Conditions for Galaxy Quenching at 0.5 < z < 2.5 from CANDELS: Compact Cores and Environment

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Received 2019 November 28; accepted 2020 March 20

Abstract. We investigate two classes of conditions for galaxy quenching at 0.5 < z < 2.5 based on the structural scaling relations of galaxies in the five Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS) fields: the formation of a compact core and the environment. We confirm that, in the entire redshift range, massive quiescent galaxies ($M_*>10^{10} M_\odot$) have much higher stellar mass surface densities within the central 1 kpc ($\Sigma_1$) and smaller sizes than star-forming galaxies in the same stellar mass range. In addition, the quiescent fractions significantly increase with the increase of $\Sigma_1$ regardless if galaxies are centrals or satellites. In contrast, we find that the overall lower-mass quiescent galaxies ($M_*<~10^{10} M_\odot$) have slightly higher $\Sigma_1$ and comparable sizes compared to star-forming galaxies of the same mass and at the same redshift. At z < 1.5, satellites have higher halo masses and larger quiescent fractions than those of centrals at a given $\Sigma_1$ (stellar mass). Our findings indicate that the significant growth of the galaxy cores is closely related to the quenching of massive galaxies since $z \gtrsim 2.5$, while the environmental effect plays an important role in the quenching of low-mass galaxies at $z \lesssim 1.5$.

Key words: galaxies: evolution — galaxies: formation — galaxies: high-redshift

1 INTRODUCTION

Galaxies can be mainly classified into two types from $z \sim 2$ to the present day according to many physical properties, such as star formation rate (quiescent vs. star-forming), morphology (bulge-dominated vs. disk-dominated), and color (red vs. blue) (e.g. Strateva et al., 2001; Kauffmann et al., 2003; Driver et al., 2006; Brammer et al., 2009; Xue et al., 2010; Schawinski et al., 2014). In the color-magnitude diagram, the location where quiescent, bulge-dominated galaxies reside is
collectively referred to as the “red sequence”, while the location occupied by star-forming, disk-dominated galaxies is collectively referred to as the “blue cloud” (Baldry et al., 2004; Blanton, & Moustakas, 2009). Observations have shown that the red sequence galaxies have significantly different structural properties from the blue cloud galaxies (Williams et al., 2010; van der Wel et al., 2014; Whitaker et al., 2017). The distribution of the bimodality leaves people with the motivation to investigate the evolutionary paths from star-forming galaxies (SFGs) to quiescent galaxies (QGs), namely the so-called quenching modes.

The quenching of star formation is closely related to the internal and external processes of galaxies. The internal quenching is also known as mass quenching (e.g. Peng et al., 2010). The quenching mechanisms involving stellar mass shut down star formation by consuming cold gas rapidly at the center of galaxies via major merger or violent disk instability events. These violent events are referred to as “compaction processes” (e.g., Barro et al., 2017) because these processes lead to the gas inflow, leaving a compact core (e.g. Di Matteo et al., 2005; Croton et al., 2006; Bell et al., 2012; Fang et al., 2013; Lang et al., 2014; Brennan et al., 2017; Liu et al., 2016, 2018). The external processes for quenching are related to the environment. Among them, the most invoked ones are ram pressure stripping, galaxy harassments and strangulation (e.g. Gunn & Gott, 1972; Larson et al., 1980; Farouki & Shapiro, 1981; Peng et al., 2010). Ram pressure stripping is associated with the removal of gas from a galaxy via super sonic heating in dense environment. In group/cluster environments, galaxies experience frequently encounters, which drive the transformation of their morphology. This process has been referred to as galaxy harassment. Furthermore, the process will be referred to as galaxy strangulation if a galaxy loses the replenishment of gas from the halo.

Many previous works have revealed that a dense stellar core is present in massive ($M_\ast \sim 10^{10}M_\odot$) QGs and the formation of such core in SFGs is the main requirement for quenching star-formation (e.g., Williams et al., 2010; Wuyts et al., 2011; Cheung et al., 2012; Fang et al., 2013; van der Wel et al., 2014). Some authors have also suggested that a central mass density threshold evolving with redshift can be important for the star formation quenching (Franx et al., 2008; Bezanson et al., 2009). Lee et al. (2018) investigated the correlation between the star formation and stellar mass surface density within the central 1 kpc ($\Sigma_1$) at $1.2 < z < 4$ using CANDELS/GOODS fields. Their results suggest that the quenching of massive galaxies is usually accompanied by the increase of the central mass density. This process is in agreement with the prediction of hydrodynamical simulations where the high-redshift spheroids undergo strong dissipation of the gas inflow and become compact (Zolotov et al., 2015; Ceverino et al., 2015).

Environmental effects are believed to be responsible for the shutdown of the star formation of low-mass satellites (e.g., Geha et al., 2012; Cora et al., 2018, 2019). On one hand, the fraction of quiescent satellites around the massive central galaxies is estimated to determine the environmental effects (Quadri et al., 2012; Balogh et al., 2016; Kawinwanichakij et al., 2016, 2017). On the other hand, the projected distance between low-mass galaxies and massive central galaxies in a massive halo is an indicator of environmental effects (Guo et al., 2017). If these low-mass QGs are quenched by the environment, theoretically the distance of QGs to the central galaxies should be, on average, shorter than that of SFGs. Recently, Guo et al. (2017) proved this point and showed that the environmental quenching is particularly distinct in the low-mass galaxies out to $z \sim 1$. Another observational evidence that involves environmental quenching is the so-called “galactic conformity” at both low and high redshifts (e.g., Weinmann et al., 2006; Knobel et al., 2015; Kawinwanichakij et al., 2016). The galactic conformity refers to the fact that satellites that are around massive quiescent centrals are more likely quenched than those around star-forming centrals. The dependences of environmental effects on the redshift and stellar mass have also been investigated recently (Wetzel et al., 2012, 2013; Darvish et al., 2016; Kawinwanichakij et al., 2017).

In this work, we start from the structural scaling relations of galaxies, and then reinvestigate the relative role played by the formation of a compact core and the environment in quench-
ing star formation in galaxies over $0.5 < z < 2.5$. We use $\Sigma_1$ to quantify the compact core. Cosmological simulations show that the increase of stellar mass density is caused by an inward migration of gas, especially in the inner 1 kpc, during the quenching (Zolotov et al., 2015; Tacchella et al., 2016). Therefore, the $\Sigma_1$ is a good indicator of the galaxy quenching associated with stellar mass. Recently, Barro et al. (2017) analyzed the relationship between $\Sigma_1$ and the mass growth over $0.5 < z < 3$ in the CANDELS/GOODS field. Their results imply that massive galaxies at high redshift experience a fast phase of core growth. Similar results have also been found by van Dokkum et al. (2014) and Chen et al. (2019). We expand the study of Barro et al. (2017) with a broader stellar mass range and a larger sample size of galaxies selected from all the five CANDELS fields. The main purpose of the work is to explore the physical explanations of the different structural scaling relations and their implications for galaxy quenching. The paper is organized as follows. In Section 2, we describe the data and the sample selection. In Section 3, we show the various structural relations explored in this analysis. We present our main results in Section 4, while a discussion and a summary are given in Section 5 and Section 6, respectively. Throughout the paper, we adopt a standard cosmology with $\Omega_M=0.3$, $\Omega_\Lambda=0.7$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. The magnitudes used in this work are in the AB system.

2 DATA AND SAMPLE SELECTION

2.1 Data

The sample used in this paper is from all the five fields (COSMOS, EGS, GOODS-N, GOODS-S and UDS) of CANDELS programs (e.g. Grogin et al., 2011; Koekemoer et al., 2011). The CANDELS group has made a multi-wavelength photometry catalog from infrared to ultraviolet for each field. Photometry in HST/WFC3 and ACS was measured by running SExtractor (Bertin & Arnouts, 1996) in dual model on the point spread function (PSF)-matched images, with the $H_{F160W}$ image as the detection image. We refer the reader to Guo et al. (2013), Galametz et al. (2013), Nayyeri et al. (2017), Stefanon et al. (2017), and Barro et al. (2019) for details.

Redshifts are available from the spectroscopy and the photometry. We give the preference to redshifts from the spectroscopy, followed by photometry if spectroscopic redshifts are not available. The 1-$\sigma_z$ scatter of the photometry is typically from 0.03 to 0.06 (e.g. Dahlen et al., 2013). Stellar masses were measured using the code FAST (e.g. Kriek et al., 2009) based on the Bruzual & Charlot (2003) stellar population templates with a Chabrier (2003) initial mass function (IMF), Calzetti et al. (2000) dust law, solar metallicity and declining $\tau$-models. The specific star formation rate (sSFR) was computed from the extinction-corrected luminosity at $\lambda \sim 2800$ (e.g. Kennicutt & Evans, 2012). We adopt the median mass and $\lambda_*$ of different SED fittings assuming different star formation histories (e.g. Santini et al., 2015). van der Wel et al. (2012) measured the galaxy structural parameters with a single Sérsic profile with GALFIT (Peng et al., 2002). The single Sérsic model enabled the Sérsic index ($n$), effective radius ($r_e$) and axis ratio to be available.

$\Sigma_1$ is calculated by running FAST code (Kriek et al., 2009) on the multi-aperture photometry of CANDELS galaxies (Liu et al., 2016, 2017, 2018). The multi-band HST mosaics were PSF-matched to the resolution of $H_{F160W}$ that has a half width at half maximum of HWHM $= 0.09''$, which corresponds to $\sim 0.73$ kpc, on average, in our redshift range. To compensate for the mass smeared outside 1 kpc of galaxies due to PSF smoothing, the $\Sigma_1$ is derived by performing a Sérsic dependent correction.

2.2 Sample Selection

To maximize the sample size and reduce the contamination of data with bad photometry, we select a subsample from all five CANDELS fields. The selection criteria are as follows:
1. Observed $H_{F160W}$ magnitude brighter than 26. Note that van der Wel et al. (2012) suggested that the errors of GALFIT measurement will increase for galaxies fainter than $H_{F160W} = 24.5$. However, the statistical results will not change significantly by applying a cut of 26 magnitude.

2. SExtractor Photometry quality flag PhotFlag = 0 to exclude spurious sources;

3. SExtractor CLASS_STAR < 0.9 to eliminate the confusion from stars;

4. $0.5 < z < 2.5$ as redshift range;

5. GALFIT quality flag $ag = 0$ in $J_{F125W}$ for $z < 1$ and $H_{F160W}$ for $z > 1$ (van der Wel et al., 2012) to ensure well-constrained GALFIT measurements.

In Figure 1, we show the CANDELS galaxies in observed $H_{F160W}$ magnitude and stellar mass plane, divided into four redshift bins. In order to select a complete sample, we estimate the stellar mass lower limits following the method given by Pozzetti et al. (2010). In each redshift bin, we choose the 20% faintest galaxies to compute the lower limits in stellar mass ($M_{lim}$) according to $\log M_{lim} = \log M_* + 0.4 \times (m_{F160W} - 26)$, where $m_{F160W}$ is the observed $H_{F160W}$ magnitude. We then choose the 95th percentile of the distribution of $M_{lim}$ as the lower mass limit, which corresponds to a 95% completeness limit. The loose limit for the apparent magnitude in the $H_{F160W}$ band allows us to include low-mass galaxies even at high redshift. The lower mass limits for the four redshift bins ($0.5 < z \leq 1.0$, $1.0 < z \leq 1.5$, $1.5 < z \leq 2.0$ and $2.0 < z < 2.5$) are 8.3, 8.6, 8.9 and 9.2, respectively in logarithm. The objects with $M_* < M_{lim}$ (shadow region in Figure 1) are discarded.

3 STAR FORMING MAIN SEQUENCE AND STRUCTURE RELATIONS

We start from the determination of the star forming main sequence (SFMS) (Daddi et al., 2007; Salim et al., 2007; Noeske et al., 2007; Elbaz et al., 2011) as plotted in the top panels of Figure 2. Previous studies have shown that the slope of the SFMS is dependent on the stellar mass (Leja et al., 2015; Contini et al., 2017a). We use a broken power-law to fit the SFMS defined...
Fig. 2  Top panels: The relationship between sSFR and stellar mass in four redshift bins. The blue points indicate star-forming galaxies that are distinguished from quiescent galaxies by the UVJ diagrams given by Williams et al. (2009). The green points show the compact star-forming galaxies, which are selected to have log Σ1.5 (M⊙ kpc−1.5) > 10.3 (see bottom panels). The cyan solid line in each panel represents the broken power-law fit to blue and green points and the pink points are median values. Quiescent galaxies (red points) are selected to lie 0.9 dex below the fitting relations, i.e., below the dashed cyan lines. Middle panels: Σ1-mass relation for our samples. The small color points are the same as in the top panels and the blue and red hollow circles represent the median values for star-forming and quiescent+cSFG galaxies, respectively. The blue and red solid lines show the best-fit for star-forming and quiescent (M* > 10^{10}M⊙)+cSFG galaxies, respectively. The green dashed lines show the results of Barro et al. (2017). Bottom panels: r_e-mass relation for our samples. The cyan solid lines and black dashed lines indicate the best-fit linear relations for star-forming galaxies and the separation of compact and non-compact SFGs given by Barro et al. (2013), respectively.

by the UVJ diagrams given by Williams et al. (2009). The broken power-law is defined as

\[
\log \text{sSFR} = \mu \left[ \log \left( \frac{M_e}{M_{\odot}} \right) - 10.0 \right] + \log C
\]  

(1)

and the fit parameters (slopes and zero points) are given in Table 1. Whitaker et al. (2014) showed that the slope of the SFMS is dependent on stellar mass and the characteristic mass is M_e \sim 10^{10.2} M_{\odot} at 0.5 < z < 2.5. The result is not affected significantly if we adopt M_e = 10^{10} M_{\odot} (i.e., the number 10 in equation 1) as the knee for each redshift bin. We define SFGs
and QGs as those that lie above and below $\Delta \log sSFR = -0.9$ (red dashed line in each panel of Figure 3). $\Delta \log sSFR = \log sSFR - \log sSFR^{MS}$). This threshold corresponds to $\sim 3\sigma$ of the SFMS. The compact star-forming galaxies (cSFGs, green points) are selected to have $\log \Sigma_{1.5} (M_\odot\text{kpc}^{-1.5}) > 10.3$ (see bottom panels in Figure 2) where $\Sigma_{1.5} = M_*/r_e^{1.5}$ (Barro et al., 2013).

We move now to the scaling relation between $\Sigma_1$ and stellar mass at the four redshift bins (middle panels in Figure 2). The relationship between $\Sigma_1$ and stellar mass is defined as

$$\log \Sigma_1 = \alpha \left[ \log \left( \frac{M_*}{M_\odot} \right) - 10.0 \right] + \log \Lambda. \quad (2)$$

Note that we select different stellar mass ranges for SFGs (all SFRs) and QGs (massive QGs) to fit the $\Sigma_1$-$M_*$ relations. The reason for this is that on the one hand, massive and low-mass QGs indeed have different $\Sigma_1$-$M_*$ relations, which prompts us to consider massive and less massive QGs separately. At the same time, we note that low-mass QGs are mostly at $0 < z < 1.0$. On the other hand, we can compare our fitting results with Barro et al. (2017) who also selected similar stellar mass ranges as us for SFGs and QGs in CANDELS. We check the difference between using only massive SFGs to fit the $\Sigma_1$-$M_*$ relation and using all SFGs and find that the slope for the former, on average, is only 0.1 higher than that of the latter. We show that the slopes ($\alpha^Q \simeq \alpha^{SP} \sim 0.85$) for QGs and SFGs almost do not change with cosmic time, which is basically consistent with Barro et al. (2017). Note that our slopes for QGs are slightly higher than those in Barro et al. (2017). We attribute this small gap to the differences in sample selection and the definition of the QGs. In order to clearly describe the trends in $\Sigma_1$-$M_*$, we divide objects into massive ($M_* > 10^{10} M_\odot$) and low-mass ($M_* < 10^{10} M_\odot$) galaxies. Considering the sample completeness of different redshift ranges, we compute the median $\Sigma_1$ (see Table 2) only using galaxies with $M_* > 10^{10.2} M_\odot$. For the median $\Sigma_1$ of QGs in Table 2, we compute it by including the QGs and cSFGs due to the fact that they have similar structures in bulge and similar size. For massive galaxies, we find that the median $\Sigma_1$ for QGs is, on average, 0.7 dex higher than that of SFGs. The difference between $\Sigma_1$ of QGs and SFGs strongly depends on redshift, which decreases by $\sim 0.5$ dex from the highest redshift bin to the lowest redshift bin (see Table 2). For low-mass galaxies, the median $\Sigma_1$ for QGs is, on average, 0.4 dex higher than that of SFGs. It can be seen that QGs and SFGs with $M_* < 10^{9.5} M_\odot$ roughly have the same evolutionary tracks in the $\Sigma_1$-$M_*$ relation, which indicates that the formation of a compact core is not the dominant mechanism in the quenching of low-mass galaxies.

In addition, most of the cSFGs locate in the same region as the massive QGs. These galaxies still lie in the blue cloud but have compact cores, which implies that the cSFGs may be a transitional population between SFGs and QGs. In order to quantify the degree of compactness, we define the vertical offset, $\Delta \log \Sigma_1 = \log \Sigma_1 - \log \Sigma_{1.5}^{SP}$, where $\Sigma_{1.5}^{SP}$ is the best-fit of $\Sigma_1$-$M_*$ relation for SFGs. This vertical offset is insensitive to the slope.

Finally, we show the relations between $r_e$ and stellar mass for different redshift bins in the bottom panels of Figure 2. Similarly to $\Sigma_1$, we fit the relations as

$$\log r_e = \beta \left[ \log \left( \frac{M_*}{M_\odot} \right) - 10.0 \right] + \log B. \quad (3)$$

We find that massive QGs exhibit a much smaller $r_e$ (steep slope) than SFGs of the same mass and redshift, but not for the low-mass QGs. The difference of the median size between massive QGs and SFGs is, on average, 0.4 dex, while the difference for less massive galaxies is only 0.18 dex. For low-mass galaxies, we find that the median difference changes from 0.05 dex to 0.29 dex with time, which may be caused by the larger scatter in the $r_e$-$M_*$ relation and the lack of high-redshift QGs. At $0.5 < z < 1.5$, we can clearly see that low-mass QGs have similar size distributions as the bulk of SFGs. The flat slope of the $r_e$-$M_*$ relation for low-mass QGs is also confirmed by simulations (Furlong et al., 2017). These results indicate that massive
In this section, we address the question of how SFGs evolve in the structural scaling relations. In order to quantify the variation in galaxy size, we compute the vertical offsets, \( \Delta \log r_e \), for quiescent and star-forming galaxies, respectively. The coefficients of \( \log \Sigma_1 = \alpha (\log M_* - 10.0) + \log A \) for quiescent and star-forming galaxies, respectively; Col.(8-9): The coefficients of \( \log r_e = \beta (\log M_* - 10.0) + \log B \) for star-forming galaxies.

4 RESULTS

4.1 Star formation quenching and compact cores

In this section, we address the question of how SFGs evolve in the structural scaling relations described in Section 3. Figure 3 shows the \( \Delta \log sSFR \) as a function of \( \Delta \log \Sigma_1 \) and Sérsic index \( n \) for each redshift-mass bin. The utilization of relative quantities at fixed redshift, instead of a threshold, has the advantage to make our results not sensitive to the fitting relations. We show that a high \( n \) is only related closely to the quenching of massive galaxies, whereas the low-mass QGs (below the red dashed line) at \( 0.5 < z < 1.5 \) do not display large \( n \). Whitaker et al. (2015, 2017) showed that galaxies with high \( n \) have a broad range of sSFR, which suggests that a high \( n \) can not be indicative of the star formation quenching for the full galaxy population. Similar trends can be revealed by Figure 4, which shows the same plot as Figure 3, but color-coded by \( \Delta \log r_e \). We summarize our findings as follows:

1) A dichotomy is displayed in the distribution of \( \Delta \log \Sigma_1 \). Galaxies with \( \Delta \log \Sigma_1 > 0 \), on average, have smaller sizes. It indicates that the growth of cores is accompanied by the decrease of galaxy sizes.

2) At \( 0.5 < z < 2.5 \), massive galaxies in each redshift bin preferentially occupy the lower right corner region where they exhibit higher \( \Delta \log \Sigma_1 \) and lower sSFR. However, at \( 0.5 < z < 1.5 \), many low-mass QGs also exhibit dense cores and small sizes. It leads to the weakness of “elbow” signature (the trend shown by pink points) that is prominent for high-redshift galaxies.

Based on other observations, many studies have constructed a picture both in the local and distant universe, where it is possible to use the mass surface density or velocity dispersion of the bulge to describe the evolutionary path of massive galaxies (Franx et al., 2008; Wake...
et al., 2012; Fang et al., 2013; Tacchella et al., 2015; Woo et al., 2015; Barro et al., 2017). Whitaker et al. (2017) used a sample selected from 3D-HST at $0.5 < z < 2.5$ to investigate the connection between star formation quenching and central mass density. They found that SFGs show larger sizes and looser cores than QGs at given stellar mass, and suggested that a threshold of central density (or velocity dispersion) which evolves with redshift is a better indicator for the quiescence of the average galaxy population. Based on cosmological simulations, Tacchella et al. (2016) showed that galaxies with $M_* > 10^{9.5}M_\odot$ at $2 < z < 4$ exhibit inside-out quenching, which is interpreted as the wet compaction event (gas-rich). Our findings in Figure 4 indicate that massive QGs may have undergone the compaction processes, which leads to the core growth and to the reduction of the size. This result for massive galaxies is consistent with previous studies. Figure 5 reveals the relationship between the quenching of galaxies and the dust content, that is, the dust content in massive galaxies decreases with the decrease of sSFR.

The results described above give us the indication that massive QGs may have undergone a period of rapid growth, which is prominent at $z \gtrsim 1.5$. This process increases the mass surface density of the core rapidly and urges the buildup of the bulge (simultaneously reduces the size). The violent star formation activities during the process reduce the dust content by feedback effects. The results support the co-evolution model of black hole and elliptical galaxies (Hopkins et al., 2008), in which the quenching is driven by gas-rich mergers that trigger starburst, and the feedback of AGNs therefore reduces the dust content. In addition, these observational results are also well consistent with the predictions of hydrodynamical simulations (Ceverino et al., 2015; Zolotov et al., 2015; Tacchella et al., 2016). However, the low-mass QGs at $0.5 < z < 1.5$ may have different star formation histories, which will be discussed in Section 4.2 and Section 5.

### 4.2 Star formation quenching and environment

Kawinwanichakij et al. (2017) found that the efficiency of environmental quenching is approximately 5 times higher than that of mass quenching at $10^{8.8}M_\odot < M_* < 10^{9.8}M_\odot$. As suggested by Hogg et al. (2003) and Quadri et al. (2012), the lowest-mass galaxies are quenched by environment. In this Section, we focus on the quenching of satellites and centrals based on a subsample.

Fossati et al. (2017) provided a catalogue of halo mass, which gives the probability density function of the halo mass, together with the probability of being a central or a satellite for each galaxy with $HST$/$H_{F140W}$ magnitude brighter than 24 in the CANDELS deep fields. We cross match our sample with their catalogue and estimate the completeness of the resulting subsample in different redshift bins as described in Sections 2.2. The lower limits of stellar mass in four redshift bins (i.e., $0.5 < z \leq 1.0$, $1.0 < z \leq 1.5$, $1.5 < z \leq 2.0$, $2.0 < z < 2.5$) are 9.1, 9.6, 9.9 and 10.2 in logarithm, respectively. We select galaxies with stellar mass higher than the lower limits to investigate the environmental quenching. In this work, a galaxy is classified as a satellite or a central if the probability of being a satellite or a central is larger than 0.5.

We select a probability of 0.5 as the critical value of classifying satellites and centrals. This coarse manipulation may lead to the misjudgment of galaxy types. In order to more accurately determine the types of galaxies, we select a probability higher than 0.7 to distinguish satellites from centrals. We do not find significant change in terms of the results in Figure 6, although the satellites are only distributed in $0.5 < z < 1.0$. In order to select more satellites, the results in the paper are all based on the probability of 0.5 as the critical value.

The top panels of Figure 6 show the quiescent fractions of satellites and centrals in different redshift and stellar mass bins. Satellites and centrals display similar trends, an increase of the quiescent fractions with increasing stellar mass. In addition, at fixed stellar mass, the quiescent fractions of satellites are higher than those of centrals. It is expected that satellites may lose the supply of cold gas (Larson et al., 1980; Bekki et al., 2002) and become more vulnerable to environmental processes when they are accreted into a larger halo, which leads to higher
Fig. 3 $\Delta \log sSFR$ vs. $\Delta \log \Sigma_1$, split into four redshift bins and three stellar mass bins. The points are color-coded by Sérsic index. The black dotted lines in each panel show that $\Delta \log sSFR = 0$ or $\Delta \log \Sigma_1 = 0$ and the red dotted lines indicate the classification criterion of star-forming and quiescent galaxies. We label the completeness of stellar mass on the left-top in each mass-redshift bin. Note that galaxies with Sérsic index $> 4$ (excess the range of colorbar) are marked as darker color points (i.e., dark red and dark blue).

quiescent fractions. Actually, satellites do have larger halo masses than centrals. For low-mass galaxies, we find that the fraction of passive galaxies for centrals at $0.5 < z < 1.5$ is roughly $\sim 5\%$, while it is $20\%$ for satellites. The significant increase in the quiescent fraction for low-mass satellites suggests that environment plays a dominant role in quenching low-mass galaxies. The bottom panels of Figure 6 show the quiescent fraction as a function of $\Sigma_1$. The results are
Fig. 4 $\Delta \log sSFR$ vs. $\Delta \log \Sigma_1$, split into four redshift bins and three stellar mass bins. The points are color-coded by $\Delta \log r_e$. All lines and labels are the same as in Figure 3. The pink points represent the median values at a given $\Delta \log sSFR$ bins.

essentially the same as those shown by the top panels of the same figure. However, we find that the rise of the quiescent fraction with stellar mass is mild at $M_* \gtrsim 10^{10} M_\odot$, while the rise with $\Sigma_1$ is steep, especially for centrals. It indicates that $\Sigma_1$ may be a better tracer of the quenching for centrals. In our sample, we do not find satellites at high redshift ($z > 1.5$), and the quiescent fractions for centrals at $M_* \sim 10^{10} M_\odot$ (corresponding to $\Sigma_1 \sim 10^9 M_\odot \, \text{kpc}^{-2}$) are very low ($\sim 5\%$) in the two higher redshift bins. However, the fractions increase rapidly with increasing stellar mass. This strengthens our conclusion that the mass quenching dominates the quenching mechanism at earlier time. The result is consistent with that suggested by Darvish et al. (2016), who found that the quiescent fraction is correlated with the environment at
Fig. 5 The same plot as Figure 3, but this time color-coded by $A_v$.

$z \lesssim 1.0$, but correlated with stellar mass out to $z \sim 3.0$. They suggested that the environmental quenching is remarkable at $z \lesssim 1.0$, whereas the mass quenching is prominent at $z \gtrsim 1.0$ (Contini et al., 2019, 2020). Similar results have been obtained by Muzzin et al. (2012) and van der Burg et al. (2013), who found that the fraction of quiescent galaxies in groups or clusters are always higher than that in the field at similar redshift.

5 DISCUSSION

5.1 The evolutionary paths of massive galaxies

As found in Figure 2, 3 and 4, QGs at $0.5 < z < 2.5$ can be classified into two types, i.e., massive QGs and low-mass QGs, and they may be quenched by different processes (Wetzel et
Fig. 6 The quiescent fraction as a function of $M_*$ (top panels) and $\Sigma_1$ (bottom panels), color-coded by the halo mass. The circles and squares represent the median values of satellites and centrals, respectively. The black vertical lines are the binomial error of fractions (Cameron, 2011) within 90% confidence interval. The quiescent fractions for satellites at $1.5 < z < 2.5$ are not shown because of the small number statistics.

Galaxies grow along the $\Sigma_1 - M_*$ relation as revealed by the middle panels of Figure 2, which is consistent with the conclusion of Barro et al. (2017). Galaxies evolve from SFGs to massive QGs following two paths. The first is the fast growth of the core triggered by major mergers and gravitational instabilities that exhaust the cold gas reservoir rapidly (van den Bosch et al., 2008; Dekel & Burkert, 2014). This fast process leads to $\Delta \log \Sigma_1 = 1.3 \Delta \log M_*$, which means that the growth of the central surface density is faster than the growth of the stellar mass (see the Figure 5 and Figure 10 of Barro et al. (2017)). These processes occur more likely at higher redshift because of the higher gas fraction at that epoch (Daddi et al., 2010; Contini et al., 2016). Such an evolutionary path increases the central compaction (high $n$) and reduces the size of galaxies. AGN and stellar feedback during the phase may remove the dust content as found in Figure 5, and further suppress the star formation (Springel et al., 2005; Terrazas et al., 2016). The second is the smooth growth in mass and central surface density by dry (gas-poor) mergers or by secular evolution (such as the existence of bars and spiral arms, Kormendy & Kennicutt, 2004) along the $\Sigma_1 - M_*$ relation at low redshift.

The cSFGs in our sample support the evolutionary paths at high and low redshifts. We can see that these cSFGs are similar to the massive QGs in structure (large central compaction and small size), but not similar in sSFR (Genzel et al., 2008; Guo et al., 2015). In addition, the percentage of cSFGs decreases over the cosmic time, which suggests that more cSFGs are formed by the fast compaction path at higher redshift (Barro et al., 2013, 2014; Fang et al., 2015). The shutdown of star formation is related to the gas fraction. Spilker et al. (2016) found the fraction of CO to be extremely low in cSFGs, which suggests that the gas-depletion timescale is short.
The relatively low number count of cSFGs also indicates a rapid quenching process, otherwise, we would see more cSFGs.

5.2 Quenching efficiency and timescale of environment

The conversion fraction, first introduced by van den Bosch et al. (2008), is used to determine the satellite quenching efficiency. It quantifies the fraction of galaxies that are quenched prematurely by environment when a galaxy is accreted as satellite by groups/clusters (Wetzel et al., 2013; Balogh et al., 2016; Fossati et al., 2017; Kawinwanichakij et al., 2017; Pintos-Castro et al., 2019; Contini et al., 2020). The computational formula is given by

\[ f_{\text{convert}}(M_s) = \frac{f_{p,\text{group}}(M_s) - f_{p,\text{field}}(M_s)}{1 - f_{p,\text{field}}(M_s)}, \]

(4)

where \( f_{p,\text{group}}(M_s) \) and \( f_{p,\text{field}}(M_s) \) are the fractions of quiescent galaxies of a given stellar mass in groups/clusters and field (i.e., the quiescent fractions of satellites and centrals), respectively. It must be noted that Equation 4 is a simplification due to the fact that we do not consider the growth in stellar mass from the time a galaxy is central to that when it is accreted onto massive halos (see, e.g., discussions in Balogh et al., 2016; Fossati et al., 2017; Contini et al., 2020). The left panels in Figure 7 show the conversion fraction as a function of stellar mass at 0.5 < z < 1.0 and 1.0 < z < 1.5. We find that the conversion fraction increases with stellar mass at \( M_s \lesssim 10^{10} M_\odot \), while it decreases with stellar mass at \( M_s > 10^{10} M_\odot \), in agreement with the theoretical predications by Contini et al. (2020) at similar redshifts. As found in the top panel of Figure 6 at 0.5 < z < 1.0, the difference in the quiescent fraction between the satellites and centrals is comparable, while the quiescent fraction for centrals significantly increases at \( M_s \gtrsim 10^{10} M_\odot \), which causes a larger conversion fraction at higher stellar mass. This does not imply that the quenching for massive galaxies correlates more with environment than with stellar mass, but that the efficiency of environmental quenching might become weak for massive galaxies because more massive central galaxies quench their star formation preferentially via internal processes driven by stellar mass. The conversion fraction is independent of redshift and roughly \( \sim 15\% \). We find that the results are consistent with that given by Balogh et al. (2016), Fossati et al. (2017) and Contini et al. (2020) at the same stellar mass and redshift ranges.

We can convert the conversion fraction into the quenching time, which is defined as the time elapsed from the accretion of the satellites to the time the galaxy become passive (McGee et al., 2009; Mok et al., 2014). For example, the conversion fraction in lowest-redshift bin is \( \sim 0.2 \) (see the left upper panel of Figure 7), and it indicates that about 20 percent of the accreted star-forming galaxies are quenched preferentially by environmental processes. Therefore, we assume that 20 percent of galaxies have been satellites for at least \( \sim 4 \) Gyr at this redshift bin according to the formalism of Figure 5 given by Balogh et al. (2016). We define the time mentioned above as the quenching time. Note that we need to assume that the quenching time is shorter than the age of the satellite. In the conversion, we neglect the contribution of the mass accretion history and of other galaxy properties. The right panels in Figure 7 show the quenching time as a function of stellar mass. We can see that the timescales are roughly \( \sim 4 \) and 4.5 Gyr at 0.5 < z < 1.0 and 1.0 < z < 1.5, respectively. The ages of the universe are 6.6 and 5.0 Gyr at \( z \sim 0.8 \) and \( z \sim 1.2 \), respectively. Therefore, galaxies at \( z \lesssim 1.0 \), have enough time to quench the star formation when they become satellites. However, the environmental effects are weak at 1.0 < z < 1.5 because the quenching timescale is comparable to the age of the universe at \( z \sim 1.2 \). It can be used to explain the slight drop in the conversion fraction at 1.0 < z < 1.5 compared with that at 0.5 < z < 1.0. Our results indicate that the environment may play an important role in ceasing the star formation at \( z \lesssim 1.5 \).
5.3 Low-mass galaxies and environmental quenching

The low-mass QGs at $0.5 < z < 1.5$ show distinct structural properties compared to massive QGs, which suggests that there is another physical process quenching preferentially low-mass galaxies. Liu et al. (2018) studied the transition of the galaxy quenching mode at $0.5 < z < 1.0$ in CANDELS. They found that galaxies show a transition from the inside-out to the outside-in quenching mode, which depends on the stellar mass. In this work, we associate the quenching of low-mass galaxies to the environment. One of the physical explanation responsible for environmental quenching is the stripping of disk gas by ram pressure stripping (Gunn & Gott, 1972; Fillingham et al., 2016), which is expected to be more efficient for low-redshift galaxies. Wetzel et al. (2013) proposed the delay-then-rapid quenching scenario which contains two stages of gas stripping. The first stage is the depletion of hot gas reservoir, which is caused by some mild physical processes (e.g., gas cooling and gradual starvation). The second stage is the consumption of cold disk gas since the lack of shelter from the hot halo. The delay-then-rapid quenching scenario has been used also in Contini et al. (2017b, 2018) and shown to be effective in reproducing the evolution of the stellar mass function from high to low redshift and give, at the same time, reasonable predictions of the evolution of SFMS relation with redshift in agreement with observations.

If we assume that the galaxies will lose the gas supply when they become satellites, then the lower efficiency of environmental quenching at $z \gtrsim 1.0$ suggests that the timescale for gas depletion is at least $\sim 3-5$ Gyr, corresponding to the time interval from $z \sim 3-6$ to $z \sim 1$. The quenching timescale is comparable to that of cold gas-depletion timescale caused by starvation.
(Guo et al., 2017; Fossati et al., 2017). The quenching timescale shown in Figure 7 is also consistent with the gas-depletion timescale. Low-mass galaxies at high redshift do not suffer the mass quenching, and at the same time, they do not suffer the environmental processes due to low mass haloes (i.e., the low efficiency of ram pressure stripping).

Cora et al. (2019) used an improved semi-analytic model of galaxy formation in which they considered a modification in the supernova feedback and in the stripping of cold gas to study the roles played by stellar mass and environment. They found that environmental quenching plays an important role in quenching low-mass satellites, whereas mass quenching dominates the quenching of more massive galaxies. Our results support the picture where the absence of cosmological accretion and the consumption of cold gas lead to the quenching of satellites.

Environmental effects are less pronounced for massive galaxies at $z \gtrsim 1.0$ (see Figure 7), which may also originate from the random distribution of positions, although Quilis et al. (2017) found that massive satellites ($M_\star > 10^{10} M_\odot$) are closer to the halo center than less massive galaxies at $z < 0.5$. In addition, whether galaxies are affected by the environment depends on their orbits when becoming satellites (Vollmer et al., 2001). For example, galaxies with a radial orbit can suffer earlier the strong environmental effects than galaxies with a circular orbit. The lower efficiency of environmental quenching for galaxies at $z \gtrsim 1.0$ than $z \lesssim 1.0$ may arise from the locations of these galaxies. High-redshift galaxies may take longer time to pass through the halo center. With the growth of halo mass and the shortening of the distance from the center of gravity, therefore the increase of efficiency of environmental quenching at lower redshift, the quiescent fractions of satellites increase at $z \lesssim 1.0$ (see Figure 6). Peng et al. (2010) showed the transition from mass quenching at $z > 1.0$ to environmental quenching at $z < 1.0$, suggesting that the quenching mechanisms are separable at this epoch. Recent studies have also found similar results (Kawinwanichakij et al., 2017; Contini et al., 2020). At $z < 0.5$, the connection of environment and star formation quenching have been well established (Yang et al., 2009; Peng et al., 2012). On average, QGs are characterized by larger environmental richness than SFGs.

6 SUMMARY

We have studied the dependence of quenching mechanisms on stellar mass and redshift using the data at $0.5 < z < 2.5$ from CANDELS five fields. The central compaction and environment traced by $\Delta \log \Sigma_1$ and satellites (centrals) respectively, have been used to determine the evolutionary trajectory of galaxies. Our main results are as follows:

(1) We find that $\Sigma_1 - M_\star$ relation can trace the evolutionary path of galaxies out to $z \sim 2.5$. Massive QGs ($M_\star > 10^{10} M_\odot$) exhibit higher $\Delta \log \Sigma_1$ than SFGs at the same stellar mass range, and the difference between them smoothly declines with the redshift, which supports the picture where massive galaxies evolve faster and earlier than less massive galaxies ($M_\star < 10^{10} M_\odot$) due to the violent compaction processes (e.g., major mergers and disk instabilities) at higher redshift. Therefore, the fast compaction events (mass quenching) dominate the quenching of massive galaxies at earlier cosmic time.

(2) Massive QGs quenched by the fast compaction processes have larger bulges (higher $\Sigma_1$) and smaller sizes than massive SFGs. In addition, the feedback triggered by AGNs and/or supernovae might play an important role in quenching the star formation of massive galaxies. The feedback processes also disperse the dust content in galaxies.

(3) Low-mass QGs at $0.5 < z < 1.5$ show distinct structures compared to the massive QGs, which is evidence that the environmental impacts have preferentially suppressed the star formation in low-mass satellites before they become more compact. At a given stellar mass, the quiescent fraction of satellites is higher than that of centrals at $0.5 < z < 1.5$. The environmental quenching timescale is roughly $\sim 4 - 5$ Gyr if the environment begins to become important at $z \lesssim 1.5$. Therefore, to a conservative degree, environment dominates the quenching mechanism of low-mass galaxies since $z \lesssim 1.0$, and it begins to play an important role since $z \lesssim 1.5$. 
(4) The upward trend of quiescent fraction of the low-mass centrals with $\Sigma_1$ at $0.5 < z < 1.5$ is mild, while the upward trend for massive centrals is steeper. It indicates that the $\Sigma_1$ may better trace the evolution of centrals.

ACKNOWLEDGEMENTS

We acknowledge the useful suggestions and discussions with M. Fossati. We acknowledge the support from the National Key Research and Development Program of China (No. 2017YFA0402703) and by the National Natural Science Foundation of China (No. 11733002).

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Conditions for Galaxy Quenching at $0.5 < z < 2.5$

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