

DUST-CORRECTED COLORS REVEAL BIMODALITY IN THE HOST-GALAXY COLORS OF ACTIVE GALACTIC NUCLEI AT $z \sim 1$

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ABSTRACT

Using new, highly accurate photometric redshifts from the MUSYC medium-band survey in the Extended Chandra Deep Field-South (ECDF-S), we fit synthetic stellar population models to compare active galactic nucleus (AGN) host galaxies to inactive galaxies at $0.8 \leq z \leq 1.2$. We find that AGN host galaxies are predominantly massive galaxies on the red sequence and in the green valley of the color–mass diagram. Because both passive and dusty galaxies can appear red in optical colors, we use rest-frame near-infrared colors to separate passively evolving stellar populations from galaxies that are reddened by dust. As with the overall galaxy population, $\sim 25\%$ of the “red” AGN host galaxies and $\sim 75\%$ of the “green” AGN host galaxies have colors consistent with young stellar populations reddened by dust. The dust-corrected rest-frame optical colors are the blue colors of star-forming galaxies, which imply that these AGN hosts are not passively aging to the red sequence. At $z \sim 1$, AGN activity is roughly evenly split between two modes of black hole growth: the first in passively evolving host galaxies, which may be heating up the galaxy’s gas and preventing future episodes of star formation, and the second in dust-reddened young galaxies, which may be ionizing the galaxy’s interstellar medium and shutting down star formation.

Key words: galaxies: active – galaxies: high-redshift – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

The colors and morphologies of galaxies form a bimodal population at $0 \lesssim z \lesssim 2$ (Blanton et al. 2003; Bell et al. 2004; Borch et al. 2006; De Lucia et al. 2007; Ilbert et al. 2009; Williams et al. 2009; Brammer et al. 2009). A red sequence contains massive galaxies and a blue cloud is composed of lower mass galaxies, while relatively few galaxies lie in the green valley in between. The observed color distribution is consistent with galaxy color evolving from blue to red by the rapid quenching of star formation (Faber et al. 2007). A central active galactic nucleus (AGN), which can heat up the galaxy’s gas (Silk & Rees 1998; Di Matteo et al. 2008) and consequently shut down star formation, can cause this rapid color evolution (Faber et al. 2007; Schawinski et al. 2007). Moreover, the observed correlation between the mass of the central black hole and the host galaxy’s mass (e.g., Tremaine et al. 2002) suggests a potential common cause of star formation and AGN accretion, e.g., mergers (Hopkins et al. 2006; Cattaneo et al. 2009). Additionally, some models invoke subsequent AGN activity to maintain the passive nature of red galaxies, by preventing future episodes of gas cooling (e.g., Croton et al. 2006; Bower et al. 2006).

Several studies show that AGN host galaxies have intermediate host-galaxy colors at $z \lesssim 1$, placing them in the green valley (Nandra et al. 2007; Bundy et al. 2008; Georgakakis et al. 2008; Silverman et al. 2008; Hickox et al. 2009; Schawinski et al. 2009a). This observation is sometimes interpreted as evidence for AGN involvement in the transition of host galaxies from

the blue cloud to red sequence. However, if this were true, we should observe at least some AGNs in blue galaxies, because it takes several hundred megayears for a stellar population to age to the colors of the green valley (Schawinski et al. 2009a). Accordingly, if the intermediate colors of the AGN host galaxies are due to aging stars, AGN activity likely follows the shutdown of star formation with a delay of several 100 Myr.

Recent studies of galaxy colors suggest that the green valley may not consist solely of a transition population of galaxies with intermediate ages, but may contain galaxies from the blue cloud reddened by obscuring dust (Bell et al. 2005; Cowie & Barger 2008; Brammer et al. 2009). The same could be true for AGN host galaxies, complicating the observational picture of the role of AGN feedback in galaxy color evolution. In this Letter, we use highly accurate photometric redshifts in the Extended Chandra Deep Field-South (ECDF-S; Cardamone et al. 2010) to investigate the host galaxies of X-ray selected AGNs at $0.8 \leq z \leq 1.2$. Throughout this Letter, we assume $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

2. COLORS AND MASSES OF GALAXIES AND AGN HOSTS

The combination of depth ($R_{AB} \sim 26$), area ($30' \times 30'$), and multi-wavelength coverage makes the ECDF-S ideal for the study of moderate luminosity AGNs and galaxies at $z \sim 1$. The MUSYC survey includes the optical ($U38UBVRIz$), near- and mid-infrared (JHK and $3.6\text{--}8.0 \mu\text{m}$) data (Gawiser et al. 2006; Taylor et al. 2009, Damen et al. 2010) needed to investigate galaxy stellar populations and medium-band observations that densely sample the galaxy spectral energy distributions (SEDs), allowing for extremely accurate photometric redshift determi-

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nations (Cardamone et al. 2010). Photometric redshifts were computed with EAZY (Brammer et al. 2008) using the full 32-band SEDs, which results in median $[\Delta z/(1+z)] \lesssim 0.01$ at $z \leq 1.2$ (Cardamone et al. 2010). Here, we study galaxies with reliable photometric redshifts ($Q_z \leq 1$; Brammer et al. 2009) at $0.8 \leq z \leq 1.2$.

We use deep X-ray imaging to identify galaxies with AGN activity since X-rays reveal all but the most obscured AGN (Brandt & Hasinger 2005). To remove potential interlopers whose X-ray emission comes primarily from star formation, we consider X-ray sources with $\log(L_{\text{XR}}) \geq 42 \text{ erg s}^{-1}$. We combine the deep 2 Ms imaging in the central Chandra Deep Field South (Luo et al. 2008) with the shallower 250 ks observations of the ECDF-S flanking this field (Lehmer et al. 2005; Virani et al. 2006).⁷ Obscured AGNs are identified by their observed X-ray hardness ratio, $\text{HR} = \frac{H-S}{H+S} \geq -0.2$, where H and S are the X-ray counts in the hard (2–8 keV) and soft (0.5–2 keV) bands. Of 1134 X-ray sources detected, 825 have reliable optical counterparts identified by a likelihood ratio method (Cardamone et al. 2008). Photometric redshifts and rest-frame fluxes are computed following the procedure of Brammer et al. (2009). Details of the redshift and rest-frame flux determinations are discussed in Cardamone et al. (2010). Combining the spectroscopic and photometric redshifts, there are 114 sources with $0.8 \leq z \leq 1.2$ and $\log(L_{\text{XR}}) \geq 42 \text{ erg s}^{-1}$, of which 80 are obscured AGNs ($\text{HR} \geq -0.2$). We use this sample of 114 AGNs to study host-galaxy properties. At the modest luminosities sampled by the ECDF-S volume (only eight sources have $\log(L_{\text{XR}}) \gtrsim 44 \text{ erg s}^{-1}$), most of the observed optical/IR light actually arises from the galaxy (e.g., Cardamone et al. 2007; Bundy et al. 2008; Silverman et al. 2008). We revisit the relative contribution of AGNs and starlight in Section 3.

We fit the galaxy and AGN host SEDs with single-burst stellar population models, for which the medium-band photometry is particularly useful. Using reliable spectroscopic redshifts where available (28 sources) and photometric redshifts otherwise (86 sources), we employ FAST (Kriek et al. 2009) to estimate the stellar mass, star-formation time scale, star-formation rate, and dust content (A_V) for each galaxy. We use stellar templates from Maraston (2005), adopting the Kroupa (2001) initial mass function and solar metallicity, and fitting Calzetti et al. (2000) dust extinction ($A_V = 0-4$). We obtain mass estimates and measurements of A_V for all galaxies and the hosts of X-ray-selected AGNs from the SED fit, and run Monte Carlo simulations varying the photometry for estimates of uncertainty in the values. Further uncertainties come from systematic effects due to assumptions of metallicity, galactic extinction laws, and the adopted stellar templates and can affect mass measurements by 0.1–0.6 dex (see, e.g., Muzzin et al. 2009; Conroy & Gunn 2010). Degeneracies in the fitting are also a concern (e.g., the age–metallicity degeneracy), so we use only the measurements of stellar mass and dust content in this Letter. Using simulated galaxy SEDs, we found that adding light from a quasar template increases the fitted mass by 0.1 dex but had very little effect on the fitted dust content in models with ages of less than 1 Gyr ($A_{V(\text{AGN+gal})} \sim A_{V(\text{gal})} + 0.1$) and no effect on the fitted A_V for models with ages greater than 1 Gyr.

The rest-frame $U-V$ color measures the strength of the 4000 Å Balmer break in the galaxy spectrum and separates red galaxies dominated by older stellar populations, which

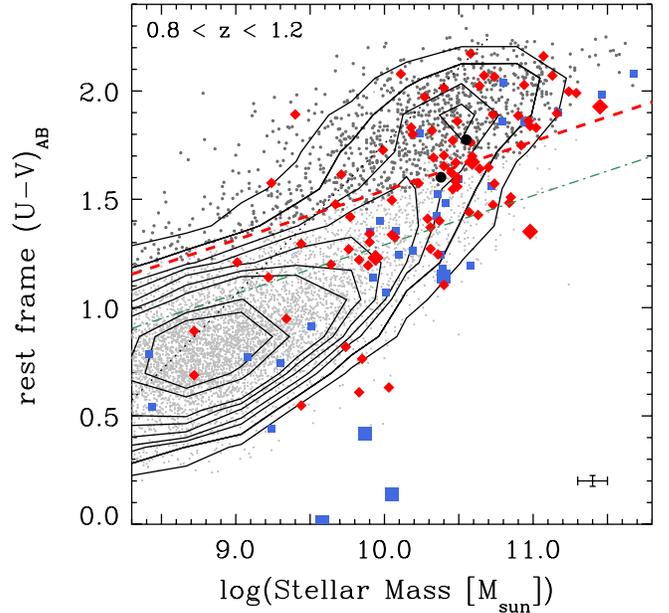


Figure 1. Galaxy population (gray points, black contours; black dotted line indicating 90% completeness) is bimodal in color vs. stellar mass. The red dashed lines show the red sequence cut defined by Borch et al. (2006) and the green dash-dotted line defines an approximate green valley region. In contrast, the X-ray selected AGNs (blue squares for unobscured AGNs, $\text{HR} \leq -0.2$; red diamonds for the obscured AGNs, $\text{HR} \geq -0.2$; and black circles for sources detected only in the full X-ray band) are distributed continuously, peaking at intermediate colors. The luminous X-ray sources ($\log(L_X) \geq 44 \text{ erg s}^{-1}$; larger symbols) are likely biased by QSO light toward bluer colors and larger masses. Monte Carlo simulation were run in EAZY to address errors due to photometric uncertainties. Typical error bars are shown in the bottom right corner. The presence of AGN host galaxies in the green valley has been interpreted to mean that AGN hosts are aging from the blue cloud to the red sequence. However, these colors can also result from dust reddening.

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

have a strong Balmer break, from blue galaxies experiencing ongoing star formation. In Figure 1, we show $U-V$ color versus stellar mass for the galaxy population. We confirm the bimodal distribution of galaxy colors at $z \sim 1$ (e.g., Bell et al. 2004; Ilbert et al. 2009). In contrast, the distribution of AGN host galaxies is continuous, extending from red to blue, as was found previously in color versus magnitude diagrams (e.g., Nandra et al. 2007; Silverman et al. 2008; Treister et al. 2009). We also confirm that AGNs are preferentially in massive galaxies ($M_{\text{stellar}} \gtrsim 10^{10} M_{\odot}$; e.g., Brusa et al. 2009).

The observed rest-frame colors of AGN host galaxies have been interpreted as indicating intermediate stellar population ages, supporting the idea that AGN activity plays a role in quenching star formation (e.g., Nandra et al. 2007). Indeed, at $z \sim 0$, AGNs are in post-starburst galaxies as assessed via spectral analysis, not just color (Schawinski et al. 2007), and post-starburst galaxies show evidence of galactic winds potentially driven by AGN feedback (Tremonti et al. 2007). However, observed colors are also affected by dust obscuration. To break this degeneracy, multiple rest-frame colors can be used to separate quiescent galaxies from those that are actively star forming but enshrouded by dust (e.g., Labbé et al. 2005; Wuyts et al. 2007). We apply this technique to investigate the nature of the AGN host-galaxy population.

3. PASSIVE VERSUS DUSTY GALAXIES

Both dusty galaxies and older stellar populations have red optical colors (e.g., $U-V$). However, near-infrared light can

⁷ The ECDF-S depth is sufficient to detect AGN with observed $\log(L_{\text{XR}}) \gtrsim 42 \text{ erg s}^{-1}$ out to $z \sim 1.2$.

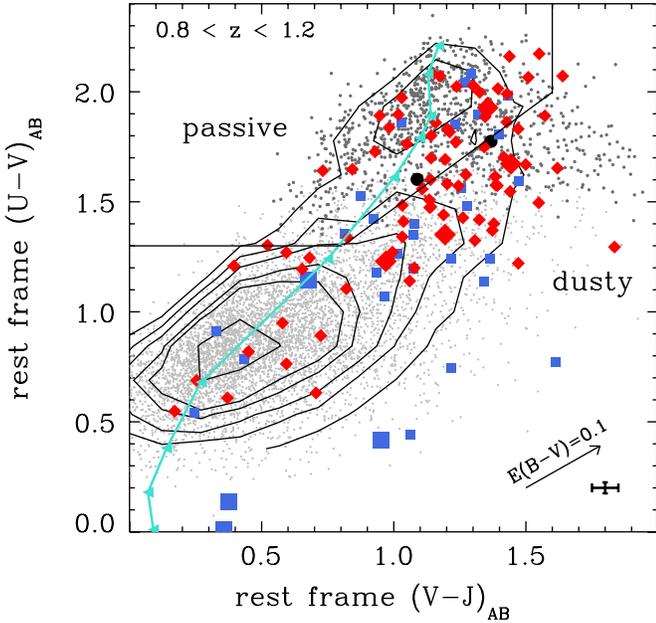


Figure 2. Distribution of galaxies in $U - V$ color vs. $V - J$ color has two peaks, one at red colors inside the passive selection region and another at blue colors (points as in Figure 1). Only half of the AGN host galaxies are located in the passive region of this diagram; the rest have colors indicative of star formation, primarily dust-obscured star formation. For objects on the red sequence in Figure 1 (dark gray points), 20% of galaxies and 20% of AGN host galaxies lie in the dust-obscured region, i.e., outside the “passive” box. Additionally, most ($\sim 75\%$) galaxies and AGNs in the green valley are dust-obscured, rather than a transition population aging onto the red sequence.

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distinguish between the two populations: given a similar $0.5 \mu\text{m}$ flux, a dusty population has more emission near $\sim 1 \mu\text{m}$ than an older stellar population. Figure 2 shows the rest-frame $U - V$ versus $V - J$ colors for galaxies in the ECDF-S, with the region occupied by passive galaxies indicated by a solid black line (red $U - V$ and blue $V - J$; Labbé et al. 2005; Williams et al. 2009). The cyan line shows a synthetic stellar population composed of a young starburst ($\tau \sim 100 \text{ Myr}$) and a more massive older stellar population (triangles indicate the model at ages of 0.025–5 Gyr). This synthetic population has the color of galaxies in the blue cloud for the first $\sim 300 \text{ Myr}$, enters the passive box after $\sim 400 \text{ Myr}$, and joins the peak of red-sequence galaxies inside the passive galaxy selection box 1 Gyr post-starburst. However, the model does not fall in the dusty region of the diagram unless significant extinction is added.

While the red-sequence galaxies (Figure 1, dark gray points) cluster inside the passive galaxy region, $\sim 20\%$ of red sequence galaxies (with $\log M_{\text{star}} \geq 10$, a completeness cut for $0.8 \leq z \leq 1.2$) scatter redder $V - J$ colors, indicating the presence of dust. This is consistent with previous findings at this redshift range (e.g., Cardamone et al. 2010; Brammer et al. 2009). Additionally, $\sim 75\%$ of the green valley galaxies are consistent with dust-reddened colors, indicating that there are far fewer objects genuinely transitioning between the blue cloud and red sequence. Similarly, $\sim 75\%$ of green valley and $\sim 20\%$ of red sequence AGN host galaxies fall outside the passive selection region. This observation calls into question the interpretation of intermediate rest-frame $U - V$ colors of AGN host galaxies as evidence that AGNs preferentially lie in galaxies aging from a blue star-forming phase to a red quiescent phase.

Overall, half of the AGN host galaxies are composed of passive stellar populations, the rest have colors indicative of younger stellar populations with varying amounts of dust reddening. Of the AGN host galaxies ($\log M_{\text{star}} \geq 10$), $\sim 50\%$ (38 out of 80) fall inside the passive selection region. The same fraction of obscured AGN host galaxies, which have minimal AGN contamination to their colors, lie inside the passive selection region (28 out of 57).

At $z \sim 1$, it is difficult to identify light from a central nuclear source, but with *Hubble Space Telescope* (*HST*) resolution it is possible to subtract the central point source and investigate uncontaminated host-galaxy colors. We compare the point-source-subtracted host-galaxy color to the total integrated color for the AGN in our sample imaged by *HST* in the GOODS survey (B. Simmons et al. 2010, in preparation). The median $V - z$ color difference ($|[V - z]_{\text{total}} - [V - z]_{\text{hostgalaxy}}|$) is 0.03 mag, and two outlying sources with large color differences have low X-ray hardness ratios, $\text{HR} \sim -0.5$, consistent with unobscured AGNs. Therefore, for the moderate luminosity obscured AGN in our *HST* sample, the integrated galaxy color does not appear to be significantly affected by the central AGN light.

To further test the effects of the integrated AGN light, we combine synthetic stellar population models with unobscured quasar templates (Vanden Berk et al. 2001; Richards et al. 2006), creating model SEDs containing the post-starburst template used in Figure 2 and up to 50% of light (normalized in the R band) from the quasar template. We then convolve these composite spectra with our filter set and use EAZY to determine the rest-frame colors. The $U - V$ colors are preferentially shifted toward the blue, but the net effect is less than 0.1 mag (and typically $< 0.03 \text{ mag}$). However, we do note that the very blue, very luminous AGNs (Figure 1, bottom right) have high X-ray luminosities and hardness ratios consistent with unobscured AGNs. In these SEDs, the blue continuum is very flat and the AGN light dominates the integrated light, causing the blue colors at optical wavelengths. Pierce et al. (2010) also simulate the addition of unobscured quasar (QSO) light to template galaxy SEDs (contributing up to 50% of the B -band flux), finding that the additional blue continuum from the QSO can bias the $U - B$ colors by up to a magnitude. For the obscured AGN, the light from the central AGN continuum distribution does not greatly affect the AGN host-galaxy colors.

The addition of the unobscured quasar light to a young stellar population makes the shorter wavelength colors slightly blue, but at longer wavelengths the composite is redder ($[V - J]_{\text{AGN+gal}} \sim [V - J]_{\text{gal}} + 0.2$). However, for models several hundred million years post-starburst (i.e., at redder $U - V$ colors), the AGN light does not change the rest-frame $V - J$ color enough to move it into the dusty region of the diagram ($[V - J]_{\text{AGN+gal}} \sim [V - J]_{\text{gal}} + 0.02$). Therefore, our finding that $\sim 50\%$ of the AGN host galaxies live in passively evolving host galaxies is robust to contamination from a central AGN source.

Following Brammer et al. (2009), we de-redden the rest-frame colors based on the A_V from the SED fit assuming a Calzetti et al. (2000) dust law ($\Delta A_V = 0.47 \times A_V$). Figure 3 shows that many galaxies in the green valley are removed in the dust-corrected $U - V$ color diagram. That is, the population of AGN host galaxies divides into blue and red populations after correcting the $U - V$ colors for the contribution of dust, just as has been seen for non-active high-redshift galaxies (Cowie & Barger 2008; Brammer et al. 2009). Roughly, half of the AGNs remain on the lower edge of the red sequence, while

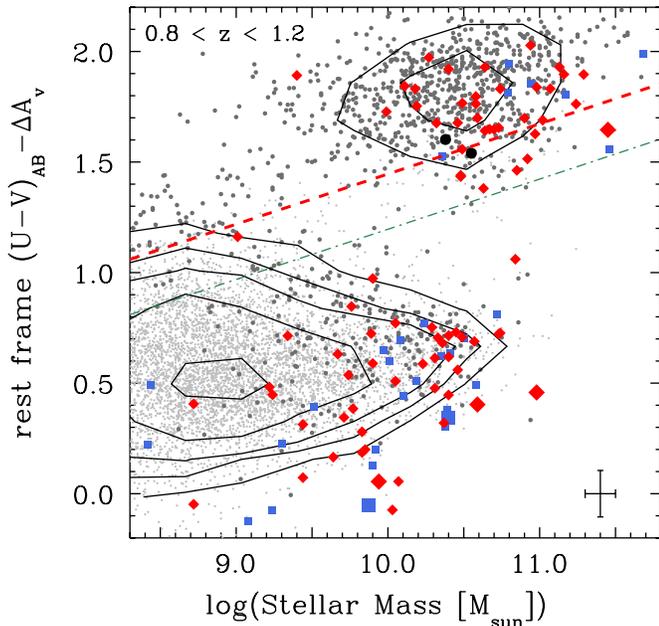


Figure 3. Dust-corrected color–mass diagram shows that AGNs and galaxies divide cleanly into red and blue colors (points as in Figure 1). Half of the AGN host galaxies at $z \sim 1$ remain on a passive red sequence, while the other half lie at the massive end of the blue cloud. The location of the AGN host galaxies on the blue edge of the red sequence suggests that these AGNs may be recent arrivals to the red sequence which will redden further as their stellar populations age.

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the other half has blue de-reddened colors. These corrected colors depend on accurate determinations of A_V from the SED fitting, which can be overestimated in galaxies that experienced a modest starburst several hundred million years ago. However, 95% of sources fitted by FAST with $A_V > 0.2$ fall outside the passive selection region in Figure 2, suggesting overestimated A_V values may affect at most 5% of the population. Follow-up deep spectroscopy is underway to confirm these AGN host galaxies’ dusty-star-forming nature.

4. DISCUSSION AND CONCLUSIONS

Using rest-frame near-infrared colors, we have shown that few AGN host galaxies in the green valley at $z \sim 1$ are genuinely transitioning from blue to red; 75% of the host galaxies with green observed colors are intrinsically blue but reddened by dust. Corrected for reddening, the observed $z \sim 1$ AGN population is evenly split between galaxies in the blue cloud and those on the red sequence.

Some models of galaxy evolution suggest that heating of the interstellar medium, due to feedback from black hole growth, could potentially quench star formation (Silk & Rees 1998; Faber et al. 2007; Schawinski et al. 2007; Di Matteo et al. 2008). The dusty, intrinsically blue, star-forming AGN host galaxies are fully consistent with the observed AGN heating up the interstellar gas and shutting down star formation. In that case, the galaxies with dust-corrected intermediate colors, ~ 5 green valley AGN hosts and ~ 50 non-AGNs, would be transitioning from the blue cloud. Since there are ~ 40 AGNs with dust-corrected blue star-forming hosts, this implies that these galaxies spend comparable times in a star-forming phase and passively evolving green valley phase. However, this is not evident that AGN quenching occurs. Follow-up studies with

deep optical and infrared spectroscopy can more accurately age-date the stellar populations and explore this possible link.

The red AGN host galaxies are actually of the same color—and thus are likely to have the same post-starburst age—as comparable X-ray-selected samples of AGNs at $z \sim 0$ (Schawinski et al. 2009a). They lie on the red sequence at $z \sim 1$ but in the green valley at $z \sim 0$ due to the evolution of the red sequence from $z \sim 0-1$ (e.g., Bell et al. 2004). Even with an effectively instantaneous cessation of star formation, a starburst takes ~ 300 Myr to age to colors consistent with the bluest edge of the $z \sim 1$ red sequence, and more gradual exponential declines of star formation take ~ 500 Myr or more. Given a typical AGN lifetime ($\sim 10-100$ Myr; Ferrarese & Ford 2005), the redder host galaxies are slightly older than one would expect if the star formation was shut down partway through the current episode of AGN activity.

Furthermore, if the presently observed AGN is responsible for the cessation of star formation, then the relative frequency of dust-corrected red AGN hosts compared to dust-corrected green AGN hosts gives a rough estimate of the duty cycle of AGN activity. That is, because there are at least 10 times as many AGNs on the red sequence as in the green valley (for $\log M_{\text{star}} \geq 10 M_{\odot}$, where our sample is complete), a continuously active AGN would have to spend 10 times as long on the red sequence as their stellar populations take to age through the green valley. Given the ages of post-starburst galaxies with colors of $U - V \sim 1.5$, this implies an AGN lifetime over ~ 1 Gyr. It therefore seems more likely that AGN activity is episodic, with the current episode of accretion beginning after the star formation was turned off. In either case, the AGN in red galaxies could represent a “maintenance mode,” in which enough energy is released into the interstellar medium to prevent future episodes of star formation (Croton et al. 2006; Hopkins et al. 2006). It is interesting to note that the lowest luminosity AGN in our sample, $\log(L_{\text{XR}}) \sim 42-42.5 \text{ erg s}^{-1}$, are preferentially red and passive. That is, a lower level of AGN activity may suffice to prevent gas cooling, whereas a more luminous AGN might be required to quench vigorous star formation.

The two populations of AGN hosts at $z \sim 1$ —in young star-forming galaxies and in older, passively evolving galaxies—appear to represent distinct phases of AGN activity. Specifically, AGNs in young, dusty-star-forming galaxies are prime candidates for quenching star formation and driving their host galaxies toward the red sequence, while AGNs in much older, red host galaxies may be keeping the interstellar gas hot and preventing future episodes of star formation.

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