs behave like point sources in blue light and lie on this line, while in red light AGNs behave more like inactive galaxies. Because all the images are convolved to 2′′ before measuring the aperture photometry, $m_{\text{in,AGN}} \approx 1 + m_{\text{out,AGN}}$ in all five filters.

3.3. The Equations for Decomposing AGN and Galaxy Light

Given the derived relationships between inner and outer magnitudes for galaxy-only (Equations (2) and (3)) and AGN-only (Equation (4)) light, we can solve for the unknown quantities $m_{\text{in,AGN}}$, $m_{\text{out,AGN}}$, $m_{\text{in,GAL}}$, and $m_{\text{out,GAL}}$. First, the total outer and inner magnitudes (both measured quantities) are simply the sum of the flux contributions from the AGN and the galaxy:

$$f_{\text{in}} = f_{\text{in,AGN}} + f_{\text{in,GAL}}$$ (5)

$$f_{\text{out}} = f_{\text{out,AGN}} + f_{\text{out,GAL}}.$$ (6)

The relationship between flux and AB magnitude is defined by $m = -2.5 \log(f_\nu) - 48.6$. Combining Equations (2) and (3) and
Table 1

| SDSS ID | R.A. | Decl. | Redshift | $M_\text{r}$ | Raw $u$ | Corrected $u$ | $\delta u$ | $C_z$ | $(u-z)$ | $\log(M_*/M_\odot)$ |
|---------|------|-------|----------|-------------|---------|--------------|----------|------|---------|------------------|
| 587732484349100048 | 147.638145 | 44.314366 | -0.21 | 16.73 | 17.00 | 0.40 | 4.19 | 3.52 | 10.18 |
| 587742060558668457 | 233.968767 | 14.517118 | -0.20 | 15.94 | 16.18 | 1.16 | 2.25 | 2.65 | 10.06 |
| 587735240099594710 | 129.386277 | 28.705193 | -0.21 | 14.88 | 14.92 | 0.21 | 2.20 | 3.39 | 10.67 |
| 587734985892731110 | 146.372371 | 9.602890 | -0.13 | 19.46 | 16.41 | 1.61 | 2.86 | 2.87 | 9.71 |
| 587739111560882185 | 214.498122 | 25.136867 | -0.16 | 14.78 | 15.20 | 1.70 | 3.09 | 3.15 | 10.73 |
| 587724224824206208 | 52.552573 | -5.543318 | -0.13 | 19.91 | 14.91 | 14.99 | 0.35 | 2.55 | 2.81 | 10.42 |
| 587734622701093005 | 121.410997 | 26.168188 | -0.17 | 15.15 | 15.21 | 0.63 | 1.90 | 2.95 | 10.62 |
| 587735695380578421 | 224.278321 | 49.669022 | -0.24 | 15.47 | 14.72 | 0.99 | 2.85 | 2.26 | 10.15 |
| 587725039018311737 | 180.309815 | -3.678079 | -0.19 | 16.09 | 16.31 | 0.70 | 2.71 | 3.30 | 10.89 |
| 158778946626295257 | 129.545598 | 24.895276 | -0.28 | 15.46 | 16.39 | 2.23 | 2.74 | 2.27 | 9.80 |
| 587732577734206246 | 161.215528 | 6.596847 | -0.27 | 15.11 | 15.15 | 0.03 | 2.09 | 2.55 | 10.85 |
| 587738616432829796 | 154.956204 | 33.367070 | -0.23 | 16.10 | 17.41 | 2.16 | 3.00 | 2.67 | 9.86 |
| 587726014003216406 | 198.274215 | 1.465598 | -0.24 | 17.31 | 17.64 | 0.32 | 2.78 | 2.92 | 10.15 |
| 587730308096686354 | 171.400663 | 54.382551 | -0.06 | 17.00 | 17.78 | 1.19 | 3.03 | 2.66 | 9.60 |
| 587741490361204744 | 141.827109 | 23.020102 | -0.26 | 16.18 | 16.36 | 0.27 | 3.00 | 3.52 | 10.89 |
| 587732771575955522 | 144.551130 | 7.727765 | -0.20 | 16.92 | 17.42 | 0.83 | 3.01 | 3.20 | 10.09 |
| 587729233053417523 | 251.839456 | 44.702175 | -0.25 | 17.41 | 17.57 | -0.31 | 2.54 | 2.88 | 9.97 |
| 587733603709063381 | 245.053147 | 40.151711 | -0.20 | 16.16 | 16.77 | 1.43 | 3.11 | 2.16 | 9.93 |
| 588010359086579732 | 180.740878 | 4.848583 | -0.20 | 15.87 | 15.98 | 0.96 | 1.89 | 3.08 | 10.58 |

Notes.

a The full catalog of 561 broad-line AGNs appears as a machine-readable table in the online journal. In addition to the columns shown here, the full catalog includes raw and corrected magnitudes and $\delta m$ measurements for all five ugriz filters.

b All magnitudes are K-corrected to $z = 0.05$ and given in AB units.

(converting to flux results in

$$f_{\text{in,GAL}} = X \cdot f_{\text{out,GAL}}^B,$$

(7)

with $X = 10^{-0.4(A_{u}-48.6-A_{g}-48.6-B-C_{DZ}-E_{C_1}-F_{C_2})}$.  

Equation (4) is similarly converted from magnitude to flux:

$$f_{\text{in,AGN}} = Q \cdot f_{\text{out,AGN}}^H,$$

(8)

with $Q = 10^{-0.4(G_{u}-48.6-G_{g}-48.6-H)}$.  

There are now four equations (Equations (5)–(8)) that describe the relationships between inner and outer magnitudes for each of the broad-line AGN and galaxy contributions. The quantities $f_{\text{in}}, f_{\text{out}},$ and $C_z$ are measured, and the coefficients $A, B, C, D, E, F, G,$ and $H$ come from our line fits in each filter and redshift bin (with three example filters and redshift bins shown in Figures 4–6). Solving these four equations for $f_{\text{in,AGN}}$ results in

$$f_{\text{in,AGN}} = f_{\text{in}} - X \{ f_{\text{out}} - (f_{\text{in,AGN}}/Q)^{H/B} \}^B,$$

(9)

(with the constants $X$ and $Q$ given in Equations (7) and (8)). We numerically solve this equation using a bisector root-finding method. After solving for $f_{\text{in,AGN}},$ the other three unknowns can be computed from Equations (5), (6), and (8). This process is repeated to derive AGN-subtracted host galaxy magnitudes in all five bands in each of the 10 redshift bins. Table 1 shows the corrected magnitudes and derived stellar masses for the 561 broad-line AGNs in the luminous and faint samples.

3.4. Error Analysis

It is necessary to ensure that our AGN/host decomposition method does not introduce errors which bias the resultant host galaxy colors and stellar masses. One assumption of our method is that galaxies have $\delta m = 0$: Figure 6 demonstrates that this is true on average, but the $\delta m$ values of individual galaxies scatter about this value. Similarly the true inner and outer magnitudes of AGN-subtracted host galaxies may have nonzero values of $\delta m,$ and our correction to $\delta m = 0$ may introduce systematic errors in their resultant colors and masses.

We investigate the errors of the $\delta m = 0$ assumption by applying the decomposition method to inactive galaxies. Figure 10 shows the changes in $(u-z)^{\prime}$ color and $M_\odot$ introduced by “correcting” inactive galaxies to $\delta m = 0$. The dispersions in these shifts represent the errors in color and mass from correcting AGN host galaxies with nonzero $\delta m$. Errors in color are small because $\delta u$ and $\delta z$ are correlated (see Figure 8). The dispersion in stellar mass is slightly larger, as indicated by the error bar in the bottom right of each panel, but mass shifts and dispersions are small among blue cloud and green valley galaxies (the typical hosts of broad-line AGNs). From Figure 10, we do not expect the $\delta m = 0$ assumption to bias the observed colors and masses of broad-line AGNs.

If our other assumption is incorrect and AGNs contaminate z-band concentration, this could also introduce significant errors in the AGN/host decomposition method. Figure 7 shows that the most luminous AGNs ($M_\text{r,AGN} < -20$) may bias $C_z$, and such systems may have larger systematic or random errors than those estimated in Figure 10. For this reason we eliminate the most luminous AGNs from the discussion and conclusions below. However, the low and moderate luminosity broad-line AGNs that make up the bulk of our sample do not exhibit biased $C_z$. For these objects the assumption that AGNs do not affect the broad-line AGN is unlikely to cause errors in the AGN/host decomposition.

4. THE HOST GALAXIES OF BROAD-LINE AGNs

The corrected galaxy-only photometry of the broad-line AGNs can be used to determine if certain types of host galaxies are more likely to exhibit broad-line AGNs. After computing the AGN-subtracted photometry, we $K$-correct to $z = 0.05$ and...
Figure 10. Bins in color and stellar mass showing the effects of our AGN/host decomposition method applied to inactive galaxies. The top panels (a) and (b) show the average shifts in \((u-z)\)' color and stellar mass, and the bottom panels (c) and (d) show the dispersion of the changes in color and mass. The text in the upper left of each panel also gives the mean shift or dispersion over all galaxies. Outside of the bins with small numbers of galaxies, there are no regions of color–mass space with unusually large shifts or dispersions in corrected color and mass.

(A color version of this figure is available in the online journal.)

infer the host galaxy stellar mass using Figure 3. Figure 11 shows total \((u-z)\)' color versus luminosity and stellar mass for broad-line AGNs in the faint sample, with contours showing the inactive galaxies for comparison. Figure 12 similarly shows broad-line AGNs and inactive galaxies in the luminous sample.

The top panels of each figure show that broad-line AGNs typically become redder, dimmer, and less massive after recovering the uncontaminated galaxy light. A few AGN hosts become so much redder without the blue point-source AGN that their masses increase, due to the higher mass-to-light ratios of similarly red inactive galaxies. Because we independently correct each filter, there are also a few AGN hosts that become bluer, presumably because they contain a reddened AGN.

To determine if broad-line AGNs are more likely to occur in certain types of galaxies, we measure the fraction of galaxies containing an AGN in bins across the color–mass diagram, as shown in the bottom panels of Figures 11 and 12. Bins are tilted (with slopes of \(\Delta(u-z)'/\Delta M_z = -0.07\) and \(\Delta(u-z)'/\Delta[\log(M_*/M_\odot)] = 0.3\)) to be parallel to the red sequence. We count the number of broad-line AGNs with corrected galaxy-only photometry in each bin, then divide by the total number of galaxies (inactive plus active) in that bin to determine the AGN fraction. Table 2 gives the broad-line AGN fraction in each bin of color and mass, as well as the AGN fraction over the entire mass slice.

In both samples, galaxies on the red sequence are least likely to host a broad-line AGN. Instead AGNs are most likely to be in the bluest host galaxies of a given stellar mass. We further explore what the preference for star-forming hosts means for the AGN–SF connection and AGN feedback in Section 5, but first test to ensure that our results are not caused by selection effects.

4.1. Selection Effects

While broad-line AGNs are the brightest and most rapidly accreting AGNs (e.g., Kollmeier et al. 2006; Trump et al. 2009), many of the weakest broad-line AGNs have significant galaxy contribution to their continua. Dim AGNs could be more difficult to detect in bright galaxies, with the broad lines diluted by host galaxy starlight. More distant galaxies also contain more starlight within the 3″ spectroscopic fiber aperture and could similarly dilute the broad emission lines of AGNs.

We test the potential selection bias against dim AGNs in luminous host galaxies by computing the AGN fraction across the color–mass diagram for dim, moderate, and luminous AGNs, as shown in Figure 13. AGN strength is quantified using the AGN-only \(u\)-band absolute magnitude, with \(M_{u,\text{AGN}}\) divisions chosen to put the same number of AGNs in each set. AGNs were drawn from the faint sample because it includes a large range in stellar mass. From Figure 13 it is clear that dim AGNs are not found less frequently in massive, luminous galaxies, and so this potential selection effect does not occur in our sample.

Figure 14 similarly tests the potential selection effect of higher distance biasing against AGN identification. The luminous sample is most appropriate for this test because it includes luminosity-limited AGNs over the full redshift range \(0.01 < z < 0.11\). In addition to measuring the broad-line AGN
Figure 11. Color–luminosity and color–mass diagrams for inactive galaxies and broad-line AGN hosts in the faint sample ($M_r < -19$ and $0.01 < z < 0.05$). The top panels (a) and (b) show total $(u - z)$ color vs. luminosity and stellar mass for both uncorrected broad-line AGNs (blue filled circles) and AGN-subtracted host galaxies (red filled circles), with lines connecting the two measurements of each AGN. The mean AGN subtraction vectors are shown by the green arrows. The bottom panels (c) and (d) show the broad-line AGN frequency in bins of color and luminosity or color and mass, using the corrected AGN host properties. The typical scatter of our AGN/host decomposition method (see Section 3.4) is shown by error bars in the upper left of each panel, and contours and points represent the inactive galaxy populations. Star-forming (blue cloud and green valley) galaxies are the most common hosts of broad-line AGNs. (A color version of this figure is available in the online journal.)

5. DISCUSSION

In this section we discuss the consequences of AGN hosts with young stellar populations for the coevolving growth of galaxies and SMBHs.

5.1. AGNs and Star Formation

A major finding of this study is that broad-line AGNs tend to lie in hosts with young stellar populations, and avoid red and quiescent host galaxies. The simplest explanation for this is if the same gas that fuels rapidly accreting, unobscured nuclear activity also rapidly formed stars in the recent past. Figure 13 suggests that the more powerful the broad-line AGN, the bluer the host galaxy: more rapidly accreting AGNs may have more powerful recent star formation in their host galaxy. Once again, this suggests that star formation and nuclear activity are fueled by the same material.

Figure 15 directly compares the broad-line AGN luminosity to the color and stellar mass of the host galaxy. AGN luminosity is quantified by AGN-only $M'_u$. In addition to corrected color and mass for broad-line AGN hosts, Figure 15 also shows the offsets in each of these quantities from inactive galaxies of similar (within 0.1 dex) mass or color. These offsets are useful to remove the degeneracy between a galaxy’s mass and its color. For example, the apparent anti-correlation between stellar mass and AGN luminosity in panel (c) is a result of the degeneracy between mass and color. Comparing AGNs and inactive galaxies of similar color, panel (d) shows no significant trend between stellar mass offset and AGN luminosity.

Panel (b) in Figure 15 shows that more luminous AGNs have bluer host galaxies in both the luminous and faint samples. This may represent a physical connection between AGN luminosity and the host galaxy’s recent star formation history. AGN luminosity probably translates to accretion rate, and so the relationship between AGN $M'_u$ and host color indicates that AGN accretion rate is correlated with the number of recently formed stars. These observations favor scenarios with similar fuel sources for both star formation and nuclear activity (e.g., Salim et al. 2007; Silverman et al. 2009), with little or no time delay between the processes fueling each.

This interpretation is robust even given the limitations of our AGN/galaxy decomposition method. Recall the assumption that AGN host galaxies have the same light distributions as inactive galaxies (quantified by $\delta m = 0$). Given the $M - \sigma$ relation (e.g. Park et al. 2012) and the requirement of a bulge to host
Figure 12. Color–luminosity and color–mass diagrams for inactive galaxies and broad-line AGN hosts in the luminous sample ($M_r^* < -20.8$ and $0.01 < z < 0.11$). The top panels (a) and (b) show uncorrected (blue) and corrected (red) total $(u-z)$ color vs. luminosity and stellar mass for broad-line AGN hosts, and the middle panels (c) and (d) show the AGN frequency in bins of color and luminosity or color and mass. The bottom panels (e) and (f) include only AGN hosts with $M_u,\text{AGN}>-20$: that is, AGNs with potentially biased $C_z$ are removed. Error bars in the upper left of each panel represent the typical scatter introduced by AGN/host decomposition (see Section 3.4), and inactive galaxies are shown by contours and points. As in the faint sample, broad-line AGNs are most common in the bluest galaxies of a given stellar mass.

(A color version of this figure is available in the online journal.)

an AGN, it is unlikely that broad-line AGNs have hosts with intrinsic $\delta m < 0$. On the other hand, the unusual blue colors of broad-line AGN hosts might indicate nuclear starbursts and intrinsic $\delta u > 0$. Applying our decomposition method to an AGN host with a nuclear starburst would oversubtract the blue light, resulting in a redder corrected galaxy $(u-z)$ color. With the presence of a nuclear starburst it is possible that the galaxy colors of AGN hosts may be even bluer than we observe.
Similarly the connection between AGN luminosity and blue host color in Figure 15 would steepen if these blue hosts contain nuclear starbursts and unusually concentrated blue light.

Another potential concern is that the broad-line AGN host galaxies appear blue due to extended scattered light from the AGN. Zakamska et al. (2006) noted that in extreme cases Type 2 quasars with $M_{\mathrm{B, AGN}} > -24$ have scattered light on $>1\text{ kpc}$ scales that dominates over the host galaxy starlight. Measuring extended scattered light for our sample is beyond the scope of this work, given the requirement for long-slit spectropolarimetry on a large number of broad-line AGNs with varying luminosities. However, we note that our broad-line AGNs are several (4–7) magnitudes fainter than the Zakamska et al. (2006) sample, and so we assume the amount of extended scattered light in this work to be negligible.

5.2. The Different Hosts of Luminous Broad-line and Weak Narrow-line AGNs

Our large sample of broad-line AGNs from the SDSS shows a strong preference for blue host galaxies. This matches earlier studies with small broad-line AGN samples, which found a similar preference for hosts with young stellar populations (Bahcall et al. 1997; Jahnke et al. 2004a, 2004b). The most $[\text{OIII}]-$luminous narrow-line AGNs also prefer star-forming host galaxies (Kauffmann et al. 2003a; Silverman et al. 2009). These classes of luminous AGNs all represent “feast mode” rapid accretion with high Eddington ratios ($\lambda_{\text{Edd}}$): Kauffmann & Heckman (2009) estimate that the most $[\text{OIII}]-$luminous narrow-line AGNs have $\lambda_{\text{Edd}} \sim 0.1$, and broad-line AGNs also have Eddington ratios of 1%–100% (Kollmeier et al. 2006; Trump et al. 2009). In future work we will directly measure and compare $\lambda_{\text{Edd}}$ in our broad-line AGN sample, but for now we simply assume that they are rapidly accreting AGNs with $\lambda_{\text{Edd}} > 0.01$.

The blue hosts of our broad-line AGNs are in contrast to the hosts of fainter narrow-line AGNs, which instead prefer green valley galaxies (Nandra et al. 2007; Salim et al. 2007; Georgakakis et al. 2008; Silverman et al. 2008; Gabor et al. 2009; Schawinski et al. 2009; Hickox et al. 2009; Kocevski et al. 2009) or all galaxy types equally (Xue et al. 2010). The host-dominated AGNs of these previous studies are, by construction, fainter than broad-line AGNs, due to either obscuration or lower accretion rates ($\lambda_{\text{Edd}} < 0.01$). Different host galaxies for broad-line AGNs and weaker host-dominated AGNs are incompatible with the historical AGN unified model (Antonucci et al. 1993). In its simplest version, the unified model uses only geometrical orientation to explain the different observed properties of broad-line and host-dominated AGNs. Both broad-line and host-dominated AGNs would then be observed in the same host galaxy types, as has been observed among intermediate-luminosity AGNs at $z \sim 1$ (Ammons et al. 2011). Our observations instead favor AGN unified models where broad-line and faint narrow-line AGNs have physically different...
Table 2

Broad-line AGN Fractions with Host Galaxy Stellar Mass and Color

| $\log(M_*/M_*)$ | ($u-z$)$^j$ | Faint Sample | Luminous Sample |
|-----------------|-------------|--------------|----------------|
|                 | $N_{gal}$   | $N_{AGN}$    | BL AGN %       |
|                 |             |              |                |
| 9.00 1.175      | 208         | 0            | 0              |
| 9.00 1.475      | 500         | 0            | 0              |
| 9.00 1.775      | 123         | 0            | 0              |
| 9.00 All colors | 835         | 0            | 0              |
| 9.25 1.250      | 198         | 1            | 0.51 ± 0.51    |
| 9.25 1.550      | 835         | 0            | 0              |
| 9.25 1.850      | 979         | 1            | 0.10 ± 0.10    |
| 9.25 2.150      | 213         | 0            | 0              |
| 9.25 2.450      | 18          | 0            | 0              |
| 9.25 All colors | 2246        | 2            | 0.09 ± 0.06    |
| 9.50 1.325      | 136         | 0            | 0              |
| 9.50 1.625      | 769         | 0            | 0              |
| 9.50 1.925      | 1292        | 4            | 0.31 ± 0.16    |
| 9.50 2.225      | 711         | 2            | 0.28 ± 0.20    |
| 9.50 2.525      | 330         | 2            | 0.61 ± 0.43    |
| 9.50 2.825      | 442         | 0            | 0              |
| 9.50 3.125      | 50          | 0            | 0              |
| 9.50 All colors | 3731        | 8            | 0.21 ± 0.08    |
| 9.75 1.400      | 58          | 0            | 0              |
| 9.75 1.700      | 462         | 1            | 0.22 ± 0.22    |
| 9.75 2.000      | 1249        | 4            | 0.32 ± 0.16    |
| 9.75 2.300      | 997         | 4            | 0.40 ± 0.20    |
| 9.75 2.600      | 668         | 4            | 0.60 ± 0.30    |
| 9.75 2.900      | 1301        | 3            | 0.23 ± 0.13    |
| 9.75 3.200      | 677         | 0            | 0              |
| 9.75 3.500      | 31          | 0            | 0              |
| 9.75 All colors | 5443        | 16           | 0.29 ± 0.07    |
| 10.00 1.475     | 19          | 0            | 438            |
| 10.00 1.775     | 222         | 0            | 0              |
| 10.00 2.075     | 844         | 3            | 0.36 ± 0.21    |
| 10.00 2.375     | 1141        | 6            | 0.53 ± 0.22    |
| 10.00 2.675     | 821         | 8            | 0.97 ± 0.35    |
| 10.00 2.975     | 1691        | 2            | 0.12 ± 0.08    |
| 10.00 3.275     | 974         | 3            | 0.31 ± 0.18    |
| 10.00 3.575     | 50          | 0            | 0              |
| 10.00 All colors| 5762        | 22           | 0.38 ± 0.08    |
| 10.25 1.550     | 8           | 0            | 200            |
| 10.25 1.850     | 90          | 0            | 1510           |
| 10.25 2.150     | 449         | 4            | 4762           |
| 10.25 2.450     | 942         | 9            | 4807           |
| 10.25 2.750     | 939         | 6            | 2513           |
| 10.25 3.050     | 1933        | 2            | 2291           |
| 10.25 3.350     | 1211        | 0            | 493            |
| 10.25 3.650     | 72          | 0            | 6              |
| 10.25 All colors| 5644        | 21           | 0.37 ± 0.08    |
| 10.50 1.625     | 4           | 0            | 54             |
| 10.50 1.925     | 16          | 0            | 511            |
| 10.50 2.225     | 142         | 3            | 2617           |
| 10.50 2.525     | 530         | 9            | 5406           |
| 10.50 2.825     | 834         | 13           | 5584           |
| 10.50 3.125     | 1957        | 6            | 11466          |
| 10.50 3.425     | 1205        | 0            | 12747          |
| 10.50 3.725     | 81          | 0            | 1220           |
| 10.50 All colors| 4769        | 31           | 0.65 ± 0.12    |
| 10.75 1.700     | 0           | 0            | 16             |
| 10.75 2.000     | 1           | 0            | 114            |
| 10.75 2.300     | 39          | 1            | 842            |
| 10.75 2.600     | 163         | 3            | 2419           |
| 10.75 2.900     | 406         | 4            | 3921           |
| 10.75 3.200     | 1622        | 2            | 10541          |
| 10.75 3.500     | 884         | 1            | 12972          |
| 10.75 3.800     | 64          | 0            | 1615           |
| 10.75 All colors| 3179        | 11           | 0.35 ± 0.10    |
| 11.00 2.075     | 1           | 0            | 11             |
| 11.00 2.375     | 5           | 0            | 104            |

Note: The table provides the number of galaxies ($N_{gal}$), the number of AGNs ($N_{AGN}$), and the percentage of AGNs (BL AGN %) for different stellar mass bins and color indices ($u-z$).
Table 2
(Continued)

| Log(M_*/M_☉) | (u − z)′ | N_{gal} | N_{AGN} | BL AGN % | N_{gal} | N_{AGN} | BL AGN % |
|---------------|----------|---------|---------|----------|---------|---------|----------|
| 11.00         | 2.675    | 16      | 0       | 0        | 536     | 9       | 1.68 ± 0.56 |
| 11.00         | 2.975    | 113     | 1       | 0.88 ± 0.89 | 1449   | 7       | 0.48 ± 0.18 |
| 11.00         | 3.275    | 801     | 3       | 0.37 ± 0.22 | 6078   | 9       | 0.15 ± 0.05 |
| 11.00         | 3.575    | 425     | 0       | 0        | 7530    | 1       | 0.01 ± 0.01 |
| 11.00         | 3.875    | 44      | 0       | 0        | 904     | 0       | 0         |
| 11.00         | All colors | 1405   | 4       | 0.28 ± 0.14 | 16614  | 28      | 0.17 ± 0.03 |
| 11.25         | 2.450    | 0       | 0       | 0        | 12      | 1       | 8.33 ± 6.67 |
| 11.25         | 2.750    | 2       | 0       | 0        | 33      | 0       | 0         |
| 11.25         | 3.050    | 6       | 0       | 0        | 186     | 1       | 0.54 ± 0.54 |
| 11.25         | 3.350    | 207     | 0       | 0        | 1769    | 1       | 0.06 ± 0.06 |
| 11.25         | 3.650    | 101     | 0       | 0        | 2453    | 2       | 0.08 ± 0.06 |
| 11.25         | 3.950    | 14      | 0       | 0        | 280     | 0       | 0         |
| 11.25         | All colors | 330     | 0       | 0        | 4737    | 5       | 0.11 ± 0.05 |
| 11.50         | 3.125    | 0       | 0       | 0        | 9       | 0       | 0         |
| 11.50         | 3.425    | 24      | 0       | 0        | 277     | 0       | 0         |
| 11.50         | 3.725    | 8       | 0       | 0        | 357     | 0       | 0         |
| 11.50         | 4.025    | 1       | 0       | 0        | 62      | 0       | 0         |
| 11.50         | All colors | 33      | 0       | 0        | 708     | 0       | 0         |

Notes. * Columns of log(M_*/M_☉) and (u − z)′ give the values associated with the lower left corner of each color–mass bin, as shown in Figures 11 and 12. Bins are 0.25 dex wide in mass and 0.3 dex high in color, and bins with less than five inactive galaxies are not shown. Rows with “all colors” give the numbers and fraction of broad-line AGNs in that entire mass slice.

Figure 15. Corrected host galaxy (u − z)′ color and stellar mass vs. AGN luminosity M_{u,AGN}. Panel (b) (top right) shows the color offsets of broad-line AGNs, defined as the difference between the corrected AGN host color and the median color of inactive galaxies with similar mass. Similarly panel (d) (bottom right) shows the offset in BL AGN host stellar mass from the median stellar mass of inactive galaxies with similar color. Red points show the faint broad-line AGN sample (M_{u,AGN} > −20; the fit excludes the most luminous AGNs because they may have biased Cz measurements (see Section 3.1 and Figure 7). Galaxies hosting more powerful AGNs typically have younger stellar populations, suggesting that the same gas needed to fuel a broad-line AGN also drives recent star formation activity.

(A color version of this figure is available in the online journal.)

accretion properties (Ho 2008; Trump et al. 2011; Antonucci et al. 2011). Broad-line AGNs might be in star-forming galaxies because such galaxies have the most abundant or efficient fuel supply for the SMBH, while other galaxy types can fuel only “famine-mode” host-dominated AGNs with low accretion rates (Kauffmann & Heckman 2009; Schawinski et al. 2010).

Kauffmann et al. (2003a) used a large sample of host-dominated AGNs to show that there may be a minimum stellar
mass of \( \log(M_*/M_\odot) > 10.5 \) required for a galaxy to host an AGN. Recently, however, Aird et al. (2012) argued that the apparent preference for massive AGN hosts is caused by selection effects, and there is instead a universal Eddington-ratio distribution of AGNs in galaxies of any stellar mass. Figure 16 shows the percentage of broad-line AGNs with host stellar mass for both the luminous and faint samples. Given the narrow distribution of high Eddington ratios for broad-line AGNs (0.01 < \( L/L_{\text{EB}} \) < 1, e.g., Kollmeier et al. 2006; Trump et al. 2009), our AGN sample is complete to \( \log(M_*/M_\odot) \sim 10 \) (Kelly & Shen 2012). Thus the luminous broad-line AGN sample (also limited by \( \log(M_*/M_\odot) > 10 \)) provides a direct test of the AGN dependence on host stellar mass. After controlling for galaxy color (right panel of Figure 16), we find a flat AGN fraction with stellar mass. This suggests that there is no stellar mass threshold for broad-line AGNs, in agreement with Aird et al. (2012).

5.3. Consequences for AGN Feedback

Theoretical simulations invoke feedback from luminous AGNs to rapidly quench star formation and transform their host galaxy colors from blue to red (Silk & Rees 1998; Fabian 2002; Di Matteo et al. 2005). Several authors have claimed observational evidence for this scenario, with host-dominated AGNs apparently preferring recently quenched green valley galaxies (Nandra et al. 2007; Georgakakis et al. 2008; Schawinski et al. 2009; Hickox et al. 2009; Kocevski et al. 2009). Since radiative-mode feedback scales with AGN strength, the broad-line AGNs in our sample would be expected to have an even greater effect in quenching star formation. However, we find precisely the opposite effect: more powerful AGNs seem to lie in bluer galaxies. If quasar winds cause significant feedback, then their galaxy-wide effects are not visible until after the broad-line AGN disappears.

Figure 17 outlines three scenarios connecting AGNs and galaxy quenching: scenario A has star formation quenched before the broad-line AGN phase, scenario B quenches during the broad-line AGN peak, and scenario C has star formation quenched well after the broad-line AGN phase. The increase in star formation during the AGN peak in all scenarios is motivated by our observed connection between AGN luminosity and blue host galaxy color. The broad-line AGN phase occurs only during the most luminous AGN activity, which means that our study probes only the region limited by the dashed “BL AGN Visible” lines in each panel.

Scenario A is immediately ruled out by the observed absence of broad-line AGNs among quenched red galaxies. However, our observations cannot distinguish between quenching during or after the broad-line AGN phase (scenarios B and C). The broad-line AGN lifetime is less than \( \sim 100 \) Myr (Martini 2004), which is roughly the same amount of time it takes for galaxy colors to change from blue to green or red after star formation.
quenches (e.g., Bruzual & Charlot 2003). Even if quenching occurs during the AGN peak, a change in galaxy colors would not be observed until after the broad-line AGN fades. This is evident in the scenario B curve in the right panel of Figure 17. So while our observations exclude AGN quenching scenarios that occur before the broad-line AGN phase, only observations of fading AGNs can distinguish between simultaneous or delayed AGN quenching.

6. SUMMARY

An aperture photometry method is used to disentangle the light of broad-line AGNs and their host galaxies at 0.01 < z < 0.11. Based on the corrected, host-only photometry, broad-line AGNs are distributed throughout the blue cloud and green valley but are very rare among red sequence hosts. Within this distribution, AGN strength is correlated to the youth of the host galaxy stellar population, such that bluer galaxies have more luminous broad-line AGNs. This suggests that broad-line AGN activity and star formation are closely coeval with little or no delay between the ignition of each. The host galaxy properties of broad-line AGN hosts also suggest that quenching of galactic star formation occurs or becomes visible only after the rapidly accreting SMBH phase: quasar winds are either unconnected to quenching or their effects are apparent only after the broad-line AGN phase has ended.

The authors from UCSC acknowledge support from NASA HST grant GO 12060.10-A, Chandra grant GO8-9129A, and NSF grant AST-0808133. Helpful discussions with Edmond Cheung and Hassen Yusef contributed to the development of this work. A.H. acknowledges support from the UC Santa Cruz Science Internship Program.

REFERENCES

Aird, J., Coil, A. L., Moustakas, J., et al. 2012, ApJ, 746, 90
Ammons, S. M., Rosario, D. J. V., Koo, D. C., et al. 2011, ApJ, 740, 3
Antonucci, R. 1993, ARA&A, 31, 473
Antonucci, R. 2011, A&AT, in press (arXiv:1101.0837)
Balkalı, J. N., Kırhakos, S., Saxe, D. H., & Schneider, D. P. 1997, ApJ, 479, 642
Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5
Blanton, M. R., & Roweis, S. 2007, AJ, 133, 734
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Cardamone, C. N., Urry, C. M., Schawinski, K., et al. 2010, ApJ, 721, 38
Cisternas, M., Jahnke, K., Inskip, K. J., et al. 2011, ApJ, 726, 57
Croton, D. J., Springel, V., White, S. D. M., et al. 2006, MNRAS, 365, 11
Di Matteo, T., Springel, V., & Hernquist, L. 2005, Natur, 433, 604
Fabian, A. C. 2002, MNRAS, 308, 39
Ferrarese, L., & Merritt, D. 2000, ApJ, 593, 9
Gabor, J. M., Impey, C. D., Jahnke, K., et al. 2009, ApJ, 691, 705
Ganguly, U., & Brotherton, M. S. 2008, ApJ, 672, 102
Gebhardt, K., Bender, R., Bower, G., et al. 2000, ApJ, 539, 13
Georgakakis, A., Nandra, K., Yan, R., et al. 2008, MNRAS, 385, 2049
Haggard, D., Green, P. J., Anderson, S. F., et al. 2010, ApJ, 723, 1447
Heckman, T. M., & Kauffmann, G. 2006, NewAR, 50, 677
Hickox, R. C., Jones, C., Forman, W. R., et al. 2009, ApJ, 696, 891
Ho, L. C. 2008, ARA&A, 46, 475
Hopkins, P. F., Hernquist, L., Cox, T. J., & Keres, D. 2008, ApJS, 175, 356
Hopkins, P. F., Hernquist, L., Cox, T. J., et al. 2011, ApJS, 175, 356
Jahnke, K., Kuhlbrodt, B., & Wisotzki, L. 2004a, MNRAS, 352, 399
Jahnke, K., Sánchez, S. F., Wisotzki, L., et al. 2004b, ApJ, 614, 568
Kauffmann, G., & Heckman, T. M. 2009, MNRAS, 397, 135
Kauffmann, G., Heckman, T. M., Tremonti, C., et al. 2003b, MNRAS, 346, 1055
Kauffmann, G., Heckman, T. M., White, S. D. M., et al. 2003a, MNRAS, 341, 33
Kelly, B. C., & Shen, Y. 2012, ApJ, in press (arXiv:1209.0477)
Kewley, L. J., Groves, B., Kauffmann, G., & Heckman, T. 2006, MNRAS, 372, 961
Kocevski, D. D., Faber, S. M., Mozena, M., et al. 2012, ApJ, 744, 148
Kocevski, D. D., Lubin, L. M., Lemaux, B. C., et al. 2009, ApJ, 700, 901
Kollmeier, J. A., Onken, C. A., Kochanek, C. S., et al. 2006, ApJ, 648, 128
Magorrian, J., Tremaine, S., Richstone, D., et al. 1998, AJ, 115, 2285
Marconi, A., & Hunt, L. K. 2003, ApJ, 589, 21
Martini, P. 2004, in Carnegie Observatories Astrophysics Series, Vol 1: Coevolution of Black Holes and Galaxies, ed. L. Cow (Oak Ridge National Lab Press), 170
Mullaney, J. R., Pannella, M., Daddi, E., et al. 2012, MNRAS, 419, 95
Nandra, K., Georgakakis, A., Willmer, C. N. A., et al. 2007, ApJ, 660, 11
Park, D., Kelly, B. C., Woo, J.-H., & Treu, T. 2012, ApJS, 203, 6
Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W. 2002, ApJ, 124, 266
Richards, G. T., Fan, X., Newberg, H. J., et al. 2002, AJ, 123, 2945
Rigby, J. R., Rieke, G. H., Donley, J. L., Alonso-Herrero, A., & Perez-Gonzalez, P. G. 2006, ApJ, 645, 115
Rovilos, E., Comastri, A., Gilli, R., et al. 2012, A&A, 546, 58
Salim, S., Rich, R. M., Charlot, S., et al. 2007, ApJS, 173, 267
Santini, P., Rosario, D. J., Shao, L., et al. 2012, A&A, 540, 109
Schawinski, K., Urry, C. M., Virani, S., et al. 2010, ApJ, 711, 284
Schawinski, K., Virani, S., Simmons, B., et al. 2009, ApJ, 692, 19
Sérsic, J. L. 1968, Atlas de Galaxias Australes (Cordoba: Obbs. Astron. Univ. Nacional Cordoba)
Silk, J., & Rees, M. J. 1998, A&A, 331, 1
Silverman, J. D., Lamareille, F., Maiers, C., et al. 2009, ApJ, 696, 396
Silverman, J. D., Mainieri, V., Lehmer, B. D., et al. 2008, ApJ, 675, 1025
Strauss, M. A., Weinberg, D. H., Lupton, R. H., et al. 2002, AJ, 124, 1810
Trump, J. R., Impey, C. D., Kelly, B. C., et al. 2009, ApJ, 700, 49
Trump, J. R., Impey, C. D., Kelly, B. C., et al. 2009, ApJ, 733, 60
Vanden Berk, D. E., Richards, G. T., Bauer, A., et al. 2001, AJ, 122, 549
Winter, L. M. 2010, ApJ, 725, 126
Xue, Y. Q., Brandt, W. N., Luo, B., et al. 2010, ApJ, 720, 368
York, D. G., Adelman, J., Anderson, J. E., Jr., et al. 2000, AJ, 120, 1579
Zakamska, N. L., Strauss, M. A., Krolik, J. H., et al. 2006, AJ, 132, 1496