QUENCHING DEPENDS ON MORPHOLOGIES: IMPLICATIONS FROM THE ULTRAVIOLET–OPTICAL RADIAL COLOR DISTRIBUTIONS IN GREEN VALLEY GALAXIES

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ABSTRACT

In this Letter, we analyze the radial ultraviolet–optical color distributions in a sample of low redshift green valley galaxies, with the Galaxy Evolution Explorer (GALEX)+Sloan Digital Sky Survey (SDSS) images, to investigate how the residual recent star formation is distributed in these galaxies. We find that the dust-corrected $u - r$ colors of early-type galaxies (ETGs) are flat out to $R_{90}$, while the colors monotonously turn blue when $r > 0.5 R_{90}$ for late-type galaxies (LTGs). More than half of the ETGs are blue-cored and have remarkable positive $NUV - r$ color gradients, suggesting that their star formations are centrally concentrated. The rest have flat color distributions out to $R_{90}$. The centrally concentrated star formation activity in a large portion of ETGs is confirmed by the SDSS spectroscopy, showing that $\sim 50\%$ of the ETGs have $\text{EW}(H_\alpha) > 6.0\, \text{Å}$. Of the LTGs, $95\%$ show uniform radial color profiles, which can be interpreted as a red bulge plus an extended blue disk. The links between the two kinds of ETGs, e.g., those objects having remarkable “blue-cores” and those having flat color gradients, are less known and require future investigations. It is suggested that the LTGs follow a general model by which quenching first occurs in the core regions, and then finally extend to the rest of the galaxy. Our results can be re-examined and have important implications for the IFU surveys, such as MaNGA and SAMI.

Key words: galaxies: evolution – galaxies: star formation

Online-only material: color figures, supplemental data

1. INTRODUCTION

Why and how galaxies stop their star formation activities and then move from the “blue cloud” to the “red sequence” (the so-called “quenching procedure”) is a key question in the study of galaxy formation and evolution. In the literature, at least two factors are proposed to affect quenching: galaxy stellar mass and environmental conditions (e.g., Peng et al. 2010). However, we are still far from a comprehensive understanding of the detailed quenching picture.

In the color–magnitude (or the color–mass) diagram, the green valley (GV) is a narrow region connecting the “blue cloud” and the “red sequence” (Strateva et al. 2001; Baldry et al. 2004; Bell et al. 2004). The galaxies in the GV were thought to be transition populations between the star-forming and the quenched galaxies (Bell et al. 2004; Wyder et al. 2007; Mendez et al. 2011; Pan et al. 2013), hence holding important clues to the process led by the quenching procedure. In a recent paper, Schawinski et al. (2014) showed that the color distributions of GV early-type galaxies (ETGs) on the $u - r$ diagram versus the $NUV - u$ diagram can be modeled by a quenching timescale of $\tau_{\text{quench}} \sim 0.1\, \text{Gyr}$, while, for the bulk of late-type galaxies (LTGs), a longer quenching timescale is required ($\tau_{\text{quench}} \sim 2.5\, \text{Gyr}$). This study suggests that morphology is another factor that can affect the detailed quenching processes in galaxies.

Recent works have found that quenching is connected with remarkable bulge growth (Bell et al. 2012; Chueng et al. 2012; Pan et al. 2013; Bruck et al. 2014), regardless of its detailed working mechanism. It is thus necessary to investigate which part of a galaxy the quenching procedure first takes place in. Recently, Abramson et al. (2014) found that the specific star formation rates ($\text{sSFRs}$) renormalized by disk stellar mass (formulated by $\text{sSFR}_{\text{disk}} \equiv \text{SFR}/M_{\text{s, disk}}$) are weakly dependent on disk masses. In their work, “mass quenching” was interpreted through more massive galaxies, which have larger bulge mass fractions—the portion of a galaxy not forming stars. Thus, when investigating how quenching is processing in galaxies, it will be more reasonable to treat galaxies as composite systems rather than integrated mass, if the data allows one to do so.

A spatially resolved study on the residual star formation in a GV galaxy may shed light on how quenching is processing in a galaxy. Large surveys such as the Sloan Digital Sky Survey (SDSS; York et al. 2000) and the Galaxy Evolution Explorer (GALEX; Martin et al. 2005) survey have provided a large sample of local galaxies to facilitate such studies. In a previous work, Suh et al. (2010) investigated the $g - r$ color profile in a sample of low redshift ETGs and found that roughly $30\%$ of them show positive color gradients, which is consistent with the existence of central star formation. Since the emissions in the ultraviolet (UV) bands are more sensitive to recent star formation than those of the optical bands, in this Letter, we use GALEX+SDSS data to study the radial UV–optical color distributions in a sample of low redshift face on GV galaxies and to investigate how the residual star formation activities are distributed in transition galaxies. Throughout this Letter, we assume a concordance $\Lambda$CDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70\, \text{km s}^{-1}\, \text{Mpc}^{-1}$.

2. SAMPLE SELECTION

Our parent sample is drawn from Schawinski et al. (2014), which contains $\sim 46,000$ galaxies at the redshift range of $z = [0.02, 0.05]$. This sample is magnitude completed to
$M_{\text{Petro}} = -19.5$ AB mag and with Galaxy Zoo (Lintott 2008, 2011) visual morphological classifications. The stellar masses are derived by fitting the five SDSS photometric bands to a library of $6.8 \times 10^6$ models of star formation histories generated from Maraston et al. (1998, 2005) stellar models. We follow the process of Schawinski et al. (2014) to select GV galaxies. First, the galaxies are $k$-corrected to $z = 0$ using the KCORRECT code of Blanton & Roweis (2007) with the SDSS five broadband photometry. Then, the magnitudes are corrected for dust reddening using estimates of internal extinction from the stellar continuum fits by Oh et al. (2011), applying the Cardelli et al. (1989) law. Then the GV is defined on the dust-corrected stellar continuum fits by Oh et al. (2011), applying the Cardelli et al. (1989) law. Then the GV is defined on the dust-corrected color–mass diagram for all galaxies, given

$$-0.70 + 0.25 \times M_* < 0.0 (u - r) < -0.30 + 0.25 \times M_*, \quad (1)$$

where $0.0 (u - r)$ is the $k$-corrected $u - r$ color index and $M_*$ is log stellar mass, respectively. This criterion is stricter than that of Schawinski et al. (2014) to ensure that our samples are not contaminated by the blue cloud and red sequence galaxies. With this criterion, about 700 ETGs and 3000 LTGs are classified as GV galaxies. To ensure that their radial color distributions can be robustly measured, only galaxies with $b/a > 0.7$ are selected. The remaining sample contains about 300 ETGs and 700 LTGs.

3. DATA REDUCTION

The GALEX NUV image has a resolution of 1 pixel $= 1.5^\prime$ and a point spread function (PSF) with FWHM $= 5.3^\prime$. The pixel size and PSF of the SDSS image are $0.396^\prime\prime$ and $1.4^\prime\prime$, respectively. To ensure that the photometric measurements are consistent across the different bands, we need to transform all of the images to the same geometry and effective resolution before doing photometry.

Following Wang et al.’s (2010) pipeline, a UV–optical matched photometric catalog has been generated by J. Li et al. (2014, in preparation). This catalog contains about 220,000 galaxies with uniform photometric measurements on the resolution and PSF-matched GALEX+SDSS images. Here, we briefly describe our data reduction. We first cross-matched the SDSS DR8 Aihara et al. (2011) spectroscopic galaxies with the GALEX GR6 frames. Then, we downloaded the matched galaxy images from the SDSS and GALEX database. For the GALEX images, only those with exposure times larger than 1000 s are used. We degraded the pixel scales of the SDSS images and registered the frame geometries to the corresponding NUV images. To match the GALEX and SDSS photometry, the SDSS image needs to be convolved the NUV PSF kernel function. The PSF kernel function was obtained by fitting a two-dimensional Gaussian function to the stacked star stamps in the corresponding GALEX NUV frame. The PSF-convolving procedure on the SDSS images was done by running IMMATCH/PSFMATCH task in IRAF. Finally, aperture photometry were done by running SExtractor (Bertin & Arnouts 1996) on the resolution and PSF-matched GALEX and SDSS images, over five different apertures, with $r = [1.5, 3.0, 6.0, 9.0, 12.0]^\prime\prime$. The SExtractor also measures the AUTO magnitude, e.g., the total magnitude of a galaxy. Figure 1 shows an example of registered and PSF-convolved images for an LTG in our sample.

The PSF-matched photometry has been compared with the SDSS public data. Good consistency is found between the SDSS c-model magnitudes and the AUTO magnitudes we measured. Finally, the magnitudes are corrected for galactic extinction using the galactic dust map (Schlegel et al. 1998).

We cross-match the GV sample selected in Section 2 with the UV–optical matched catalog and obtain 117 ETGs and 219 LTGs. Among these, 9 ETGs and 13 LTGs classified as Seyfert galaxies on the BPT diagram are rejected (Baldwin et al. 1981). The final sample containing 108 ETGs and 206 LTGs will be used to investigate their NUV–optical radial color distributions in the next section.

4. RESULTS

4.1. $u - r$ and NUV $- r$ Radial Color Distributions

In Figure 2, we show the radial dust-corrected SDSS $u - r$ color distributions. The dust correction on the colors is done by using a single $E(B - V)$ value (drawn from Oh et al. 2011) at all radii, because it is difficult to know how extinction varies at different radii. The radii are normalized by $R_{90}$, the radii enclosed 50% SDSS $r$-band petrosian fluxes. To present the results more clearly, we divide the sample into two subsamples, according to their $C_{r=1\prime.5} - C_{\text{auto}}$, $C_{r=1\prime.5}$ and $C_{\text{auto}}$ are the color indices measured in the central $r = 1.5^\prime$ aperture and that of the whole galaxy, respectively. A galaxy having $C_{r=1\prime.5} - C_{\text{auto}} < 0.0$ means that its color in the core is bluer than that of the whole. We call galaxies of this category “blue-cored.” In this sense, “red-cored” galaxies have $C_{r=1\prime.5} - C_{\text{auto}} > 0.0$.

As also shown in Schawinski et al. (2014), the GV ETGs, on average, are less massive than LTGs. ETGs also have more compact morphologies and approximately 35% of our ETGs have $R_{90} < 8.0$. Therefore, the measurements of the outer colors in these small-size ETGs will be seriously contaminated by the background and are not reliable. For the $R_{90} < 8.0$ galaxies, we use gray lines to represent their color profiles. Note that rejecting

5 The sample was downloaded from http://data.galaxyzoo.org/.

6 http://iraf.noao.edu/
Figure 2. Radial dust-corrected $u-r$ color profiles. The left panels show the results of ETGs and LTGs are shown in the right panels. To clarify, we binned the samples into two subsamples according to their $C_r=1^\prime.5-C_{\text{auto}}$. The radial color profiles of blue-cored galaxies are shown in the upper panels (blue lines). The gray lines represent the color distributions with SDSS $R_{90}<8.0$ arcsec. The thick black line represents the median color profile.

(A color version and supplemental data of this figure are available in the online journal.)

these small-size galaxies will not affect our main conclusions on the radial color distributions. However, they will be included to maintain a large ETG sample size.

Out of 108 ETGs, 24 are blue-cored, as shown in the upper left panel in Figure 2. This fraction is significantly larger than that of LTGs, which is only 28 out of 206. For the red-cored subsamples, we find that color profiles are different between ETGs and LTGs: most ETGs show a very mild color gradient out to $3R_50$ ($\approx R_{90}$ for ETGs), whereas LTG colors decrease when $r > 0.5R_50$.

Figure 3 shows the radial NUV $-r$ color distributions. NUV $-r$ is a widely explored color index in the literature (Salim et al. 2005; Wyder et al. 2007; Wang et al. 2010). Interestingly, this figure shows dramatically different features compared to the $u-r$ color distributions. For ETGs, we find that 68 out of 108 have inner blue NUV $-r$ colors, e.g., their recent star formations are concentrated in central regions. The rest show very flat NUV $-r$ color profiles.

For LTGs, more than 90% show uniform NUV $-r$ color distributions. Their NUV $-r$ colors monotonously decrease beyond $r \sim 0.5R_50$, which can be interpreted by red bulges plus blue disk components, which are still actively forming stars. We also find that the integrated NUV $-r$ colors of ETGs are systematically redder than those of LTGs, confirming the findings of Schawinski et al. (2014). Thanks to the GALEX photometry, we are able to investigate the recent star formation activities in GV galaxies in more detail. It is impossible when only the SDSS photometry is available.

4.2. A Test of the Color Profile on Simulated Images

The issue that we are most concerned with is how the PSF impacts the galactic color profiles. Is the color profile we measured on an image with a $5.3$ PSF robust?

To answer this question, we have performed a test on the simulated images. For each galaxy, we use its SDSS $r$-band image to simulate its corresponding image in the NUV band. To be simplified, we only discuss the simplest case here. First the SDSS $r$-band image is degraded to $1.5$/pixel to match the NUV resolution. The NUV flux at the radius, $r$, of the simulated image ($f_{\text{NUV},r}$) is then given:

$$f_{\text{NUV},r} = f_{\text{SDSS},r} \times 10^{kr} \times 10^{-3.5/2.5},$$  \hspace{1cm} (2)

where $f_{\text{SDSS},r}$ is the flux at $r$ on the SDSS $r$-band image and $k$ is a given gradient value, respectively. By definition, the NUV $-r$ color at $r$ is

$$(\text{NUV} - r)_r = 2.5 \log_{10}(f_{\text{SDSS},r}/f_{\text{NUV},r}) = 3.5 - 2.5kr.$$  \hspace{1cm} (3)

The value $(\text{NUV} - r)_{r=0} = 3.5$ is the median color at galactic centers, which is taken directly from Figure 3. Another set of images, namely the simulated PSF-convolved images, are also created by convolving the image we simulated with the NUV PSF. Finally, we measure the NUV $-r$ color index on the two sets of simulated images to investigate how the PSF will impact the output color profile.

We select an LTG with $R_{90} = 15.0$ and show the result in Figure 4. In the upper and lower panels, we simulate a color
Figure 3. Same as Figure 2, but shown in dust-corrected NUV − r colors.

(A color version and supplemental data of this figure are available in the online journal.)

Figure 4. In the top panels, we simulate the galaxy to have a steep NUV − r color gradient. The left panel shows the NUV − r color map measured on the images without convolving the NUV PSF. The one shown in the middle panel is measured on the PSF-convolved images. The right panel shows a comparison of the two kinds of color profiles. The thick red lines indicate the given color profile, the red dots indicate the color index measured on each pixel, and the vertical line indicates our color profile detecting threshold, $r = 12''0$. In the lower panels, we simulate the galaxy to have a mild gradient.

(A color version of this figure is available in the online journal.)
profile with a steep and mild gradient, respectively. Interestingly, we find the shape of the output color profile looks quite similar to those measured on the real images. For both cases, we find that the color profiles measured on the simulated PSF-convolved spectra are basically consistent with the prior given profiles. The color profile is smoothed at galactic centers by the PSF, as seen in Figure 4. We find that the color deviation becomes evident at $r > 15''$, which is likely owing to the low surface brightness at the radii larger than $R_0$. To conclude, we find the color profile for a $R_0 \sim 10.0''$ galaxy is not seriously modified by the NUV PSF, and our results are highly robust.

4.3. Star Formation Activities at Galaxy Centers

The H$\alpha$ emission is a good tracer of instantaneous SFR (Kennicutt 1998). In this subsection, we investigate the star formation in the central 3/0' region in our sample using the SDSS spectroscopy. The EW(H$\alpha$) values are taken from the MPA/JHU catalog. In Figure 5, we plot the EW(H$\alpha$) versus EW(H$\beta$) diagram. It can be seen that the bulk of GV galaxies have strong H$\alpha$ emissions, i.e., EW(H$\alpha$) < 10 Å, showing that the star formation rate is low in the core of GV galaxies. In the subsection above, we have found that a large fraction of ETGs have blue-core NUV − r colors. Interestingly, in Figure 5, we find that nearly half of the ETGs have EW(H$\alpha$) > 6.0 Å, confirming that star formation occurs in their core regions. We call galaxies with EW(H$\alpha$) > 6.0 Å as “H$\alpha$ emitter” in the following. This fraction is significantly lower in LTGs, indicating that the residual star formation in LTGs is mostly attributable to the galactic disk.

The star formation strength was found to link with galaxy mass, as demonstrated by the famous star-forming “main sequence” (Peng et al. 2010; Fang et al. 2012). We check whether the different core EW(H$\alpha$) distributions in ETGs and LTGs are due to their different mass distributions. The sample is divided into two subsamples according to their stellar mass. The dividing mass threshold is set to $\log(M_*/M_\odot) = 10.2$, the mass that can roughly separate galactic properties into two main groups (Kauffmann et al. 2003; Nair & Abraham 2010). The H$\alpha$ emitter fraction is 21/39 \approx 0.54 and 34/69 \approx 0.49 in the low- and high-mass ETG subsamples, respectively. The fractions are 28/64 \approx 0.44 and 43/142 \approx 0.30 in the LTGs, respectively. Thus, the different EW(H$\alpha$) distributions between ETGs and LTGs cannot be explained by their different mass distributions.

Under the ΛCDM paradigm, an ETG is formed through hierarchical mergers. The E+A galaxies, also called post-starburst galaxies, are considered to be the products of galaxy interactions and the progenitors of red ETGs. In Figure 4, the box enclosed EW(H$\beta$) > 3.0 Å and EW(H$\alpha$) < 6.0 Å define our E+A selection criterion. It can be seen that most E+A galaxies have early-type morphologies, though the number of LTGs is significantly larger than ETGs. However, even in GV ETGs, E+A galaxies only compose a small fraction, suggesting that most red ETGs may not have undergone the E+A phases in their past.

5. SUMMARY AND DISCUSSION

Our main finding is that GV ETGs have dramatically different radial NUV − r color distributions compared to LTGs. A larger fraction of ETGs have blue cores, both represented by $u − r$ color and NUV − r color. More than half of the ETGs show blue-core NUV − r colors and the remainder have flat color distributions out to $R_0$. Compared to ETGs, nearly all LTGs have uniform color profiles that can be well-interpreted as red bulges plus blue disk components. The larger fraction of central star formation in ETGs than in LTGs is confirmed by the SDSS spectra. We will discuss our findings in this section.

5.1. Implications on ETGs Evolution

We are not the first to report the inner blue phenomenon in ETGs; it has been mentioned in some previous works (Jeong et al. 2009; Suh et al. 2010). It is likely attributable to a starburst or its residual in the galactic center. Under the ΛCDM paradigm, a major merger of two gas-rich LTGs will induce gas inflow to trigger a central starburst (Springel et al. 2005). Strong starbursts will soon be suppressed by AGN feedback and the star formation will shut down quickly, then produce an E+A remnant, as predicted by models (Hopkins et al. 2006). Some previous works also found evidence that powerful AGNs can drive strong gas outflows and may lead to a rapid decrease in star formation host galaxies (Page et al. 2012; Cimatti et al. 2013). Interestingly, Schawinski et al. (2010) found that roughly 50% of blue ETGs show merger features in deep images, supporting this scenario. Some previous studies also found that a large fraction of E+A galaxies show very obvious interaction features (Goto 2005; Yang et al. 2008). However, the E+A population only composes a very small portion of the total GV ETGs. We suggest that most red ETGs may not have undergone the E+A phases in their past.

Star formation in the cores of ETGs can alternatively be explained by the contribution of a “cooling flow” (Brown & Bregman 1998; Wang et al. 2010). In the X-ray observations, some ETGs have relatively lower temperatures in the core regions and can induce gas inflow. The inflow of cool gas can fuel an AGN or trigger star formation activity in the center of ETGs. This scenario explains the star formation in the center without the requirement of a strong starburst triggered by a merger.

5.2. Implications on LTGs Evolution

We find that most GV LTGs host inactive cores and blue disk components. The central masses of LTGs can be built either by secular evolution (Kormendy & Kennicutt 2004) or the central starbursts. Wang et al. (2012) found that LTGs with

Figure 5. Left: the EW(H$\beta$) vs. EW(H$\alpha$) diagram. ETGs are shown in red solid circles and LTGs are shown in blue triangles. The measurements are drawn from the MPA catalog. Right: the EW(H$\alpha$) distributions. ETGs are shown by the solid red histograms and ETGs are by the shadow blue histograms, respectively. The box encloses galaxies defined as E+As.
strong bars either have enhanced central star formation rates or star formation that is suppressed compared to the mean. Masters et al. (2011) found that redder LTGs are more likely to have bars. These findings suggest that the central mass builds up and the subsequent quench in a portion of LTGs is likely driven by bars. Other mechanisms such as galaxy interactions are needed to explain the quenched LTGs without bars.

The color gradients of LTGs are consistent with the inside-out disk growth scenario. Wang et al. (2011) found evidence that disk galaxies follow an inside-out disk growth model. In this model, the $\mathrm{H}_\text{I}$ gas is accreted onto the outer disk and forms new stars through which the disk galaxy assembles its stellar mass. The long quenching timescale required for an LTG, as modeled in Schawinski et al. (2014), is likely due to the long timescale of removing/exhausting the cool gas on its gaseous disk.

However, we note that several LTGs have inner blue color profiles. We have checked their SDSS images and found that four out of nine of them have visible tidal interaction features. Among these, one is classified as an E+A galaxy. Thus, the central star formation in these LTGs is likely driven by galaxy interactions. The rest have much smaller bulge components than most LTGs, and their SDSS spectra show relatively strong $\mathrm{H}\alpha$ emission lines. Thus, they are possibly in the process of bulge building. However, the fraction of blue-cored LTGs is so small and will not hamper our final conclusion.

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