GREEN GALAXIES IN THE COSMOS FIELD

ZHIZHENG PAN1,2,3, XU KONG1,2,3, AND LU LU FAN1,2,3

1 Center of Astrophysics, University of Science and Technology of China, Hefei 230026, China; panzz@mail.ustc.edu.cn, xkong@ustc.edu.cn
2 Key Laboratory for Research in Galaxies and Cosmology, Chinese Academy of Sciences, Hefei 230026, China
3 Key Laboratory for the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, Kunming 650011, China

Received 2013 April 9; accepted 2013 August 5; published 2013 September 20

ABSTRACT

We present research on the morphologies, spectra, and environments of ≈2350 “green valley” galaxies at $0.2 < z < 1.0$ in the COSMOS field. The bimodality of dust-corrected NUV–r* color is used to define “green valley”; it removes dusty star-forming galaxies from galaxies that are truly transitioning between the blue cloud and the red sequence. Morphological parameters of green galaxies are intermediate between those of blue and red galaxy populations, both on the Gini–asymmetry and the Gini–M–20 planes. Approximately 60%–70% of green disk galaxies have intermediate or big bulges, and only 5%–10% are pure disk systems, based on morphological classification using the Zurich Estimator of Structural Types. The obtained average spectra of green galaxies are intermediate between blue and red ones in terms of [O II], Hα, and Hβ emission lines. Stellar population synthesis on the average spectra shows that green galaxies are on average older than blue galaxies but younger than red galaxies. Green galaxies and blue galaxies have similar projected galaxy density (Σ0) distributions at $z > 0.7$. At $z < 0.7$, the fractions of $M_\star < 10^{10.0} M_\odot$ green galaxies located in a dense environment are found to be significantly larger than those of blue galaxies. The morphological and spectral properties of green galaxies are consistent with the transitioning population between the blue cloud and the red sequence. The possible mechanisms for quenching star formation activities in green galaxies are discussed. The importance of active galactic nucleus feedback cannot be well constrained in our study. Finally, our findings suggest that environmental conditions, most likely starvation and harassment, significantly affect the transformation of $M_\star < 10^{10.0} M_\odot$ blue galaxies into red galaxies, especially at $z < 0.5$.

Key words: galaxies: evolution – galaxies: formation – galaxies: interactions – galaxies: stellar content

Online-only material: color figures

1. INTRODUCTION

Many observational properties of galaxies in the local universe, such as optical colors (Strateva et al. 2001; Baldry et al. 2004), spectral indices (Kauffmann et al. 2003b), and morphological parameters (Driver et al. 2006) exhibit bimodal distributions. Deeper surveys such as DEEP2 (Willmer et al. 2006), COSMOS (Zamojski et al. 2007), and NEWFIRM (Brammer et al. 2009) have revealed that the bimodality of galaxy properties exists up to $z \approx 2$. Generally, galaxies are categorized into two main populations: red quiescent galaxies and blue star-forming galaxies. The red quiescent galaxies, mainly E/TGs, lie on a relatively narrow ridge (the red sequence) in the color–magnitude diagram (CMD). The blue star-forming galaxies, mainly late-type galaxies (LTGs), are distributed throughout the so-called blue cloud. Galaxies located in the joint blue cloud and red sequence region are called “green valley” galaxies (hereafter green galaxies).

Studies on galaxy evolution reported that red galaxies have grown in stellar mass by a factor of two to four, whereas the number density of luminous blue galaxies has dropped strongly since $z \approx 1$ (Bell et al. 2004; Faber et al. 2007; Bolzonella et al. 2010; Ilbert et al. 2010; Brammer et al. 2011). The transformation of a significant fraction of blue galaxies into red galaxies during this cosmic time has been suggested by some previous works (Faber et al. 2007; Pozzetti et al. 2010). However, the transition timescale must be short (Faber et al. 2007; Martin et al. 2007; Balogh et al. 2011), since the bimodality will never be observed if the transition timescale is over a Hubble time. Green galaxies are therefore considered to be a transitioning population migrating toward the red sequence. However, only a few studies have focused on this less prominent population. Some works have reported that a large fraction of green galaxies are not truly transitioning, but are dusty, star-forming galaxies (Brammer et al. 2009; Salim et al. 2009).

The physical properties of green galaxies have been revealed, to some extent, in earlier works. Based on the DEEP2 redshift survey, Coil et al. (2008) found that the co-added spectra of green galaxies have higher [O III]/Hβ ratio than the spectra of blue galaxies at $z \approx 1$. Furthermore, the large-scale clustering amplitude of green galaxies is similar to that of red galaxies. However, green galaxies show similar clustering amplitude to blue galaxies at a scale of ~1 Mpc. Using Sloan Digital Sky Survey (SDSS) main galaxy sample, Zehavi et al. (2011) showed that green galaxies have a clustering amplitude that can be found between the amplitudes of red and blue galaxies. Balogh et al. (2011) reported that they discovered a large transitioning galaxy population in X-ray groups at $0.85 < z < 1.0$ in the COSMOS field, and that these galaxies reside in the optical green valley (GV). Most of these galaxies have bulges and small disk components, with half of them showing prominent Hδ absorption lines. Mendez et al. (2011) studied the morphologies of green galaxies in the AEGIS field and found that green galaxies are intermediate between blue and red populations in terms of concentration, asymmetry, and morphological type; furthermore, removing dusty galaxies from the green galaxy sample would not alter this result. Goncalves et al. (2012) studied the star formation history (SFH) of about 100 GV galaxies at $z \approx 0.8$ based on Keck spectra, and found that the transformation happened more rapidly for more massive
galaxies. Most previous studies are based on very small samples or focused on a very narrow redshift range. A specific study of the physical properties and redshift evolution of this population can be conducted using a large and homogeneous sample that spans a wide redshift range, along with deep multi-band photometry, spectra, high-resolution images, etc.

One of the key questions that emerges is: which physical mechanisms are responsible for quenching star formation activities in blue galaxies and the resulting transformation? Different star-formation-quenching mechanisms have been proposed. Of these, mergers can effectively convert LTGs into ETGs, both in observation and simulation. A major merger can change the overall galaxy morphology as well as form bulges and trigger starburst, which can quickly consume gas or expel them through shocks from supernova feedback (Springel et al. 2005; Robertson et al. 2006). Another possible quenching mechanism is active galactic nucleus (AGN) feedback. In this scenario, the AGNs heat gas to prevent them from forming new stars (Bower et al. 2006; Tremonti et al. 2007). The AGN feedback scenario is observationally supported by X-ray imaging of evacuated cavities around massive galaxies (McNamara et al. 2000; McNamara & Nulsen 2007).

Interestingly, some studies have found that the AGN detection rate is high in GV (Nandra et al. 2007; C o i le ta l .2009). Meanwhile, environmental effects can lead to quenching, as suggested in a great deal of works. For example, studies based on the Hubble Space Telescope (HST) have shown that distant clusters have larger fractions of LTGs than local clusters (Dressler et al. 1997; Fasano et al. 2000; Lubin et al. 2002). These studies found that the fraction of S0 galaxies has significantly increased since $z \sim 0.7$, whereas the fraction of spiral galaxies has decreased significantly. The most favored explanation is that dense environment can effectively quench star formation activities in blue galaxies and turn them into S0 galaxies (Vogt et al. 2004; Moran et al. 2007).

In this paper, we use COSMOS data to study the transitioning population and constrain mechanisms that lead to star formation quenching. The COSMOS survey (Scoville et al. 2007), the largest contiguous survey with HST, provides a combined data set including multi-band photometry covering the X-ray, ultraviolet (UV), optical, infrared, millimeter, to radio bands (Bertoldi et al. 2007; Capak et al. 2007b; Hasinger et al. 2007; Sanders et al. 2007; Zamojski et al. 2007). Morphological parameters measured using Advanced Camera for Surveys (ACS) imaging are also available (Koekemoer et al. 2007). The zCOSMOS survey (Lilly et al. 2007) provides approximately 10,000 galaxy spectra in the 1.4 deg$^2$ COSMOS field, thereby facilitating the exploration of spectral characteristics. The photometric redshifts of COSMOS galaxies are extremely accurate (Ilbert et al. 2009), and allows for the measurement of galaxy environment. Thus, COSMOS provides an ideal data set for selecting a large transitioning galaxy sample and for studying this sample in detail.

This paper is organized as follows. Section 2 presents the data set used for the study. Section 3 defines red, green, and blue galaxies, as well as their mass limits. Section 4 presents the morphologies, stacked spectra, and environments of red, green, and blue galaxies. Section 5 discusses the possible mechanisms responsible for quenching star formation activities. A summary of our conclusions is presented in Section 6. Throughout this paper, a concordance ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ is assumed. All magnitudes are quoted with AB normalization, unless explicitly noted otherwise.

2. DATA

2.1. Photometric Redshift Catalog

The large samples required for this work necessitate the use of photometric redshifts. We use the COSMOS photometric redshift catalog (Version 1.8) published by Ilbert et al. (2009). Accurate photometric redshifts were computed using 30 broad, intermediate, and narrowband photometries, which included the UV (Galaxy Evolution Explorer (GALEX)), optical–NIR (Subaru, Canada–France–Hawaii Telescope, United Kingdom Infrared Telescope and National Optical Astronomy Observatory), and mid-IR (Spitzer/IRAC). Ilbert et al. (2009) computed the photometric redshifts of the COSMOS galaxies using the Le Phare$^4$ codes with a $\chi^2$ template-fitting method, which included a novel treatment of the emission lines. To generate the photometric catalog, all images were point-spread-function-matched and fluxes were measured with SExtractor over an aperture with a diameter of 3″ at the position of the Subaru $i^\ast$ band detection.

Ilbert et al. (2009) included nine templates generated by Polletta et al. (2007) to fit the UV-to-mid-IR data. To recover the spectral energy distribution (SED) of blue galaxies, 12 additional templates were generated using the BC03 model (Bruzual & Charlot 2003) with starburst ages ranging from 0.03 to 3 Gyr. A comparison of the photometric and spectroscopic redshifts showed that the accuracy is $\sigma_{(z_{\text{phot}} - z_{\text{spec}})}/(1 + z_{\text{spec}}) = 0.009$ for $i^\ast < 22.5$, $\sigma_{(z_{\text{phot}} - z_{\text{spec}})}/(1 + z_{\text{spec}}) = 0.011$ for $i^\ast < 24.0$, and $\sigma_{(z_{\text{phot}} - z_{\text{spec}})}/(1 + z_{\text{spec}}) = 0.057$ for $24.0 < i^\ast < 25.0$ at $z < 1.25$. The SED template-fitting procedure also provided the best-fit rest-frame absolute magnitudes and dust-corrected NUV$-r^\ast$ color (thereafter (NUV$-r^\ast$)$_{\text{corr}}$). Other galaxy physical properties, such as stellar mass and instantaneous best-fit template star formation rate (SFR$\text{template}$), were estimated by adopting BC03 models with a Chabrier initial mass function and an exponentially declining star formation history (SFR $\propto e^{-t/T}$, $t$ in the range 0.1–30 Gyr). To check the robustness of SFR$\text{template}$, Ilbert et al. (2010) estimated SFR$\text{IR}$ from the IR luminosity $L_{\text{IR}}$, where $L_{\text{IR}}$ was extrapolated from the Spitzer MIPS 24 μm flux using Dale & Helou’s (2002) library. The SFR$\text{template}$ and SFR$\text{IR}$ were found to be consistent upon comparison (see Figure 27 of Ilbert et al. 2010). In the following sections, SFR refers to the best-fit model SFR (SFR$\text{template}$). For more details, please refer to Ilbert et al. (2010).

2.2. Morphological Catalog

More than one million high-resolution galaxy images in the COSMOS field, observed by HST, are readily available for morphological studies. In previous works, automatic morphological classifications based on the parameters measured on the initial galaxy images were used to improve efficiency and avoid subjectivity (Capak et al. 2007a; Scarlata et al. 2007; Tasca et al. 2009). Here we briefly summarize the Zurich Estimator of Structure Types (ZEST) catalog (Scarlata et al. 2007) used in this paper.

ZEST classifies galaxy morphology based on a principal component analysis (PCA) of the galaxy structure nonparametric diagnostics, which include asymmetry A, concentration C, Gini coefficient G, the second-order moment of the brightest 20% galaxy pixels $M_2$, and the ellipticity of the light distribution $\epsilon$. PCA shows that the first three principal component variables contribute more than 90% of the original data set, and thus can completely describe galaxy

---

4 http://www.cfht.hawaii.edu/~arnouts/LEPHARE/lephare.html
structure. ZEST classifies galaxy morphologies into three main types: elliptical galaxies \(T_{\text{ZEST}} = 1\), disk galaxies \(T_{\text{ZEST}} = 2\), and irregular galaxies \(T_{\text{ZEST}} = 3\). Disk galaxies are assigned into four bins based on their “bulgeness” parameter \(B_{\text{ZEST}}\), which roughly correlates with the bulge-to-disk ratio \([B/D]\). For galaxies brighter than \(i^* = 22.5\), ZEST fits their surface brightness profile with a Sérsic model. Higher values of \(B_{\text{ZEST}}\) indicate smaller bulges and larger disks, with \(B_{\text{ZEST}} = [0.1, 2, 3]\), which correspond to the following range of Sérsic indices \(n\): \(n \geq 2.5, 1.25 \leq n \leq 2.5, 0.75 \leq n \leq 1.25\), and \(0 \leq n \leq 0.75\), respectively. The final ZEST catalog contains 131,532 sources down to \(i^* = 24.0\).

The ZEST morphologies were tested using visual classification on a \(z = 0\) sample. It is found that the ZEST classifications agree well with the published morphologies. Among disk galaxies with \(B_{\text{ZEST}} = 0\), approximately 85% are classified as elliptical and SO–Sab types. Among disk galaxies with \(B_{\text{ZEST}} = 2\), the SO–Sab, Sb–Scd, and Scd types comprise 5%, 45% and 50%, respectively. The ZEST classifications begin to disintegrate at faint magnitude. Scarlata et al. (2007) quantified the efficiency of ZEST classifications by degrading the signal-to-noise ratio \((S/N)\) of bright galaxies with well-determined morphologies. They reported that down to \(k_{14} = 22.5\), the determination of the final \(T_{\text{ZEST}}\) or \(B_{\text{ZEST}}\) in 90% of the galaxies does not change. The fraction identified as the original morphological type is about 65% down to \(k_{14} = 24.0\).

2.3. The 10k zCOSMOS Spectroscopic Sample

The zCOSMOS spectroscopic survey (Lilly et al. 2007) targets the galaxies in the COSMOS field with the Visible Multi-Object Spectrograph mounted on the ESO Very Large Telescope. The zCOSMOS survey has released about 10,000 galaxy spectra limited to \(i^* = 22.5\), covering a 1.4 deg\(^2\) field of view. The spectra range from 5500 Å to 9700 Å, with a medium resolution of \(R \sim 600\). Redshifts were measured by the VIPGI software package. Results show that more than 97% of the spectra at \(0.5 < z < 1.25\) can yield very secure redshifts. Further information on zCOSMOS and the 10k sample are presented in Lilly et al. (2007).

3. SAMPLE SELECTION

3.1. Green Galaxy Selection

Our parent sample contains 113,162 galaxies extracted from the COSMOS photometric redshift catalog (version 1.8), with magnitudes and redshifts limited to \(i^* = 24.0\) and photometric redshift \(z_{\text{phot}} = 1.2\), respectively. The magnitude and redshift limits ensure that our sample maintains high photometric redshift accuracy. There are many methods to define GV, usually exploiting the natural bimodal distribution of color indices such as \(U - B\) (Nandra et al. 2007; Yan et al. 2011), \(U - V\) (Brammer et al. 2009; Moreco et al. 2010), and \(NUV - r\) (Wyder et al. 2007). In many dusty starburst galaxies, a large amount of internal dust absorbs UV emission, resulting in a red galaxy color. As mentioned in the first section, a significant fraction of green galaxies are virtually dust-obscured. To remove dusty star-forming galaxies from the real transitioning galaxy sample, we use the dust-corrected \(NUV - r\) color to classify our sample.

Considering that considerable differences in extinction curves are expected from galaxy to galaxy, to obtain suitable dust extinction, Ilbert et al. (2009) used different extinction curves depending on the best-fit template obtained in the template-fitting procedure. They applied a test on the zCOSMOS sample with spectroscopic redshifts. They determined the best-fit-template color excess \(E(B - V)_{\text{best}}\) in the range of \(E(B - V)_{\text{best}} = (0.0, 0.5)\), using only passbands with \(\lambda > 3000(1 + z)\) Å. As shown in Ilbert et al. (2009), the \(E(B - V)_{\text{best}}\) value does not significantly depend on the adopted extinction law. Then, they compared the rest-frame observed magnitude \(m_{\text{obs}}\) and the predicted intrinsic magnitude without extinction \(m_{\text{template}}\) at \(z_{\text{rest-frame}} < 3000\) Å to discriminate between different extinction curves. Figure 4 in Ilbert et al. (2009) shows that for galaxies with template redder than the starburst template SB3, \(m_{\text{obs}} - m_{\text{template}} / E(B - V)_{\text{best}}\) mainly follows the Prevot et al. (1984) extinction curve. For galaxies bluer than SB3, the Calzetti et al. (2000) extinction law was found to be more appropriate. Ilbert et al. (2009) allowed an additional 2175 Å bump for the Calzetti law if a smaller \(\chi^2\) is produced. No reddening was allowed for galaxies redder than SB.

Figure 1 shows \((NUV - r)_{\text{corr}}\) as a function of redshift for \(M_*>10^{10.0} M_\odot\) galaxies. The most remarkable feature is that \((NUV - r)_{\text{corr}}\) clearly shows a bimodal distribution up to \(z \approx 1\). In addition, the global galaxy color shows significant evolution since \(z \approx 1\) for both red sequence galaxies and blue star-forming galaxies. Galaxies turn red toward low redshifts, which demonstrates that global star formation activities decline with cosmic time (Bell et al. 2004; Brammer et al. 2011).

As the first step, we need to determine a criterion which can select homogeneous green galaxies without bias toward red or blue galaxies at all redshifts. Ilbert et al. (2010) classified galaxies into “quiescent” when \((NUV - r)_{\text{corr}} > 3.5\), “high activity” when \((NUV - r)_{\text{corr}} < 1.2\), and “intermediate activity” when \(1.2 < (NUV - r)_{\text{corr}} < 3.5\). As global galaxy
color evolves significantly with redshift, the sample selected with a constant color cut over a wide redshift range can be biased toward red and blue galaxies at high and low redshifts, respectively. To minimize the bias, we have included the redshift evolution in our green galaxy selection scheme. In Figure 1, two green lines represent our selection criterion for the green galaxy sample given by

\[ 2.8 - 0.54z < (\text{NUV} - r^+)_\text{corr} < 3.4 - 0.54z, \]  

where \( z \) is the photometric redshift. Red and blue galaxies are defined using \((\text{NUV} - r^+)_\text{corr} \geq 3.4 - 0.54z\) and \((\text{NUV} - r^+)_\text{corr} \leq 2.8 - 0.54z\), respectively. We use a non-zero slope in our selection criterion. The slope \( \alpha = -0.54 \) came from the linear fitting of the median color for “quiescent” galaxies at 10 redshift bins within the range of \( z = [0.2, 1.2] \). Our definition of green galaxies is much stricter than the “intermediate activity” in Ilbert et al. (2010) and considers the redshift evolution of galaxy color, which can help us to compare the truly transitioning population with the active and quiescent populations at the same cosmic epoch. The (NUV – r+)corr color has been found to be well correlated with the specific star formation rate (sSFR, defined as \( \text{sSFR} = \text{SFR}/M_\odot \); Salim et al. 2005). The median sSFR of our green galaxy sample is about log(sSFR) = −10.2 at \( z = 1.0 \) and log(sSFR) = −10.8 at \( z = 0.2 \). We find that more than 95% of the galaxies in our sample lie on a very narrow ridge in the (NUV – r+)corr versus sSFR diagram. About 3% of the galaxies have high sSFR and red (NUV – r+)corr, indicating that these may be extremely dusty starburst galaxies with underestimated dust extinction. We reject these galaxies from further analysis. Likewise, the \( z < 0.2 \) or \( z > 1.0 \) green galaxies were excluded because of the small sample size within these two redshift ranges.

It is worth noting that at \( z \approx 0.1 \), the GV is centered at \((\text{NUV} - r^+)_\text{corr} \approx 3.0\), which seems to be much bluer than when it was first reported in several GALEX papers (Wyder et al. 2007; Martin et al. 2007). Wyder et al. (2007) studied the UV–optical CMD using GALEX and SDSS data and found that GV is centered at \((\text{NUV} - r^+)_\text{corr} \approx 4\) (see Figure 25 in Wyder et al. 2007). The diversity is due to the different data depths used in these two papers. The data in Wyder et al. (2007) are limited to \( r = 17.6 \), which is much shallower than that used in this paper (\( R_{\text{lim}} \approx 25.0 \)). Our sample is volume-complete for the faintest source detected in Wyder et al. (2007) \( (M_r = -16.0) \) out to \( z \approx 0.25 \). Thus, the volume-corrected CMD in Wyder et al. (2007) should be considered when comparing these two works. Keeping this in mind, excellent consistency between Figure 1 in this study and Figure 25 in Wyder et al. (2007) is observed, which shows that the GV regions lie around \((\text{NUV} - r^+)_\text{corr} \sim 3\).

In a magnitude-limited sample, the minimum stellar mass for which observations were completed depends on the redshift and stellar mass-to-light ratio (M/L). Here, the low stellar mass limits were defined to reduce the fraction of optically faint sources. To estimate the completeness mass we consider the galaxies in the faintest 20% of our sample and derive the stellar mass (\( M_{\text{lim}} \)) they would have if their apparent magnitude were equal to the limiting magnitude (i.e., \( i^* = 24.0 \)). Then we define as the completeness mass the value of the 95% of the distribution of \( M_{\text{lim}} \) galaxies above this stellar mass limit define an 80% complete sample in stellar mass (see Pozzetti et al. 2010). We calculate the low-mass limit for each redshift bin within the redshift range of \( z = [0.2, 1.0] \), with bin size of \( \Delta z = 0.1 \). The values of the low-mass limits for the COSMOS sample used in the study are similar to those in the literature (Tasca et al. 2009; Pozzetti et al. 2010; Giodini et al. 2012).

Figure 2 shows the color–mass relation for galaxies within \( z = [0.2, 1.0] \). To separate the “red sequence” and “blue cloud” more clearly, we plot the contours of the galaxy number density. The vertical lines show the low-mass limits, which remove a larger fraction of active galaxies from the initial sample compared with red and green galaxies. In the literature on stellar mass functions, authors normally utilized different low-mass limits for star-forming and quiescent populations (Pozzetti et al. 2010; Ilbert et al. 2010; Giodini et al. 2012). The current paper focused on GV galaxies located in a relatively narrow region in the CMD. For the green populations, their low-mass limits do not significantly depend on color. For blue galaxies, the low-mass limits maintain 47.6% and 12.8% of the initial sample at \( z = [0.2, 0.3] \) and \( z = [0.9, 1.0] \), respectively. For green galaxies, the mass limits maintain approximately 70%–85% of the initial sample in all redshift bins. The conclusion of the present work is derived from the majority of green galaxies and are not significantly affected by the low-mass limits.

Table 1

| Redshift | Mass Limit \( \log(M/M_\odot) \) | \( N_{\text{blue}} \) | \( N_{\text{green}} \) | \( N_{\text{red}} \) |
|----------|-----------------|----------------|----------------|----------|
| 0.2–0.3  | 8.4             | 3101           | 156            | 842      |
| 0.3–0.4  | 8.7             | 5522           | 405            | 1824     |
| 0.4–0.5  | 8.9             | 3763           | 303            | 1072     |
| 0.5–0.6  | 9.1             | 3327           | 286            | 794      |
| 0.6–0.7  | 9.4             | 3751           | 453            | 1599     |
| 0.7–0.8  | 9.5             | 3198           | 189            | 1157     |
| 0.8–0.9  | 10.0            | 2068           | 345            | 1927     |
| 0.9–1.0  | 10.3            | 1265           | 210            | 1278     |

Figure 3 shows the color–color diagram \((M(\text{NUV}) - M(r^+)) \) versus \((M(r^+) - M(J)) \). Optical–near-IR color is prevalently used to separate truly passive populations from dusty star-forming galaxies (Williams et al. 2009; Bundy et al. 2010). In Figure 3, red galaxies are located in a tight clump in each redshift bin, which are separated clearly from blue star-forming galaxies. Green galaxies mainly reside in the joint regions between red and blue galaxies.

In summary, using the (NUV – r+)corr versus redshift diagram, we classify galaxies in the COSMOS field into three subsamples, with 10,493 red, 2347 green, and 25,996 blue galaxies, respectively. We divide our sample into eight redshift bins with bin size \( \Delta z = 0.1 \) within the redshift range \( z = [0.2, 1.0] \). In each redshift bin, a low-mass limit \( M_{\text{lim}} \) was set to reduce the bias toward faint galaxies. Information on our sample is summarized in Table 1.

3.2. Comparison Sample

Next, the properties of green galaxies are compared with those of red and blue galaxies. To ensure that the differences
Figure 2. (NUV − rₜₜₜ)corr color as a function of stellar mass for galaxies with i > 24.0 within the redshift range of z = [0.2, 1.0]. The grayscale represents the galaxy number density. The red dashed line denotes the color cut of (NUV − rₜₜₜ)corr = 3.5. Green dots are the green galaxies that meet our selection criterion. The solid vertical line shows our low-mass limit for each redshift bin. (A color version of this figure is available in the online journal.)

Figure 3. Rest-frame M(NUV) − M(rₜₜₜ) vs. M(rₜₜₜ) − M(J) (no dust correction) from z = 0.2 to z = 1.0, for galaxies above the low-mass limit. The grayscale represents the galaxy number density. Red and blue contours include 95%, 80%, and 60% of the red and blue galaxies, respectively. Green dots denote the green galaxies in our sample. (A color version of this figure is available in the online journal.)

shown in the comparisons are driven by different star formation properties of different samples but are not driven by their different mass distributions, red and blue comparison samples were created with similar stellar mass distributions to that of the green sample. For a green galaxy with stellar mass M₀ and redshift z₀, matched galaxies from either the red or blue samples were initially chosen. The matched galaxy has stellar mass |Mₘ − M₀| < 0.10 dex at the redshift slice of |z − z₀| < 0.02(1 + z₀), where Mₘ and z are the stellar mass and redshift of the matched galaxy, respectively. Given that there are few blue galaxies with stellar mass log(Mₘ/M⊙) > 11.0, the upper mass limit of green galaxies was set to log(Mₘ/M⊙) = 11.0. The number of matched galaxies (N_match) depends on M₀ and z₀. About 98% of green galaxies have N_match > 15 in both the red and blue samples. A galaxy was then randomly selected from the matched sample for comparison of physical properties with the green galaxy. Thus, for a green galaxy sample selected from a certain redshift bin, a comparable blue or red sample with the same size and mass distribution was prepared. This procedure eliminated the selection effect in subsequent comparisons.
Figure 4. Gini coefficient (G) vs. asymmetry (A) diagram. Green galaxies are denoted by green dots. The numbers of the red and blue comparison sample are 15 times that of the green sample. The grayscale represents the galaxy number density of the comparison sample. The red and blue contours enclose 30%, 60%, and 90% of the red and blue galaxies, respectively. The blue square, green circle, and red triangle mark the average Gini coefficient and asymmetry of the blue, green, and red sample, respectively. The error bars are the standard deviations of the G and A distributions for each sample.

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

4. RESULTS

4.1. Morphology

We cross-matched our galaxy sample with an angular diameter of $D = 3.0'$ with the ZEST catalog. The median separation value of the first closest counterpart is about $0.2'$. Then, a proper separation distance, $D_{\text{separate}} < 0.5'$, is chosen. Considering that the ZEST catalog covers a smaller area $(\approx 1.6 \text{ deg}^2)$ compared with the photometric catalog $(\approx 2 \text{ deg}^2)$, our final sample contains $\approx 25,000$ galaxies with ZEST morphological classifications.

4.1.1. The (Gini–Asymmetry) and (M20–Gini) diagrams

Many previous studies found that ETGs and LTGs are roughly separable on the Gini coefficient $G$ and asymmetry parameter $A$ diagram (Abraham et al. 1996; Lotz et al. 2004; Kong et al. 2009). More information on the parameter definition can be found in Conselice et al. (2000) and Glasser (1962). In brief, ETGs have compact cores and regular surface brightness distributions and thus have high $G$ and low $A$ values. For LTGs the situation is opposite. Galaxies can be roughly classified as early types, late types, or irregular types based on their locations on the $(G–A)$ plane (Capak et al. 2007a).

The $G–A$ diagrams of both green and comparison samples are plotted in Figure 4. A total of 15 blue and 15 red comparison samples were used. The blue and red contours show the $G$ and $A$ distributions of the blue and red comparison samples, respectively. Red galaxies have high $G$ and low $A$ values, indicating that they are compact and have regular surface brightness distributions. Indeed, most red galaxies are classified as early-type (E+S0) or early-type spirals. Conversely, blue galaxies have low $G$ and high $A$ values and are mostly classified as disk or irregular galaxies. The bulk of blue and red galaxies are located in different regions on the $G–A$ plane, but some blue and red galaxies have similar $G$ and $A$ values and reside in the joint regions. Interestingly, green galaxies are mostly distributed in the joint regions. The average $G$ and $A$ values of green galaxies are also between those of blue and red galaxies at each redshift bin. Note that our sample spans a redshift range of $z = [0.2, 1.0]$. The ACS $i_{814w}$ band corresponds to 4000–6700 Å in the rest frame within this redshift range. It has been shown that the morphological $K$ correction within this wavelength range is small (Lotz et al. 2004), and that the ZEST classifications are still robust (Bundy et al. 2010).

Figure 5 shows the $M_{20}$ parameter versus the Gini coefficient diagram. This diagram can also effectively classify galaxies into early-types or late-types (Lotz et al. 2006; Kong et al. 2009; Wang et al. 2012). To illustrate the robustness of morphological classification using Gini and $M_{20}$, we show some randomly selected galaxies on the $G–M_{20}$ plane. The symbols are replaced by HST/ACS images (Figure 6). Generally, red quiescent galaxies with high $G$ and low $M_{20}$ values have spheroidal morphologies, whereas blue star-forming galaxies with low $G$ and high $M_{20}$ values have disk-like morphologies. Visual inspection of green galaxy images in Figure 6 suggests that most green galaxies have prominent bulges and significant disk components. Our findings are in agreement with those of Balogh et al. (2011) and Mendez et al. (2011), that is, green galaxies are mostly at the morphologically transitioning stage between blue and red galaxies.

4.1.2. Bulgeness

This subsection investigates the bulge properties of disk galaxies ($T_{\text{ZEST}} = 2$). Disk galaxies compromise approximately 75% of the total galaxies. The ZEST morphological classification assigns disk galaxies in four bins according to their bulge-to-disk ratio, which is described as the bulgeness parameter $B_{\text{ZEST}}$. Since it is hard to fully separate galaxies into different types using bivariate distributions such as shown in Figures 4 and 5, the bulgeness parameter allows one to investigate the morphologies of green galaxies in more detail.
Figure 5. $M_{20}$ vs. Gini diagram. Symbols are the same as in Figure 4.

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

Table 2

| Redshift | Mass Range $\log(M/M_\odot)$ | Galaxy Number | $B_{\text{blue}}^a$ | $B_{\text{green}}$ | $B_{\text{red}}$ |
|----------|-----------------------------|---------------|-------------------|------------------|----------------|
| 0.2–0.3  | 10.0–11                     | 26            | [4, 11, 9, 2]     | [3, 11, 9, 3]    | [16, 19, 1, 0] |
| 0.3–0.4  | 10.0–11                     | 94            | [12, 38, 32, 12]  | [27, 41, 25, 1]  | [50, 40, 4, 0]  |
| 0.4–0.5  | 10.0–11                     | 99            | [12, 37, 37, 13]  | [23, 52, 22, 2]  | [46, 50, 3, 0]  |
| 0.5–0.6  | 10.0–11                     | 108           | [10, 38, 23, 7]   | [26, 56, 20, 6]  | [43, 55, 9, 1]  |
| 0.6–0.7  | 10.0–11                     | 191           | [17, 63, 64, 47]  | [41, 88, 47, 15] | [57, 114, 17, 3]|
| 0.7–0.8  | 10.0–11                     | 85            | [9, 25, 27, 23]   | [11, 46, 21, 7]  | [26, 49, 9, 1]  |
| 0.8–0.9  | 10.0–11                     | 170           | [22, 52, 55, 41]  | [29, 80, 39, 22] | [49, 98, 22, 1] |
| 0.9–1.0  | 10.0–11                     | 90            | [10, 29, 30, 21]  | [14, 43, 26, 7]  | [22, 61, 6, 1]  |
| 0.2–0.3  | <10.0                      | 65            | [2, 15, 34, 14]   | [2, 27, 33, 3]   | [5, 30, 36, 4]  |
| 0.3–0.4  | <10.0                      | 123           | [3, 28, 62, 30]   | [9, 46, 58, 10]  | [8, 72, 41, 2]  |
| 0.4–0.5  | <10.0                      | 59            | [2, 15, 25, 17]   | [1, 28, 25, 5]   | [6, 31, 21, 1]  |
| 0.5–0.6  | <10.0                      | 31            | [1, 6, 13, 11]    | [1, 13, 14, 3]   | [5, 16, 10, 2]  |
| 0.6–0.7  | <10.0                      | 50            | [1, 10, 17, 22]   | [1, 20, 23, 6]   | [2, 28, 17, 3]  |

Note. $^a$ Number of disk galaxies classified as $B_{\text{ZEST}} = [0, 1, 2, 3]$. For red and blue galaxies, the number is averaged over 15 different comparison samples, respectively.

Figure 7 shows the fractions of red, blue, and green disk galaxies with different $B_{\text{ZEST}}$ parameters as a function of redshift. The green galaxies were categorized into two subsamples according to their stellar mass. Only the results of low-mass galaxies at $z < 0.7$ were shown in the figure because there are few low-mass green galaxies at high redshift. The error bars were derived as the standard deviations from the 15 red and blue comparison samples. For green galaxies, the error bars were computed by 1000 bootstrap resamplings. More information can be found in Table 2.

In the high mass bin, red galaxies are mainly composed of $B_{\text{ZEST}} = 0$ and $B_{\text{ZEST}} = 1$ types, accounting for about 85%–95%. The fractions of these two types also show very strong redshift evolution from $z \approx 0.7$. Our findings are in good agreement with those of Bundy et al. (2010, see their Figure 3), suggesting that $\log(M_*/M_\odot) = [10.0, 11.0]$ red sequence disk galaxies are more bulge-dominated and abundant from $z \approx 0.7$. Note that there are rare red pure disk galaxies within this mass range. Blue galaxies show more stable $B_{\text{ZEST}}$ values and mild redshift evolution. The fraction of blue pure disks decreases from $z \approx 0.7$ to 5%–10% green disk galaxies are classified as pure disk systems.

Galaxies with $\log(M_*/M_\odot) < 10.0$ have very different $B_{\text{ZEST}}$, in that nearly no bulge-dominated galaxies are present within this mass range for all three samples. The $B_{\text{ZEST}}$ of low-mass red disks shows no redshift evolution. However, the fraction of blue pure disk galaxies decreases from 45% at $z \approx 0.65$ to 20% at $z \approx 0.25$. The $B_{\text{ZEST}}$ evolution trends of green galaxies and
red galaxies are similar. The most striking feature is that, even at lower mass, the fraction of green pure disk systems and red galaxies is similar.

In summary, the fraction of green galaxies classified as $BZEST = 0$ and $BZEST = 1$ is significantly higher than that of star-forming galaxies, and the fraction classified as $BZEST = 3$ is only about 5%–10%. Compared with red galaxies, most green galaxies still have significant disk components, which implies that green disks are also at an intermediate stage between blue and red disks. The lack of green pure disk galaxies suggests that the suppression of star formation activities may be connected with galaxy bulge formation. Considering the great $BZEST$ differences between green and blue galaxies, the scenario that green galaxies are simply faded blue galaxies is disfavored.

4.1.3. Comparison with the Mixed Sample

In the two subsections before, the morphological parameters of green galaxies are found to be intermediate between those of red and blue galaxies. However, it is still not clear whether green galaxies form a distinct population or their observed morphological properties can be explained by a simple mix of blue and red galaxies. To answer this question, the morphological parameters of green galaxies are compared with those of the “mixed” sample. As the morphologies of blue and red galaxies significantly differ from each other, the morphological parameter distributions of the “mixed” samples depend on the ratio of blue to red galaxies ($N_{blue}/N_{red}$).

This section explains the process of creating a combined “mixed” sample, with fixed blue to red ratio of $N_{blue}/N_{red} = P/(1 - P)$, where $P \in (0, 1)$. First, for a green galaxy with stellar mass $M_0$ and redshift $z_0$, a blue-matched sample and a red-matched sample were formed. This was done to meet the required stellar mass $|M_0 - M_*| < 0.10$ dex at the redshift slice of $|z - z_0| < 0.02(1 + z_0)$, where $M_*$ and $z$ are the stellar mass and redshift of the matched galaxy, respectively. Then we generate a uniform random number $r_0$ between 0.0 and 1.0. When $r_0 \leq P$, we randomly select a galaxy from the blue-matched sample; otherwise, we select a galaxy from the red-matched sample to form the “mixed” sample. A combined blue and red galaxy sample with fixed blue to red ratio was thus formed. This procedure also assures the “mixed” sample and the green sample are matched in mass and redshift.

![Figure 6. $M_{20}$ vs. $G$ diagram for some randomly selected galaxies at $0.6 < z < 0.7$. Red, green, and blue galaxies are denoted with red circles, green crosses, and blue triangles, respectively. The HST/ACS postage-stamp images for each subsample represent morphologies for galaxies in various locations of this diagram. (A color version of this figure is available in the online journal.)](image)

![Figure 7. Fraction of red, blue, and green disk galaxies with different $BZEST$ parameters as a function of redshift. For a certain subsample, the fraction is defined as the disk galaxy number with a certain $BZEST$ in the subsample divided by the total disk galaxy number in the subsample in that redshift bin. Blue galaxies are indicated by blue triangles, green galaxies by circles, and red galaxies by squares. For blue and red comparison samples, the error bars are the 1σ standard deviations of 15 resamplings. The error bars of the green galaxies are derived from 1000 bootstrap resamplings. (A color version of this figure is available in the online journal.)](image)
The $G$–$A$ diagram of the green and “mixed” samples is shown in Figure 8. The green galaxies were divided into four redshift bins from which mixed samples with five different blue-to-red ratios were created. In each panel, 15 different mixed samples were used to minimize the random disturbance. As shown in Figure 8, low $N_{\text{blue}}/N_{\text{red}}$ yields low average $A$ and high $G$ values, and the trend is reversed at high $N_{\text{blue}}/N_{\text{red}}$ ratios. Green galaxies have similar average $A$ values with the “mixed” samples when $N_{\text{blue}}/N_{\text{red}} = 0.2/0.8$, whereas the average $G$ value is significantly lower. The most reasonable compromise of average $A$ and $G$ values between green and “mixed” samples is observed when $N_{\text{blue}}/N_{\text{red}}$ is around 1.0. However, it is clear that the $G$ scatters in the green sample are significantly smaller than those of the “mixed” samples, as shown in the three middle rows across all redshift ranges. Green low $G$ systems have low $A$ values, which means that they are more regular than those with similar $G$ values in the “mixed” samples. Therefore, a simple combination of blue and red galaxies cannot reproduce the morphological properties of green galaxies.

Using a different method, Mendez et al. (2011) also demonstrated that green morphological parameter distributions are statistically different (at $2\sigma$ level) from those of a simple mix of blue and red galaxies. Our finding is consistent with that presented by Mendez et al. (2011). Thus green galaxies most likely form a distinct population, but this phenomenon is not due to selection effects.

4.2. Spectral Analysis

4.2.1. Average Spectra of Galaxies

$z$COSMOS provides about 10,000 galaxy spectra down to $i^* = 22.5$, facilitating further exploration of spectral...
characteristics of green galaxies. However, most of the spectra have very low S/N and are difficult to analyze individually. To obtain a higher S/N, an average spectrum for each subsample was created using the stacking method (Eisenstein et al. 2003; Schiavon 2007; Chen et al. 2009; Shu et al. 2012).

Next, the photometric catalog was cross-matched with the zCOSMOS spectroscopic sample using a 1′ angular diameter, from which a sample containing about 550 green galaxies, 1800 red galaxies, and 6000 blue galaxies was generated. The sample was divided into two redshift bins, \( z = [0.2, 0.5] \) and \( z = [0.5, 1.0] \). There are few blue galaxies with stellar mass \( M_* > 10^{11.0} M_\odot \) and at \( z > 0.5 \) most red and green galaxies have stellar mass \( M_* > 10^{10.5} M_\odot \). Hence, a mass range of \( \log(M_* / M_\odot) = [10.0, 11.0] \) for \( z = [0.2, 0.5] \) and \( \log(M_* / M_\odot) = [10.5, 11.0] \) for \( z = [0.5, 1.0] \) was chosen. Blue galaxies have low \( M/L \) ratio and dominate the low-mass end in a flux-limited sample, which means that direct stacking without weighting for the blue sample mostly reflects the signatures of low-mass galaxies. For the red sample the situation is reversed. To create average spectra with the same mass distribution, galaxies were weighted as a function of mass and redshift for each subsample. We determine the number of galaxies within the mass and redshift bins (at the low-redshift bin, \( \triangle \log(M_*) = 0.34 \); at the high-redshift bin, \( \triangle \log(M_*) = 0.25 \); redshift bin size is \( \Delta z = 0.1 \)) both in the full sample and in each subsample. We then weigh each spectrum by the number of the full sample divided by the number in the subsample. This procedure allows the breaking of the mass dependence.

The average spectra of red, green, and blue galaxies are shown in Figure 9. In the low-redshift bin, the average spectra range from 4600 to 6700 Å and are normalized to the average flux between 5050 Å and 5100 Å. In the high-redshift bin, the spectra are shown at shorter wavelength, including the [O II] lines. Each average spectrum is stacked by more than 100 individual spectra (except the green sample in the low-redshift bin). Given that the mass dependence has been minimized in the stacking procedure, these average spectra can be treated as the “representative spectra” of each subsample.

The red average spectra are dominated by absorption lines. The emission lines reflecting (directly or indirectly) star formation activities, such as H\( \alpha \) and [O II], are rare in the red spectra. The strong jump at 4000 Å and very strong Ca H+K absorption lines demonstrate that red galaxies are dominated by old stellar populations. The metal lines, such as the Mg b and the G-band absorption lines, are most remarkable in the red spectra. Briefly, the red average spectra are typical quiescent galaxy spectra. There are strong emission lines in the blue spectra. The strong [O II], H\( \alpha \), and H\( \beta \) emission lines demonstrate that blue galaxies are still at the active stage and forming stars.

Interestingly, the green spectra are significantly different from the red and blue ones. The [O II], H\( \alpha \), and H\( \beta \) emission lines are still visible, but obviously much weaker than those of star-forming galaxies. Specifically, the [O III]/H\( \beta \) ratios of green spectra are higher than those of blue spectra, confirming the result of Coil et al. (2008). However, in the low-redshift bin, we find that the [N II] \( \lambda 6583/H\alpha \) ratio of the green spectrum is still significantly lower than that of a typical AGN. The continua of green spectra are very similar to those of red galaxies. Specifically, the 4000 Å break of green galaxies is between the blue and red ones, indicating that the average stellar age of green galaxies is between the ages of the red and blue ones.

The high S/N average spectra allow the extraction of galaxy SFH information by comparing them with stellar population synthesis models. This is done by comparing the average spectra in the \( z = [0.5, 1.0] \) bin with STARLIGHT.® STARLIGHT aims to fit an observed spectrum with a linear combination of theoretical simple stellar populations (SSPs). The model
the SSP base consisted of N spectrum of STARLIGHT is given by

\[ M_i = M_{i0} \left( \sum_{j=1}^{N} x_j b_{j,\lambda} r_{\lambda} \right) \otimes G(u_\lambda, \sigma_\lambda), \]

\[ (\log t_u)_L = \sum_{j=1}^{N} x_j \log t_j, \quad (\log t_u)_M = \sum_{j=1}^{N} u_j \log t_j, \]

where \( M_i \) is the model spectrum, \( M_{i0} \) is the synthesis flux at the normalization wavelength \( \lambda_0 \), \( x_j \) is the so-called stellar population vector, \( b_{j,\lambda} \) is the jth SSP spectrum at \( \lambda \), and \( r_{\lambda} \equiv 10^{-0.4(A - A_0)} \) represents the reddening term. \( G(u_\lambda, \sigma_\lambda) \) gives the line-of-sight stellar motions which are modeled by a Gaussian distribution centered at velocity \( u_\lambda \) and with a dispersion \( \sigma_\lambda \). \( N \) is the total number of SSP models. In our work, the SSP base consisted of \( N = 126 \) SSPs, with 6 metallicities \((Z = 0.005 \, Z_\odot, 0.02 \, Z_\odot, 0.2 \, Z_\odot, 0.4 \, Z_\odot, Z_\odot, 2.5 \, Z_\odot)\) and 21 ages (from 1 Myr to 7.5 Gyr), which were taken from evolutionary models in BC03. The maximum age corresponded to the cosmic age at \( z = 0.5 \). The galactic extinction law of Cardelli et al. (1989) with \( R_V = 3.1 \) was adopted. Emission lines were masked in the fitting procedure. STARLIGHT produced the SSP fraction, dust attenuation \( A_\lambda \), velocity dispersion \( \sigma_\lambda \), and stellar mass \( M_\ast \). Following Cid Fernandes et al. (2005), the flux- and mass-weighted average ages are defined respectively as

\[ \langle \log t_u \rangle_L = \sum_{j=1}^{N} x_j \log t_j, \quad \langle \log t_u \rangle_M = \sum_{j=1}^{N} u_j \log t_j, \]

density was adopted as a local galaxy density estimator. Capak et al. (2007a) showed that the use of photometric redshift can also correctly characterize galaxy density in the COSMOS field. To be consistent with previous studies (Capak et al. 2007a; Ilike U et al. 2012), the 10th nearest neighbor was used in our analysis. The local galaxy density was calculated as \( \Sigma_{10} = 11/(\pi D_{p,10}^2) \), where \( D_{p,10} \) (in Mpc) is the projected proper distance to the 10th nearest neighbor. The projected densities were computed using \( i^\prime < 24.0 \) galaxies. A redshift slice centered on each galaxy with \( \pm \Delta z = 0.033(1 + z) \) was used, corresponding to \( \pm 3\sigma_{\text{photoz}} \) where \( z \) is the redshift of the central galaxy. Galaxies located near the masked regions or survey edge were excluded from the statistics. To check the reliability of the density estimator, the sample was cross-matched with the released COSMOS field X-ray group catalog (George et al. 2011). The results show that the X-ray group members (which have group member likelihood \( P_{\text{mem}} \geq 0.5 \)) are mostly located at the high \( \Sigma_{10} \) end at each redshift bin.

Figure 11 shows the \( \Sigma_{10} \) histograms for blue, green, and red galaxies indicated by the blue, green filled, and red lines, respectively. The \( \Sigma_{10} \) distributions were averaged over 15 different comparison samples. The error bars in the figure show the standard deviations of the 15 different comparison samples. In addition, the \( \Sigma_{10} \) histograms for the \( z < 1.0 \) X-ray group members are plotted (shown as black shaded histograms). The global \( \Sigma_{10} \) at low redshift is higher than that at high redshift, due to galaxy density evolution and flux limit for observation. The \( \Sigma_{10} \) was not normalized relative to the median galaxy density at each redshift bin. Blue galaxies always prefer to reside in less dense environments, as shown in Figure 11. Conversely, red galaxies are preferentially found in dense environments. Group members dominate the high density end of each redshift bin as expected. However, the environmental diversities of blue and red
galaxies decrease with increasing redshift. This can be attributed to the different galaxy compositions in dense environments at different redshifts. At low redshift, galaxies in groups or clusters are mainly red and quiescent. However, at high redshift, a large fraction of group members still form stars and with blue colors. This was first reported in Butcher & Oemler (1978) and is called the “B-O” effect.

The cumulative distribution curve of each sample is shown below the histogram panel. At \( z < 0.7 \), green galaxies and red galaxies have similar \( \Sigma_{10} \) distributions, as shown in Figure 11. Compared with blue galaxies, there is a larger fraction of green galaxies residing in dense regions, especially at \( z < 0.5 \). However, in all panels at \( z > 0.7 \), green galaxies and blue galaxies have similar \( \Sigma_{10} \) distributions. In some redshift bins, the differences between the three cumulative lines are very subtle, which may not be sufficient to conclude that the \( \Sigma_{10} \) distributions of these subsamples are statistically different. However, the consistent \( \Sigma_{10} \) trend for green galaxies at \( z < 0.7 \) suggests that environmental effects may play a more important role in the formation of this population at subsequent cosmic epochs.

To investigate the environmental dependence of stellar mass, the green galaxy sample was divided into two mass bins at \( z < 0.7 \): \( \log(M_*/M_\odot) = [10.0, 11.0] \) and \( \log(M_*/M_\odot) < 10.0 \). The \( \Sigma_{10} \) distributions of the binned samples are shown in Figure 12. Interestingly, the \( \Sigma_{10} \) distributions of red and green galaxies remarkably differ from those of blue galaxies in the low-mass bin: in comparison with the blue samples, the red and green samples have larger fractions of galaxies residing in dense environments.

However, the remarkable density distribution differences among these three subsamples shown in the low-mass bin are diluted in the high mass bin. To show the \( \Sigma_{10} \) distribution differences more statistically, we extend the Kolmogorov–Smirnov (KS) tests to the three distributions and summarize the results in Table 3. The result of the KS test gives small probabilities (<1%) that the \( \Sigma_{10} \) of the green and blue galaxies are drawn from

| Redshift | Mass Range (log(M*/M_\odot)) | Galaxy Number | Probability | Probability |
|----------|-------------------------------|---------------|-------------|-------------|
| 0.2–0.3  | <10.0                         | 99            | 0.1634      | 5.35E-5     |
| 0.3–0.4  | <10.0                         | 201           | 0.1913      | 2.6E-14     |
| 0.4–0.5  | <10.0                         | 166           | 0.4676      | 0.00013     |
| 0.5–0.6  | <10.0                         | 66            | 0.0389      | 0.01625     |
| 0.6–0.7  | <10.0                         | 74            | 0.1497      | 0.08104     |
| 0.2–0.3  | 10.0–11                       | 33            | 0.2636      | 0.86874     |
| 0.3–0.4  | 10.0–11                       | 138           | 0.6733      | 0.00331     |
| 0.4–0.5  | 10.0–11                       | 137           | 0.0959      | 0.65454     |
| 0.5–0.6  | 10.0–11                       | 150           | 0.0514      | 0.12042     |
| 0.6–0.7  | 10.0–11                       | 261           | 0.6705      | 8.27E-5     |

(A color version of this figure is available in the online journal.)
Figure 12. Σ₁₀ distributions of blue (blue), green (green filled), and red galaxies (red) at \(z = [0.2, 0.7]\) shown in two mass bins: \(\log(M_*/M_\odot) = [10.0, 11.0]\) and \(\log(M_*/M_\odot) < 10.0\).

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

the same distribution at \(z < 0.5\) when \(\log(M_*/M_\odot) < 10.0\). For the \(\log(M_*/M_\odot) = [10.0, 11.1]\) bin, the KS test gives larger probabilities, in good agreement with the visual inspection.

In summary, green galaxies at \(z > 0.7\) have similar Σ₁₀ distributions to those of star-forming galaxies. At lower redshift, low-mass green galaxies have similar Σ₁₀ distributions to those of quiescent galaxies; they preferentially reside in dense environments, especially at \(z < 0.5\). Our findings suggest that environmental effects may be crucial for quenching star formation activities in \(\log(M_*/M_\odot) < 10.0\) galaxies at \(z < 0.7\). For more massive galaxies, quenching does not show clear dependence on local galaxy environment.

5. DISCUSSION

5.1. The Nature of Green Valley Galaxies

In the above analysis, green galaxies are found to have significantly different morphological and spectral characteristics from blue and red galaxies. Their morphological properties cannot be produced by a simple mix of blue and red galaxies, and they most likely form a distinct population. This subsection discusses the components of the green population.

The simplest explanation for the presence of green galaxies is that they are transitioning galaxies, which have fading original star formation, on the way toward the red sequence. The transitioning scenario is required to explain the observed redshift evolution in stellar mass functions for star-forming and quiescent populations. Some properties of green galaxies, such as the average Gini coefficient, the bulgeness parameter, and the stacked emission lines, are intermediate between those of blue and red galaxies. These results can be expected if green galaxies are at the transition stage.

However, there are other possible ways to explain the existence of green galaxies. One possible explanation is that green galaxies are rejuvenated red galaxies. Red galaxies obtain gas supply either from gas-rich minor mergers or from gradual accretion, then start low level star formation activity and return to the GV. They might move to the red sequence again after the gas is exhausted. This scenario is supported by the observation of ETGs in the FUV and NUV bands, which reveals that a considerable fraction (about 15%–30%) of ETGs have low levels of recent star formation activities. Many studies favored the scenario that the star formation in ETGs are triggered in hitherto quiescent galaxies. Such phenomenon is termed “rejuvenation” in the literature (Rampazzo et al. 2007; Thomas et al. 2010; Thilker et al. 2010; Marino et al. 2011). It is important to evaluate the proportion of these sources in the GV. Fang et al. (2012) studied the extended star-forming early-type galaxies (ESF-ETGs) in low-redshift GV and estimated that \(\approx 13\%\) of GV galaxies have similar UV–optical color and stellar mass to those of ESF-ETG candidates. Another possible explanation is that galaxies are relatively stationary in the GV because of inefficient star formation. In this picture, galaxies will have low levels of star formation for very long periods of time due to quasi-static gas accretion from the intergalactic medium (IGM) and never reach true passivity (Salim et al. 2012). This so-called “incomplete quenching” phenomenon could also be possibly related to “morphology quenching” as demonstrated in Martig et al. (2009). In this scenario, after the cold stream fueling star formation shuts down, further fragmentation of gaseous disks (e.g., the ability to form stars) can be suppressed by a deepening central potential well or the declining self-gravity of the gas. This model predicts large bulges and slow quenching in disks.

About 20% of green galaxies are classified as ETGs by ZEST. Assuming all these ETGs are “rejuvenated” red galaxies, they
would only occupy a small fraction of the entire green sample. In Figures 6 and 7 we find that the majority of green galaxies host bulge components as well as significant disks. Their significant disk components are more possibly inherent rather than forming from later gas accretion. It is difficult to distinguish those green galaxies due to “incomplete quenching,” which prevents an accurate proportion estimation. Nevertheless, galaxies in this category should not be dominant in the GV because they are expected to stay in the GV for long periods of time, which makes it difficult to explain the color bimodality. In summary, the observed properties of green galaxies are consistent with the transition scenario. A modest proportion of green galaxies might have different origins and evolutionary paths.

5.2. Comparison with Previous Studies

In this paper, the GV was defined using dust-corrected NUV−r+ color. Because the dust-corrected NUV−r+ color is a good tracer of sSFR, in the current paper, the GV is equivalent to an intermediate sSFR (log(sSFR) ~ -10.5). In some previous studies, the GV was defined using an optical color index such as U−B or U−V. Since neither U−B nor U−V is sensitive to intermediate sSFR, GV galaxies defined using the intermediate sSFR will be degenerate with red sequence galaxies in the U−B or U−V CMD. We have investigated U−B selected GV galaxies using the criterion of Mendez et al. (2011) and found, on the one hand, that about 75% of them have log(sSFR) > -10.0, and only about 20% of them have log(sSFR) = [-10.0, -11.0]. On the other hand, we found that about 45% of log(sSFR) = [-10.0, -11.0] galaxies are degenerate with red sequence galaxies in the M_B versus U−B diagram. The differences between optical color and sSFR GV selections should be known when comparing our work with others.

Mendez et al. (2011) studied morphologies of ≈300 green galaxies in the AEGIS field within the redshift range of z = [0.4, 1.2]. They showed that green galaxies are generally massive (∼10^{10.5} M_☉) disk galaxies with high concentrations. The findings of Mendez et al. (2011) are confirmed by the current work based on a larger green galaxy sample selected from a similar redshift range. Thanks to the large green galaxy sample, the morphology of less massive M_∗ < 10^{10} M_☉ green galaxies was also investigated. These less massive green galaxies have not shown significant increase in their concentration since z ≈ 0.7.

We also found that green galaxies have high [O III]/Hβ ratio as reported in Coil et al. (2008). Coil et al. (2008) interpreted this as greater AGN activity in green galaxies compared with blue galaxies. The samples of Coil et al. (2008) were selected from the DEEP2 survey and mainly covered the redshift range of z = [0.7, 1.5]. For the galaxies at z = [0.2, 0.5], the [N II] λ6583 and Hα emission lines are shown. As shown in Figure 9, the [N II] λ6583/Hα ratio of a typical green galaxy is significantly higher than that of a blue galaxy, yet it is still lower than a typical Seyfert galaxy (Kauffmann et al. 2003a). Therefore, in this work, a typical green galaxy will be classified into the “transition” class using the BPT diagram (Baldwin et al. 1981).

Coil et al. (2008) found that green galaxies have similar clustering amplitude at a small scale (<1 Mpc) compared with blue galaxies, whereas at larger scales green galaxies show clustering amplitude that is close to that of red galaxies. Coil et al. (2008) explained that green galaxies are residing in the same dark matter halo as red galaxies, but are mainly spread in the outskirts. Galaxy properties are expected to correlate with the parent dark matter halo, inside which densities are evaluated on scales comparable with a typical virial radius (∼~1 Mpc).

Figure 11 shows that green galaxies at z > 0.7 have similar σ_10 distributions to blue galaxies. In comparison with red galaxies, green galaxies tend to prefer lower density environments, which is also in agreement with the findings of Coil et al. (2008). Balogh et al. (2011) reported the existence of a large green galaxy population in the X-ray group. We will compare our results with those of Balogh et al. (2011) and discuss this in detail in Section 5.5.

5.3. Quenching Connected with Bulge Formation

About 90% of green disk galaxies have bulge components. Specially, the fraction with a prominent bulge is about 60%–70% in the green disk sample, and only ≈35% in the blue disk sample. The presence of bulge in the majority of green galaxies suggests that star formation quenching in this population possibly accompanies or is connected with bulge formation.

Recent studies have found that quiescent galaxies are mostly associated with the presence of bulges. Bundy et al. (2010) found that passive disks typically have Sa–Sb morphological types and large bulges, based on COSMOS data; Kauffmann et al. (2012) found that there are clear thresholds in the bulge-to-disk ratio and in the stellar surface density that demarcates the location of quiescent galaxies. They proposed that the processes associated with bulge formation play an important role in depleting the gas in galaxies; Bell et al. (2012) studied a sample from CANDELS and found that most quiescent galaxies host prominent bulges, and many of them have significant disks. They argued that a prominent bulge (perhaps associated with a supermassive black hole) is an important condition for quenching star formation on galactic scales over the last 10 Gyr. Our findings confirm that both green and red galaxies tend to have prominent bulges.

Cheung et al. (2012) searched for traces of possible quenching processes through galaxy structural parameters and found that the central surface stellar mass density best discriminates between the red sequence and blue cloud. They found that red sequence bulges are roughly twice as massive as blue cloud bulges at the same stellar mass. Their results suggest that the innermost structure of galaxies is most physically linked to quenching. Some possible quenching mechanisms are discussed in Cheung et al. (2012). However, the ways by which these mechanisms relate to bulge build-up is still unclear.

The current study finds that a small fraction (about 5%–10%) of green disk galaxies does not harbor identified bulge components. This finding is consistent with that of Mendez et al. (2011), who reported that 12% of their green galaxies have B/T = 0. We stress that there is no clear boundary separating green and blue galaxies in the morphological parameter planes. These bulgeless green disks must have their star formation suppressed by other mechanisms without forming galactic bulges.

5.4. Quenching Connected with AGNs

There are some recent indications that AGNs inhabit the GV, both from X-ray surveys (Nandra et al. 2007; Coil et al. 2009) and optical line-ratio diagnostics (Salim et al. 2007). However, it is still unclear whether there are direct relationships between AGNs and star formation quenching processes in green galaxies. On the one hand, some studies found observational evidence that a powerful AGN can drive high speed outflow expelling the interstellar mediums and will suppress the star formation of its host galaxy in a very short period of cosmic time (Feruglio...
et al. 2010; Sturm et al. 2011; Page et al. 2012). On the other hand, studies based on large samples reported that AGNs have complicated relationships with star formation activities, but may not be directly responsible for quenching star formation (Bundy et al. 2008; Alonso-Herrero et al. 2008; Aird et al. 2012). Until now, despite recent progress, how AGNs regulate star formation and shape global galaxy properties is highly debatable.

To understand the role of AGN feedback, it is important to compare the properties of AGN host galaxies with those of inactive galaxies. Consider the fact that when a galaxy hosts an AGN, its observed SED is a superposition of the AGN’s and the host component’s. Thus one must subtract the AGN contribution from the total observed flux before deriving the correct color and mass of the host galaxy. Studying the link between AGNs and their hosts is a key question in astrophysics. However, this is beyond the scope of the current work. In this paper, we will just briefly discuss the recent advances in this field.

Xue et al. (2010) found that moderate-luminosity AGN hosts have no apparent color bimodality on the CMD. When matched in mass, AGN hosts lie in the same region on the CMD as inactive galaxies. They suggested that the presence of moderate-luminosity AGN activity does not have a significant effect on the galaxy color. Bongiorno et al. (2012) explored the host-galaxy properties of ≈1700 AGNs in the COSMOS field, and found AGN hosts are mainly massive red galaxies. They found no conclusive evidence suggesting that AGNs have powerful influence on the star-forming properties of their host galaxies. Rosario et al. (2013a) studied the properties of X-ray-selected AGN hosts in the Cosmic Assembly Near-IR Deep Legacy Survey and found that the colors, color gradients, and stellar population properties of AGN hosts are similar to those of inactive galaxies with the same stellar mass. However, in a more recent study, using far-infrared observations of the two Chandra Deep Fields, Rosario et al. (2013b) found that the UV-to-optical colors of AGNs are consistent with equally massive inactive galaxies at the same redshift, whereas their FIR distributions are statistically similar to those of star-forming galaxies.

Understanding the importance of AGN feedback requires a complete AGN sample spanning a wide luminosity range. The AGN samples used in previous studies are selected using X-ray, spectral indices, or IR SEDs. As suggested in many previous studies, a significant fraction of obscured AGNs will not be identified in insufficient deep X-ray surveys. The IR AGN selection criteria are relatively insensitive to dust obscuration. However, as suggested in Mendez et al. (2013), the IR selection appears to be biased toward selecting high-luminosity AGNs. We have used the mid-IR AGN selection criteria from Donley et al. (2012) to select AGNs from our galaxy sample. Ninety AGNs were selected using IRAC photometry, and most of them are blue. However, this must be a small fraction of the actual number, which is likely owing to the relatively shallower photometry in IRAC bands with respect to the optical bands. In summary, whether AGN feedback is responsible for quenching cannot be well constrained in our study.

5.5. Quenching Connected with Environmental Effects

Galaxies in dense regions are influenced by environmental conditions, such as galaxy interactions, tidal forces due to the cumulative effect of many weaker encounters, and gas stripping due to interaction with the IGM, which can affect (more or less) their evolutionary paths. A great deal of works support the fact that dense environments are especially important for gas stripping/removal in LTGs and turning them into ETGs (Boselli & Gavazzi 2006; Cooper et al. 2006; van den Bosch et al. 2008; Smith et al. 2010; van der Wel et al. 2010; Weinmann et al. 2010).

Our findings show that green galaxies exist in various environments, indicating that environmental effect is not the sole explanation responsible for star formation quenching in this population. In Section 4.1.2, most green disks are found to host significant bulges as well as disk components. These green disks are likely the progenitors of S0 or passive spirals. Bundy et al. (2010) found that passive spirals in the COSMOS field harbor large bulges, but are not confined to dense environments. However, less massive green galaxies ($M_* < 10^{10.0} M_\odot$) at $z < 0.7$ prefer dense environments, strongly suggesting that environmental conditions may play an important role in quenching at later cosmic times.

Although both morphological evolution (Kovac et al. 2010) and star formation activity are influenced by the environment, the dominant mechanism affecting galaxy evolution in dense environments is still debatable. Because there are only one to two clusters in the COSMOS field, strong ram pressure stripping, which works in cluster cores, will not play a dominant role in quenching in this study. In a group environment, frequent galaxy interactions are expected to be especially efficient in influencing galaxy evolution. Tidal interactions can trigger star formation (Lambas et al. 2003; Nikolic et al. 2004; Li et al. 2008), which could be a factor in the transformation of blue star-forming galaxies to red quiescent galaxies (Wong et al. 2011; Patton et al. 2011).

Comparing the merger rate between blue, green, and red galaxies may be helpful in assessing the role of mergers in the formation of green galaxies. However, accurate measurement of merger fraction requires spectroscopic redshifts and very high sampling rate. The zCOSMOS survey has a low sampling rate (<0.1) for galaxies with close companions ($D_{\text{separation}} < 5''0$), which restricts an accurate merger rate measurement. We note that the ways by which mergers shape galaxy properties have been widely discussed in the literature. Perez et al. (2009) suggested that, at intermediate densities, close pairs could have experienced more rapid transition onto the red sequence than isolated galaxies. Ellison et al. (2010) found that there is a clear enhancement of the bulge/total ratio (B/T) when pairs have small separations ($<30 h^{-1}$ kpc). They interpreted this as the signature of central star formation in interacting pairs. Mendez et al. (2011) found that most green galaxies in the AEGIS field are not classified as mergers, and their merger rate is even lower than that of blue galaxies. Alonso et al. (2012) studied galaxy pairs in SDSS groups and found that the CMD of group/cluster pairs consists of a clear excess of extremely blue and red galaxies with respect to that of the control sample. Most of these studies suggest that mergers enhance star formation activities, and the interacting galaxies evolve more rapidly than their isolated counterparts. If this is the case, then the interacting galaxies will pass their GV phase in a shorter time than isolated galaxies. Thus, the results shown in Mendez et al. (2011) and Alonso et al. (2012) are natural.

In galaxy groups, very weak ram pressure can strip gas, thereby gradually shutting off star formation. This process is known as “strangulation.” “Harassment,” which is known as the cumulative effects of many weak encounters and tidal interactions, also works in a group environment. These two mechanisms are thought to be especially important to the evolution of low-mass galaxies (Barazza et al. 2002; Haines et al. 2006, 2008). As compared with merger or strong galaxy–galaxy
interactions, strangulation and harassment mainly act on gas content and will not modify galaxy structure directly. Violent merging of two spiral galaxies is most likely to produce a bulge-dominated ETG. Simulations have shown that the remnants of strangulation should have similar structures to those of disk systems. The GV defined by George et al. (2011) targeted seven galaxy groups in the COSMOS field and claimed that they discovered a large fraction of transitioning galaxy population in X-ray groups at 0.85 < z < 1.0. However, their sample size is much smaller (about 100 galaxies in total and about 20 of them are green galaxies) than ours. They used the k-corrected (V − z) color index to define the GV, whereas we use the dust-corrected NUV−r* color. Thus the composition of green galaxies is quite different in these two works, as also discussed in Section 5.2. In the left panel of Figure 13 we show (NUV − r*)corr and (V − z)0.9 for galaxies at 0.8 < z < 1.0, with the green galaxy criterion of Balogh et al. (2011) shown in vertical dashed lines. It is obvious that these two criteria select different galaxies. The GV defined by the (V − z)0.9 color is contaminated by many dusty blue galaxies. Galaxies are more efficiently separated into two main categories (blue star-forming and red quiescent) using the dust-corrected NUV−r* color. In addition, our GV definition, which can exclude the contaminants of star-forming or quiescent galaxies more efficiently, is much stricter than that of Balogh et al. (2011). We suggest that the dust-corrected NUV−r* color is more reliable for selecting truly transitioning galaxies.

Following Balogh et al. (2011), the (V − z)0.9 color distribution of X-ray group galaxies was compared with that of field galaxies to check whether there was a large amount of transitioning galaxies at 0.8 < z < 1.0. The group members were selected as galaxies with $P_{\text{mem}} \geq 0.1$ in the X-ray group catalog of George et al. (2011). A low $P_{\text{mem}}$ limit was applied in order to keep a high group member completeness. As illustrated in George et al. (2011), a $P_{\text{mem}} \geq 0.1$ member selection limit maintains 95% of the true group members but brings in about 35% field contaminants. The field galaxies were selected as those residing in sparse environments (which have log($\Sigma_{10}$) < 0.5 and $P_{\text{mem}} = 0.0$ when cross-matched with the X-ray group catalog). The results are shown in the middle and right panels in Figure 13. As shown in Figure 13, the (V − z)0.9 color distribution of field galaxies is very similar to that reported in Balogh et al. (2011). Given that the purity of the selected group members is about 65%, there is a need to determine if “fake” group members will distort the color distribution of “true” group members.

To do this the color distribution of “interlopers” was subtracted from that of the selected group members. The purity and completeness are formally given by

$$p = \frac{N_{\text{selected}} - N_{\text{interlopers}}}{N_{\text{selected}}}, \quad c = \frac{N_{\text{true}} - N_{\text{missed}}}{N_{\text{true}}}$$

where $N_{\text{true}} = N_{\text{selected}} + N_{\text{missed}} - N_{\text{interlopers}}$. There are 443 galaxies with $P_{\text{mem}} \geq 0.1$, thus the number of “fake” group members is about 443 × (1−0.65) ≃ 155. These 155 interlopers were assumed to have the same color distributions as those of field galaxies. The (V − z)0.9 color distribution of the interlopers-selected group members is shown as a solid histogram in the middle panel of Figure 13. For comparison, the dust-corrected NUV−r* distribution is plotted in the right panel of Figure 13. We find that group members tend to have redder color with respect to field galaxies, whether defined by (V − z)0.9 or NUV−r*. The (V − z)0.9 color distribution of group member is perfectly consistent with that reported in Balogh et al. (2011). Compared with the (V − z)0.9 color distribution of field galaxies, there is a remarkable excess of green and red galaxies located in groups at the expense of blue galaxies. The excess of galaxies residing in the GV is not seen after dust correction. Most of the $M_* > 10^{10.1} M_\odot$ green galaxies defined by the (V − z)0.9 color fall in the massive star-forming category when using the dust-corrected NUV−r* classification. In summary, we successfully reproduced the results of Balogh et al. (2011). However, after dust correction, there is no excess of $M_* > 10^{10.1} M_\odot$ group galaxies residing in the GV with respect to the field.
5.6. The Formation of Red Galaxies

Previous works have suggested a significant growth of red sequence galaxies since $z \approx 1.0$. Recently, Moustakas et al. (2013) measured the evolution of the stellar mass function from $z = 0$–1 using the PRIMUS and SDSS data. On the one hand, they found that the space density of massive star-forming galaxies has declined by 54% since $z \approx 1$. On the other hand, the most massive quiescent galaxies have largely been in place since $z \approx 1$. The build-up of the red sequence occurs significantly at intermediate and low masses, where they found a factor of 2-3 increase in the number density of $10^{10.5}$–$10^{10}$ $M_\odot$ galaxies since $z \approx 0.5$. In this study, our findings suggest that a significant fraction of these low-mass red sequence galaxies are likely quenched due to environmental effects.

We find that the build-up of red sequence is strongly mass-dependent. At $z > 0.7$, the majority of red galaxies are massive, with $\log(M_*/M_\odot) > 10.0$. Less massive galaxies join the red sequence at $z < 0.7$. Age downsizing, according to which less massive galaxies contain younger stellar populations, has been prevalently found in studies on ETGs (Thomas et al. 2005; Zhu et al. 2010; Pan et al. 2012). Some models have been proposed to explain this observation (Faber et al. 2007; Pozzetti et al. 2010). Pozzetti et al. (2010) proposed a scenario wherein intermediate-mass galaxies gradually decrease their star formation activities to intermediate values, and finally to values similar to those of quiescent galaxies, by means of either the exhaustion of the gas reservoir or cold gas accretion, or by quenching due to AGN feedback. For the schematics of this scenario, one can refer to Figure 21 of Pozzetti et al. (2010). In this scenario, massive star-forming galaxies have shorter quenching timescale. Finally, they evolve onto the red sequence on a timescale of 1–2 Gyr, and undergo dynamical transformation into spheroidal galaxies.

Our findings suggest that quenching is related to both mass and local density environment. However, which process (mass quenching and environment quenching) plays the dominant role is still unclear. Peng et al. (2010) have taken an empirical approach to identify how mass and environment affect the “quenching” process at different cosmic epochs. They found that the effects of mass and environment are completely separable to $z \sim 1.0$. The physical origins of environment quenching have been discussed in Section 5.5, but the actual physical mechanism leading to mass quenching remains largely unknown. Peng et al. (2010) summarized the dominant mechanism responsible for quenching as follows: at high masses ($M_* > 10^{10.5}$ $M_\odot$), mass quenching always plays a dominant role. At lower masses, merger quenching works at $z > 0.5$ and environment quenching works at $z < 0.5$. Our results can be well explained by the Peng et al. (2010) model, although the mass and redshift thresholds separating the dominant mechanism are slightly different in these two works.

6. SUMMARY

In this paper, a sample of $\approx 2350$ green galaxies was constructed using dust-corrected NUV–$r^\prime$ color in the COSMOS field, after which their properties were compared with those of mass-matched blue and red samples at $0.2 < z < 1.0$. The findings are summarized as follows.

1. Green galaxies are mostly located in the joint region of blue and red galaxies in the galaxy structural parameter diagrams, both on the Gini–asymmetry plane and the $M_{20}$–Gini plane.

2. Red disk galaxies mostly host large or intermediate bulge components, accounting for about 80%–90% of the population. The fraction of green galaxies with large or intermediate bulges accounts for about 60%–70%, which is much higher than that of blue galaxies (about 35%). Only 5%–10% of green spirals are classified as pure disk systems. Most green galaxies still harbor significant disk components.

3. The stacked spectra of green galaxies have intermediate emission lines, such as [O II], H$\beta$, and H$\alpha$. The SSP decomposition of the stacked spectra shows that green galaxies have a small fraction of young stellar populations, whereas the old populations account for very large fractions. The average metallicity of green galaxies is higher than that of blue galaxies and lower than that of red galaxies.

4. The environments of green galaxies were explored using the local galaxy density $\Sigma_\theta$. At $z > 0.7$, green galaxies tend to reside in environments with similar density to that of blue galaxies, whereas at lower redshift, a large proportion of $M_* < 10^{10.0}$ $M_\odot$ green galaxies reside in dense environments, which is significantly different from that of $M_* < 10^{10.0}$ $M_\odot$ blue galaxies.

Our findings support the fact that the physical properties of green populations are consistent with those of the transitioning populations between blue star-forming galaxies and red quiescent galaxies. We are able to reproduce the color distribution for X-ray group members as reported in Balogh et al. (2011) at $0.8 < z < 1.0$. However, no excess of green galaxies is found in groups compared with the field after dust correction. Our findings support the galaxy evolution model of Peng et al. (2010).

We thank the referee for thoughtful comments and insightful suggestions that improved our paper greatly. This work is supported by the National Natural Science Foundation of China (NSFC; Nos. 11225315, 11203023, and NSFC 11320101002), and the Chinese Universities Scientific Fund (CUSF) and the Specialized Research Fund for the Doctoral Program of Higher Education (SRFDP; No. 20123402110037). This work is also supported by the Open Research Program of the Key Laboratory for the Structure and Evolution of Celestial Objects, CAS. We thank the COSMOS team for making their excellent data publicly available, and Dr. Guanwen Fang and Dr. Tao Wang for valuable discussion.

REFERENCES

Abraham, R. G., Tanvir, N. R., Santiago, B. X., et al. 1996, MNRAS, 279, L47
Aird, J., Coil, A. L., Moustakas, J., et al. 2012, ApJ, 746, 90
Alonso, S., Mesa, V., Padilla, N., & Lambas, D. G. 2012, A&A, 539, 46
Alonso-Herrero, A., Pérez-González, P. G., Rieke, G. H., et al. 2008, ApJ, 677, 127
Baldry, I. K., Glazebrook, K., Brinkmann, J., et al. 2004, ApJ, 600, 681
Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5
Balogh, M. L., McGee, S. L., Wilman, D. J., et al. 2011, MNRAS, 412, 2303
Barazza, F. D., Binggeli, B., & Jerjen, H. 2002, A&A, 391, 823
Bell, E. L., van der Wel, A., Papovich, C., et al. 2012, ApJ, 753, 167
Bell, E. L., Wolf, C., Meisenheimer, K., et al. 2004, ApJ, 608, 752
Bertoldi, F., Carilli, C., Aravena, M., et al. 2007, ApJS, 172, 132
Bolzonella, M., Kovač, K., Pozzetti, L., et al. 2010, A&A, 524A, 76B
Bongiorno, A., Merloni, A., Brusa, M., et al. 2012, MNRAS, 427, 3103
Boselli, A., & Gavazzi, G. 2006, PASP, 118, 517
Bower, R. G., Benson, A. J., Malbon, R., et al. 2006, MNRAS, 370, 645
Brammer, G. B., Whitaker, K. E., van Dokkum, P. G., et al. 2009, ApJL, 706, L173
Brammer, G. B., Whitaker, K. E., van Dokkum, P. G., et al. 2011, ApJ, 739, 24
