The Effect of Environment on Star Formation Activity and Morphology at 0.5 < z < 2.5 in CANDELS

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Abstract

To explore the effect of environment on star formation and the morphological transformation of high-redshift galaxies, we present a robust estimation of localized galaxy overdensity using a density estimator within the Bayesian probability framework. The maps of environmental overdensity at 0.5 < z < 2.5 are constructed for the five CANDELS fields. In general, the quiescent fraction increases with overdensity and stellar mass. Stellar mass dominates the star formation quenching for massive galaxies, while environmental quenching tends to be more effective for the low-mass galaxies at 0.5 < z < 1. For the most massive galaxies (M* > 10^{10.5} M_☉), the effect of environmental quenching is still significant up to z ∼ 2.5. No significant environmental dependence is found in the distributions of Sérsic index and effective radius for SFGs and QGs separately. The primary role of environment might be to control the quiescent fraction. And the morphological parameters are primarily connected with star formation status. The similarity in the trends of quiescent fraction and Sérsic index along with stellar mass indicates that morphological transformation is accompanied by star formation quenching.

Unified Astronomy Thesaurus concepts: Galaxy quenching (2040); Galaxy structure (622); Galaxy environments (2029)

1. Introduction

It is well known that the galaxies in the universe can be broadly subdivided into two classes: quiescent galaxies (QGs) with spheroidal morphologies and little star formation, and star-forming galaxies (SFGs) characterized by disk-like morphologies and intensive star formation (Strateva et al. 2001; Baldry et al. 2004). Previous studies have demonstrated that star formation activities and morphologies of galaxies are closely correlated out to z ∼ 2.5 (e.g., Strateva et al. 2001; Ball et al. 2006; Franx et al. 2008; Wuyts et al. 2011; Bait et al. 2017; Gu et al. 2018). Star formation activities and morphologies of the observed galaxies are probably the results of several complicated physical processes such as violent mergers, tidal harassment, disk instability, gas cycles, and energy feedback from active galactic nuclei (AGNs) or starbursts (Conselice 2014; Somerville & Davé 2015). In general, two major factors (internal and external) are considered to play crucial roles in the evolution of galaxies, which can change the status of galaxies from star-forming to quiescent and possibly change the appearance we observe as well (Baldry et al. 2006; Peng et al. 2010; Darvish et al. 2016; Kawinwanichakij et al. 2017). However, the physical mechanisms behind the processes of star formation quenching and morphological transformation, and how these processes change with environment and redshift, are still up for debate.

The mechanisms driven by internal physical processes are often referred to as “mass quenching” (Peng et al. 2010). Energy feedback from AGNs and supernovae are regarded as internal mechanisms that cease the star formation in galaxies by heating, expelling, and consuming gas (Larson 1974; Croton et al. 2006). A massive bulge in the center of a galaxy may help to maintain the stability of gas dynamics in the disk to avoid collapse, which is referred to as “morphological quenching” (Martig et al. 2009). The slow rearrangement of energy and mass results in internal secular evolution driving gas migration from the outskirts to the center and suppresses star formation on a long timescale (Kormendy & Kennicutt 2004).

It is known that the universe is web-like, composed of clusters, galaxy filaments, great walls, and large voids on a large scale. Besides the internal physics, it has been long established that the external environment in which galaxies reside is another crucial factor for galaxy evolution. A galaxy’s environment in the local universe is supposed to influence galaxy properties such as colors (Balogh et al. 2004; Blanton et al. 2005; Bamford et al. 2009), star formation rates (SFR) (Kauffmann et al. 2004; Peng et al. 2010), and morphologies (Dressler 1980; Goto et al. 2003; Skibba et al. 2009). Generally speaking, the galaxies residing in dense environments tend to be older, redder, more spheroidal, and less star-forming. Various physical mechanisms are commonly invoked to explain the effects driven by the galaxy environment. For example, “strangulation” refers to the mechanism whereby the ceasing of the gas supply leads to exhausting the remaining gas on a long timescale, and finally, to quiescence (Larson et al. 1980; van den Bosch et al. 2008; Peng et al. 2015). Ram pressure stripping can strip the cold gas rapidly and result in the suppression of star formation on a short timescale due to interactions between the galaxy and intracluster/group media (Gunn & Gott 1972). Similarly, the cumulative effect of many weaker encounters takes gas away from a galaxy via tidal forces, which is referred to as “galaxy harassment” (Farouki & Shapiro 1981). Mergers and strong galaxy–galaxy interactions are also assignable triggers that shape the galaxy properties fundamentally, including star formation, angular momentum, morphology, and nuclear activity (Toomre & Toomre 1972; Hopkins et al. 2008).
In the local universe, star formation activities and morphologies of galaxies are closely related to their environments (e.g., Goto et al. 2003; Baldry et al. 2006; van der Wel et al. 2007; Ball et al. 2008). Based on the Galaxy Zoo project, it is found that the morphology-environment correlation is weak at a given color, but color still strongly depends on the environment at fixed morphology (Skibba et al. 2009); and at fixed stellar mass, color is more sensitive to variations in the environment than morphology (Bamford et al. 2009). Researchers concluded that this is an excess of environment dependence on color compared with that on morphology. Bait et al. (2017) also report that the morphologies of massive galaxies are strongly correlated with specific star formation rates (SSFRs) and independent of environment, which indicates that local massive galaxies are dominated by the physical process shaping the morphology and determining the star-forming state at the same time.

Using the data from the DEEP2 galaxy survey, Cooper et al. (2007) suggest that the color–density relation is the consequence of environment effects at $z \lesssim 1.3$. From the $z$-COSMOS galaxy redshift survey, the morphology–density relation persists up to $z \sim 1$ at fixed stellar mass and becomes flatter toward the high-mass end (Tasca et al. 2009). For a given Hubble type of galaxies at $z = 0.4–0.8$, no significant evidence is found that star formation (traced by the [O II] equivalent width) depends on local environment (Poggianti et al. 2008). More recently, Paulino-Afonso et al. (2019) report a stronger dependence of morphology on stellar mass than environment at $z \sim 0.8$. Lemaux et al. (2019) estimate the timescale associated with accretion and quenching, and it is long at $0.55 < z < 1.4$, suggesting that rapid environmental processes (e.g., ram pressure stripping and galaxy harassment) may not be the primary process in this cosmic period. It is well reported that the separable effects of stellar mass and environment on galaxy properties have been observed at $z \sim 1$ (Baldry et al. 2006; Peng et al. 2010; Muzzin et al. 2012; Darvish et al. 2016). It is evidenced that gravity environment has probably already played a role in galaxy evolution in early epochs. Measuring how the star formation activities and the morphologies of galaxies change with galaxy mass, environmental density, and redshift will undoubtedly help to constrain the environmental effects on galaxy evolution as a function of cosmic epoch.

The high-$z$ clusters provide the ideal laboratories for studying the evolution of galaxies within dense environments at earlier times. Studies of the two galaxy clusters at $z > 2$ reveal that the number galaxies are mostly dominated by star-forming systems, which gives new insight into the environmental effect at early epochs (Wang et al. 2016; Darvish et al. 2020). A stronger suppression of star formation is found by Newman et al. (2014) under the environment of a cluster at $z = 1.8$. Sazonva et al. (2020) find that the galaxies in two of four clusters possess morphologies distinguishable from the galaxies in fields, but this is not the case for the other two clusters. The lack of well-defined galaxy clusters at high redshifts raises potential uncertainty and the incompleteness of quiescent galaxies haunts studies of the spectroscopically confirmed clusters or spectroscopic surveys. The discrepant results may be caused by different cosmic epochs, dynamical states of clusters, and statistical bias.

Building up a map of environmental density based on deep surveys opens up another way to investigate environmental effects. Recently, these is an increasing number of studies to quantify the environmental density up to $z \sim 2$. Fossati et al. (2017) reconstruct the density map using the projected density within a fixed aperture of $r_{ap} = 0.75$ kpc. Kawinwanichakij et al. (2017) introduce the Bayesian estimator by considering the distances to all $N$ nearest neighbors (Ivezić et al. 2005; Cowan & Ivezić 2008). Guo et al. (2017) tactfully define the projected distance between the low-mass galaxy and the nearest massive galaxies as an environmental indicator. Ji et al. (2018) investigate the possible evidence of environmental effects by measuring the small-scale angular correlation function for different types of galaxies. Chartab et al. (2020) present a weighted-kernel density estimation by adopting a von Mises kernel rather than a two-dimensional symmetric Gaussian kernel, which is more suitable in the case of spherical coordinates (e.g., Darvish et al. 2015). The different definitions of environment should describe intrinsically disparate physical meanings on different physical scales (e.g., Haas et al. 2012; Muldrew et al. 2012; Etherington & Thomas 2015).

To gain a deeper understanding of the environmental effects on galaxy evolution since cosmic noon ($z \sim 2$), in this paper, we apply the Bayesian-based method (Cowan & Ivezić 2008) with a correction to construct the overdensity maps for the five fields of the Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey (CANDELS; Grogin et al. 2011; Koekemoer et al. 2011). First, we employ the Bayesian metric as the environmental indicator which takes the distances of all the $N$ nearest neighbors into consideration (Ivezić et al. 2005), and exhibit a better performance on the density estimation. The overdensity measurements can be affected by the redshift evolution of co-moving number density due to the observation limit. To avoid this, we introduce a correction factor on the overdensity estimation which represents the intrinsic correlation between the number density and the Bayesian environmental indicators. We analyze the mass and environmental effects on star formation quenching and structural transformation. Then, we explore the environmental effects for SFGs and QGs, respectively.

The layout of this paper is as follows. In Section 2, we review the basic data from the 3D-HST and CANDELS programs. In Section 3, we present the method of the overdensity measurements. The results of quiescent fraction and morphology are shown in Sections 4 and 5. In Section 6, we further discuss the dependence of morphologies on stellar mass and environment for the star-forming galaxies and quiescent galaxies at $0.5 < z < 2.5$. The conclusion is summed up in Section 7. Throughout the paper, we employ a $\Lambda$CDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.30$, $\Omega_{\Lambda} = 0.70$.

2. Data Description and Sample Selection

2.1. Data Description

The 3D-HST and CANDELS programs provide WFC3 and ACS spectroscopy and photometry over $\sim$900 arcmin$^2$ in five fields (Grogin et al. 2011; Koekemoer et al. 2011; Skelton et al. 2014; Momcheva et al. 2016). They provide precise grism spectroscopy and photometric redshifts, which make possible to estimate the local environmental densities over the redshift range $z \sim 0.5$–2.5. Our galaxy sample is taken from the “best” redshift catalogs of the five CANDELS fields (Momcheva et al. 2016). It merges the grism-based results of CANDELS with the $H$-band-selected catalogs from Skelton et al. (2014), together
with the stellar population parameters, rest-frame colors, and SFRs. Here we give a brief description.

The “best” redshifts are organized by giving a priority as spectroscopic redshift, grism redshift, and photometric redshift. The mean uncertainty of photometric redshift in the five fields is $\Delta z/(1 + z) \approx 0.02$. The grism redshifts, with uncertainty $\Delta z/(1 + z) \approx 0.003$ in general, are more accurate than the photometric redshifts. The optimal choice is the spectroscopic redshift. When the spectroscopic redshift is not available, the secondary choice would be the grism redshift, then the photometric redshift. Once redshift is well determined, the rest-frame colors are derived from the filter response function and the best-fit template for each individual source with the EAZY code. Stellar population parameters are determined with the FAST code (Kriek et al. 2009), assuming exponentially declining star formation histories, solar metallicity, Calzetti et al. (2000) dust extinction law, and Bruzual & Charlot (2003) stellar population synthesis models with a Chabrier (2003) initial mass function. The e-folding timescale ($\tau_{G4}$) and age ($\tau_{G5}$) are regarded as the representatives of galaxy morphology. Morphology measurements are taken from van der Wel et al. (2014), in which galaxy images are fitted by assuming a single Sérsic profile with GALFIT (Peng et al. 2002). The constraints are set to limit the Sérsic index from 0.2 to 8, the effective radius from 0.3 to 400 pixels, the axis ratio from 10 to 1, and the Sérsic index from 0.2 to 8.

The rest-frame optical morphologies are depicted by the CANDELS WFC3 $J$- and $H$-band images for the galaxies at $z < 1.5$ and those at $z > 1.5$, respectively. In this work, the Sérsic index $n$ and the effective radius $r_e$ are regarded as the representatives of galaxy morphology. Morphology measurements are taken from van der Wel et al. (2014), in which galaxy images are fitted by assuming a single Sérsic profile with GALFIT (Peng et al. 2002). The constraints are set to limit the Sérsic index from 0.2 to 8, the effective radius from 0.3 to 400 pixels, the axis ratio from 10 to 1, and the Sérsic index from 0.2 to 8. The dust attenuation ($A_V$) is allowed to vary between 0 and 4 in increments of 0.1.

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The lower limit of criterion (2) is set due to the small volume of the CANDELS survey at lower redshifts, whereas the upper limit is set due to the high $M_{\text{lim}}$ at higher redshifts.

The faintest 20% of quiescent galaxies is considered to estimate the completeness limit ($M_{\text{comp}}$) with the interval of $\Delta z = 0.25$. With the typical mass-to-light ratio ($M_*/L$) for each galaxy, the stellar mass limit $M_{\text{lim}}$ at a redshift slice can be derived if their apparent magnitude equals the magnitude limit. In detail, the stellar mass limit $M_{\text{lim}}$ at a specified redshift can be derived by $\log(M_{\text{lim}}) = \log(M_*) + 0.4(H - H_{\text{lim}})$, where $H_{\text{lim}}$ is set as the magnitude limit of our sample ($H_{F160W} = 25$). Then $M_{\text{comp}}$ is defined as the upper envelope of the $M_{\text{lim}}$ distribution below which lie 90% of the $M_{\text{lim}}$ values at a given redshift. Figure 1 shows the mass completeness limit for the quiescent galaxies at four redshift bins. This method ensures the 90% completeness of quiescent galaxies at any redshift. The mass completeness limits can be parameterized as a function of redshift, $M_{\text{comp}}(z) = 9.11 + 1.34 \ln(z)$, denoted by the black line, which describes how the mass completeness limits vary from $z = 0.5$ to 2.5 (Quadri et al. 2012). To analyze the quiescent fractions and morphologies at different redshifts, we define four mass-complete subsamples at four redshift bins with the redshift interval of $\Delta z = 0.5$. We only apply 9.2, 9.6, 10.0, and 10.4 as the minimum stellar masses at the four redshift bins, which have been denoted with green lines in Figure 1.
Table 1
Calculated Limits of Stellar Mass Completeness for Quiescent Galaxies and Adopted Limits from $z = 0.5$ to 2.5

| Redshift | $M_{\text{comp}}$ | $M_{\text{adopt}}$ | $N$ | $f_{\text{phot}}$ | $f_q$ |
|----------|------------------|--------------------|-----|-----------------|------|
| 0.50–0.75 | $10^{7.58}$      | $10^{7.2}$         | 6196 | 37%             | 19%  |
| 0.75–1.00 | $10^{6.91}$      |                    |      |                 |      |
| 1.00–1.25 | $10^{7.21}$      | $10^{6.4}$         | 4262 | 38%             | 20%  |
| 1.25–1.50 | $10^{7.02}$      |                    |      |                 |      |
| 1.50–1.75 | $10^{6.90}$      | $10^{6.0}$         | 2270 | 46%             | 28%  |
| 1.75–2.00 | $10^{9.97}$      |                    |      |                 |      |
| 2.00–2.25 | $10^{10.12}$     | $10^{10.4}$        | 874  | 53%             | 28%  |
| 2.25–2.50 | $10^{10.38}$     |                    |      |                 |      |

Notes.
- a The completeness limit $M_{\text{comp}} (M_\ast)$ at the given redshift.
- b The adopted limits $M_{\text{adopt}} (M_\ast)$ with the redshift interval of $\Delta z = 0.5$.
- c The corresponding size of the mass-complete subsample $N$.
- d The photometric fraction of subsample $f_{\text{phot}}$.
- e The quiescent fraction of subsample $f_q$.

The traditional method calculates the local environmental density of quiescent populations at the four redshift bins are 19%, 20%, 46% and 53%, respectively.

3. Measurement of Environmental Overdensities

Environmental density can be traced by means of enclosed neighboring galaxies in the projected plane. The projected overdensity of galaxies is also referred to as a tracer of the local environment. The nearest-neighbor estimator corresponds to the scale of the interhalo environment (Muldrew et al. 2012). Although a pure density-based definition of the environment of galaxies (probably due to the view angles) cannot fully separate them into real physical structures, it is still an effective way to trace the most high overdensity regions (Shattow et al. 2013). In this work, we adopt a Bayesian metric (Cowan & Ivezić 2008). It is defined as

$$\Sigma_N' = \Sigma_N/(\delta_{i-1}d_i^2),$$

where $d_i$ is the projected distance toward the $i$th nearest neighbor in projected two-dimensional space of the characteristic redshift bin. The traditional method calculates the local environmental density via $\Sigma_N \propto 1/(\sigma d_N^2)$, where $d_N$ is the $N$th nearest-neighbor distance (Dressler 1980; Baldry et al. 2006). The Bayesian environmental density considers the contribution of all the first, second, ... $N$th nearest neighbors which can give improved accuracy in mapping the probability density distribution compared to the traditional method (Ivezić et al. 2005; Cowan & Ivezić 2008).

Besides the indicator of environmental density, the width of the redshift bin is the other key factor. Choosing a small width leads to a lack of galaxies which may not reflect the true projected density of a large-scale structure. Conversely, a large redshift width would bring about severe contamination in the excess signal of the high-density region by foreground and background galaxies. In this work, the calculation of local overdensity for a galaxy involves the galaxies within the individual redshift slice of $|\Delta z| = 2\sigma_z(1 + z)$. Conservatively, we adopt the uncertainty of the photometric redshift as the redshift uncertainty ($\sigma_z = 0.02$). If the probability density function of redshift follows a Gaussian distribution, the setting of $2\sigma_z$ width ensures that most members (95.4%) in the large-scale structure should be taken. But, contamination from randomly superposed galaxies with larger redshift uncertainty may dilute the density estimates to some degree. We also apply a narrower width $\pm 1.5\sigma_z (1 + z)$ as a test, and find no change in the main conclusion.

Due to the observation limit of the galaxy survey, the comoving number densities of the observed galaxies tend to be less as the redshift increases. It is foreseeable that the more galaxies are observed inside the volume, the greater the average environmental densities would be, and vice versa. Thus, we define the dimensionless overdensity, $1 + \delta_N'$, as the indicator of galaxy environment:

$$1 + \delta_N' = \frac{\Sigma_N'}{\langle \Sigma_N' \rangle_{\text{uniform}}} = \frac{\Sigma_N'}{k_N'\Sigma_{\text{surface}}},$$

where $\Sigma_{\text{surface}}$ is the surface number density in units of $\text{arcmin}^{-2}$ within the redshift slice of a given galaxy. The denominator, $\langle \Sigma_N' \rangle_{\text{uniform}}$, represents the standard of the Bayesian environmental densities when galaxies are distributed in a uniform condition at the given $\Sigma_{\text{surface}}$, where $k_N'$ is a correction factor that describes the intrinsic linear correlation between $\Sigma_{\text{surface}}$ and the standard of the Bayesian density at a given redshift (see the Appendix for details). In this way, the overdensity becomes more essential in representing the excess of galaxy density. When $\log(1 + \delta_N') > 0$, it means the environmental density for a given galaxy exceeds the density standard in the uniform condition and vice versa.

The small value of $N$ may cause fluctuation in the density values due to the Poisson noise and the redshift uncertainty of foreground and background galaxies. In this work, we use a Bayesian density estimator based on distances to all 10 nearest neighbors ($\Sigma_{10}'$) as the environmental tracers (Cowan & Ivezić 2008). Figure 2 shows the Bayesian densities $\Sigma_{10}'$ (left) and the overdensities $1 + \delta_{10}'$ (right) as a function of redshift with four quantiles. Since we consider the intrinsic relation between surface number densities and the Bayesian environmental densities, our overdensity represents the value of observed Bayesian density relative to its standard in the uniform condition at a given redshift. Therefore, the medians and ±25th percentiles of the distribution of overdensities show small amplitude variation over 0.5 < $z$ < 2.5 (see the right panel of Figure 2).

4. Quiescent Fraction

In this section, we exhibit how the quiescent fraction evolves along with stellar mass and overdensity ($1 + \delta_{10}'$) over a wide redshift range of 0.5 < $z$ < 2.5. As shown in Figure 1, the mass completeness limits as a function of redshift are denoted by the black line. To be conservative, the following results are based on the four mass-complete subsamples with the redshift interval $\Delta z = 0.5$. As discussed in Section 2.2, we only apply 9.2, 9.6, 10.0, and 10.4 as the minimum logarithms of stellar mass at four redshift bins. The adopted limits of stellar mass, seen in Table 1, are represented with the green lines in Figure 1.
4.1. Quiescent Fraction as a Function of Overdensity

In this section, we investigate the fraction of quiescent galaxies as a function of overdensity and redshift at fixed mass bins. Figure 3 shows the quiescent fractions as a function of the overdensities \(1 + \delta_{10}^i\) at different stellar mass and redshift bins. Different colors represent different mass bins: (i) \(9.2 < \log(M_*/M_\odot) < 9.6\) (blue), (ii) \(9.6 < \log(M_*/M_\odot) < 10.0\) (orange), (iii) \(10.0 < \log(M_*/M_\odot) < 10.4\) (green), (iv) \(10.4 < \log(M_*/M_\odot) < 10.8\) (red), and (v) \(\log(M_*/M_\odot) > 10.8\) (purple). The pink and cyan shaded regions mark the highest quartile and the lowest quartile of the environmental overdensities. The error bars are estimated by the bootstrap method with 1000 times resamplings.

As shown in Figure 3, the quiescent fractions change as a function of overdensity at the fixed stellar mass bin. At the lowest redshift bin \((0.5 < z < 1.0)\), quiescent fractions of galaxies are susceptible to overdensities for all stellar mass bins. A significantly higher quiescent fraction can be found in denser environments at a fixed stellar mass. The enhancements of the quiescent fraction are roughly 20\%–40\% as the \(1 + \delta_{10}^i\) changes from 0 to 0.8. Allen et al. (2016) find that the fraction of quiescent galaxies with \(> 10^{9.2} M_\odot\) increases from 33\% to 55\% from the field to the cluster core at \(z \sim 0.95\). Our results are also inconsistent with previous works (Darvish et al. 2016; Kawinwanichakij et al. 2017).

Paulino-Afonso et al. (2018) also find that the less massive galaxies \((10 < \log(M_*/M_\odot) < 10.75)\) have a jump of quenched fraction from \(~10\% to ~60\%\) at intermediate to higher density regions, but for \(\log(M_*/M_\odot) > 10.75\), they find no dependence of the quenched fraction on local density, this being nearly constant at \(~30\%\). This discrepancy may be caused by the different environmental tracers, the different selections of quiescence, and the sampling of spectroscopic observations.

Meanwhile, there are also differences between quiescent fractions of galaxies with different stellar masses. This reveals that the quiescent fraction at fixed overdensity tends to be higher for more massive galaxies. In general, the quiescent fraction of galaxies increases with both stellar mass and overdensity at \(0.5 < z < 1.0\). The limit of our sample is down to \(10^{9.2} M_\odot\) at the lowest redshift bin. Compared with the \(~30\%\) enhancements of quiescent fraction by overdensity, we find the difference is not significant in quiescent fraction between \(M_\bullet \sim 10^{9.4} M_\odot\) and \(M_\bullet \sim 10^{8.8} M_\odot\) at the fixed overdensity. On the other hand, there are clear observable signs of environmental quenching for the low-mass galaxies \((M_\bullet < 10^{10} M_\odot)\) at \(0.5 < z < 1.0\). This implies that mass quenching may not be important for the low-mass galaxies with \(M_\bullet < 10^{10} M_\odot\), compared with environmental quenching. It supports the idea that environmental quenching plays a more significant role in the truncation of star formation at
At a given stellar mass, there is a significant gap (~20%) in $f_Q$ between the galaxies in the highest and lowest overdensity quartiles. Indeed, this supports the idea that environmental quenching has played an effective role for the whole range of stellar mass considered at $0.5 < z < 1.0$. At $z > 1.0$, the gap is not statistically significant at the low-mass end between the two overdensity quartiles. However, the fractions of quiescent galaxies are found to be significantly elevated ~40% from $\sim 10^{9.8} M_\odot$ to $\sim 10^{11} M_\odot$. The median offset of $f_Q$ between the two quartiles is roughly half of that caused by stellar mass. Given that the relation between $f_Q$ and stellar mass is weak at the low-mass end (also see the left panel of Figure 3), environmental quenching tends to be more effective than mass quenching for these low-mass galaxies. According to the results above, we suppose that both mass quenching and environmental quenching are responsible for the quenching of galaxies at $0.5 < z < 1.0$, while environmental quenching tends to be more effective for low-mass galaxies.

Regardless of the galaxies in the lowest and highest-density quartiles, the mass dependence of $f_Q$ is still established out to $z = 2$. Figure 3 also illustrates that the most massive galaxies have quiescent fractions no less than the galaxies with lower mass at a given overdensity in general. This is also in agreement with Kawinwanichakij et al. (2017), who show the increasing fraction of quiescent galaxies with $>10^{10.5} M_\odot$ out to $z = 2$. Similarly, Darvish et al. (2016) find that the quiescent fraction also depends on stellar mass down to $10^{9.5} M_\odot$ at $1.5 < z < 2.0$.

This mass dependence seems to persist only for the galaxies in the highest quantile, but vanishes for the galaxies in the lowest quantile at $2.0 < z < 2.5$. In this work, no significant sign of mass dependence is found in the lowest quantile at $2.0 < z < 2.5$. However, Darvish et al. (2016) find that the quiescent fraction in the dense environment depends on stellar mass down to $10^{10} M_\odot$ at $2 < z < 3.1$ as well as in the lowest density. The cause of the discrepancies in the lowest density might be cosmic variance, how the environment is traced, and different definitions of quiescence. Larger contamination by galaxies with larger uncertainty in photometric redshift may also tend to dilute the density estimates. Larger and deeper surveys with large spectroscopic and/or photometric data sets are still needed to resolve this issue.

It is found that the galaxies in the highest quantile show an increasing trend of quiescent fraction with rising stellar mass. From another perspective, we mention above that for the most massive galaxies with $M_\star > 10^{10.8} M_\odot$, the quiescent fraction is also elevated in the denser environments at all redshifts considered. The most massive galaxies in the dense environments seem to have the highest probability of being quenched.

**Figure 4.** Quiescent fraction as a function of stellar mass at fixed overdensity and redshift bins. The hollow and solid symbols correspond to the lowest density quartile and the highest-density quartile. The error bars indicate the uncertainties based on Poisson statistics.

0.5 < z < 1.0 for low-mass galaxies, in general agreement with previous studies (e.g., Peng et al. 2010; Li et al. 2011; Sobral et al. 2011; Darvish et al. 2016; Li et al. 2019).

For galaxies at a higher redshift bin ($z > 1.0$), their quiescent fraction also changes strongly with overdensity at the highest mass end ($M_\star > 10^{10.8} M_\odot$). For the most massive galaxies, this suggests that environmental quenching still plays a role out to $z \sim 2.5$. This is generally consistent with previous works that claim the influence of dense environments on suppressing star formation still persists up to $z \sim 2.0$, (Fossati et al. 2017; Guo et al. 2017; Kawinwanichakij et al. 2017; Ji et al. 2018; Chartab et al. 2020). Interestingly, the quiescent fraction for the highest-density bin is unusually high at $2 < z < 2.5$ compared to all the other samples. This might be simply because of cosmic variance. However, the “downsizing” scenario also suggests that quenching for the more massive galaxies might happen earlier, in agreement with the quiescent fraction for the highest-density bin at $2 < z < 2.5$. For the most massive galaxies, the quiescent fraction is also elevated in denser environments at all redshifts considered. The most massive galaxies in the dense environments seem to have the highest probability of being quenched.

The hollow and solid triangles correspond to the lowest and the highest overdensity quartiles, respectively.

**4.2. Quiescent Fraction as a Function of Stellar Mass**

It has been shown that the fraction of quiescent galaxies is also a function of stellar mass (e.g., Baldry et al. 2006). In this section, we investigate how the fraction of quiescent galaxies varies with stellar mass and redshift. Figure 4 shows the quiescent fractions of galaxies in the lowest and highest-density quartiles as a function of stellar mass at different redshift bins. The hollow and solid triangles correspond to the lowest and the highest overdensity quartiles, respectively.

The cause of the discrepancies in the lowest density might be cosmic variance, how the environment is traced, and different definitions of quiescence. Larger contamination by galaxies with larger uncertainty in photometric redshift may also tend to dilute the density estimates. Larger and deeper surveys with large spectroscopic and/or photometric data sets are still needed to resolve this issue.

It is found that the galaxies in the highest quantile show an increasing trend of quiescent fraction with rising stellar mass. From another perspective, we mention above that for the most massive galaxies with $M_\star > 10^{10.8} M_\odot$, the quiescent fraction is also elevated in the denser environments at all redshifts considered. The most massive galaxies in the dense environments seem to have the highest probability of being quenched.
The “downsizing” scenario points to quenching for the most massive galaxies being accomplished on a very short timescale (Cowie et al. 1996). It is likely that both the mass and environment quenching mechanisms play important roles in the quenching of the most massive galaxies. Halo quenching might be an alternative mechanism where the massive host halo ($M_{\text{host}} > 10^{12} M_\odot$) heats the infalling cold gas via shocks (e.g., Birnboim & Dekel 2003). The “overconsumption” model combines the effects of gas supply disruption (i.e., starvation) and gas consumption via star formation and outflow (McGee et al. 2014; Balogh et al. 2016), which could also explain the quenching of the most massive galaxies at high redshifts.

5. Morphologies of Galaxies

The galaxy morphology is another entry point into investigating the environmental effects of galaxy evolution. Environmental processes have been proposed to play a crucial role in the formation of galaxy morphology (Conselice 2014; Somerville & Davé 2015). In this work, the Sérsic index $n$ and effective radius $r_e$ are adopted as the representatives of galaxy morphologies.

We aim to investigate how Sérsic index and effective radius change with stellar mass, overdensity, and redshift. Figure 5 shows the median values of Sérsic indices and effective radii as functions of stellar mass in different environments. The hollow and solid symbols correspond to the lowest and the highest overdensity quartiles, respectively. The bars represent 1σ errors which are estimated by the bootstrap method with 1000 times resampling.

The variation of quiescent fraction with stellar mass closely resembles the median Sérsic index as a function of stellar mass. At the lowest redshift bin ($0.5 < z < 1.0$), stellar mass dominates the growth of the Sérsic index. As stellar mass increases, the median values of Sérsic indices in different environments tend to increase in general. This points to the idea that continuous assembly of stellar components in a galaxy could result in growth of the central bulge, which leads to gas consumption and star formation quenching. For the low-mass galaxies at $0.5 < z < 1.0$, however, the quiescent fraction increases faster from the lowest to highest overdensities while the median Sérsic index remains constant. The change in quiescent fraction is faster than the change in galaxy Sérsic index toward the low-mass end. This indicates that some low-mass galaxies quenched by some environmental processes (e.g., ram pressure stripping, strangulation) would retain the morphologies of their star-forming progenitors (Gunn & Gott 1972; Larson et al. 1980). Massive quiescent galaxies prefer to reside in the high-density environment. Additionally, the divergence between the median values of $n$ for the lowest and highest-density quartiles is slight at the low-mass end. The divergence seems to be enlarged toward the high-mass end. For our mass-limited subsample at $0.5 < z < 1.0$, the high-density environment can enhance Sérsic indices of the galaxies at $0.5 < z < 1.0$, particularly for massive galaxies.

At higher redshifts ($z > 1.0$), the divergences tend to be smaller compared with those at $0.5 < z < 1.0$. This shows that the environmental influence on the Sérsic index is negligible. As for $z > 1$, there is no statistically significant difference (given the error bars) between two overdensity quarters. However, there is evidence that the quiescence of the galaxies still relies on stellar mass at $z > 1.0$. For our mass-limited subsamples, the overall changes driven by mass at $z > 1.0$ are weaker than those at $0.5 < z < 1.0$. Therefore, the bulge growth (i.e., increase of Sérsic index from 1 to 4) is mainly driven by stellar mass. The enhancement of Sérsic indices by stellar mass is stronger than the environmental influence, even at the lowest redshift bin.

According to the bottom panels of Figure 5, the median size shows a weak dependence on stellar mass at $0.5 < z < 1.0$. For our mass-limited subsample at $0.5 < z < 1.0$, the sizes of the galaxies in dense environments are slightly smaller as a whole, except for the most massive galaxies. For our mass-limited
subsamples at $z > 1$, no obvious evidence of environmental and mass effect on galaxy size can be found.

6. Discussion

The activity of star formation should be the most direct and intrinsic difference between SFGs and QGs. Cooper et al. (2007) conclude that the color–density relation is the consequence of environment effects for the preference of red galaxies in dense environments at $z \lesssim 1.3$. Evidence of environmental quenching also is provided by the decreasing SFR from the outskirts to the center of a distant cluster or from low overdensity to high overdensity (Muzzin et al. 2012; Darvish et al. 2016). The SFR–density trend of a mixed sample may reflect a change in the quiescent fraction rather than a change in SFRs (Patel et al. 2009). As more QGs are found in high-density regions, this finding is compatible with the results that the SSFRs of SFGs are independent of environment at fixed stellar mass (Muzzin et al. 2012; Darvish et al. 2016). Color might be primarily dependent on stellar mass. Once the mass is fixed at $\log(M_\star/M_\odot) > 10.7$, the color–density relation is flatter globally (Cuccia et al. 2010). These relevant works suggest that the primary role of environment is to control the quiescent fraction. Stellar mass might be the primary predictor of star formation.

The morphology–density relation may also be controlled by the change of the ratio between red and blue galaxies. Similar to the SSFR–density relation, it is found that the morphology–density relation in the local universe implies that the environment can also shape the morphologies of galaxies (Dressler 1980; Goto et al. 2003; Bamford et al. 2009; Skibba et al. 2009), which still maintains at higher redshift (van der Wel et al. 2007; Tasca et al. 2009; Kovač et al. 2010; Nantas et al. 2013; Allen et al. 2016; Krywult et al. 2017; Paulino-Afonso et al. 2019). By a mean SFR for each morphology types, Poggianti et al. (2008) predict the SFR-density relation by using the morphology–density relation (the fractions of the morphological types as a function of density). The equivalence of the two relations suggests that neither of two is more fundamental than the other. By assuming a constant value of Sérsic index ($n = 1$ for SFGs, and $n = 4$ for QGs), Paulino-Afonso et al. (2019) predict that the overall trends of $n$ depends on stellar mass and environment, which is different in approach but equally satisfactory in result.

Based on the overdensity maps derived by the Bayesian metric for the five CANDELS fields, the large size and wide redshift coverage of our sample facilitates investigating the environmental effect on quiescent faction and morphology. We further explore the environmental effect on galaxy morphologies by splitting galaxies into SFGs and QGs. In this work, we only compare morphologies of galaxies as a function of stellar mass in two density quarters.

In Figure 6, the median values of Sérsic indices and effective radii are shown as a function of stellar mass at fixed overdensity and redshift bins. We also overlap the two general relations (Lang et al. 2014; van der Wel et al. 2014). For the mass–$n$ relation from Lang et al. (2014), the median values of $n$ as a function of stellar mass are also presented at $0.5 < z < 1.5$ and $1.5 < z < 2.5$. For the mass–size relations from van der Wel et al. (2014), the median values of $r_e$ for QGs and SFGs are denoted by the black dashed and solid lines. In addition, the size–mass relation for SFGs and QGs (Allen et al. 2016) are also overlapped by green and magenta lines, with cluster galaxies within 0.5 virial radius and field galaxies denoted by dashed–dotted and dot lines. The size–mass relation for QGs at $z = 1.8$ in field from Newman et al. (2014) are also presented as a yellow dotted line.

The environmental influence on galaxy morphologies for SFGs and QGs at high redshifts is still discrepant. Bassett et al. (2013) find that quiescent galaxies in the outskirts of a cluster at $z \sim 1.6$ have smaller Sérsic indices, compared to the field galaxies.
whereas the SFGs in clusters and fields show no difference in morphology. However, Allen et al. (2016) find that the cluster SFGs within 0.5 virial radius at $z = 0.92$ have a higher fraction of Sérsic indices with $n > 1$ than field SFGs. But for QGs, it is consistent in Sérsic index, $n \sim 2$ regardless of the distance from the cluster center. Regardless of the structural difference between SFGs and QGs, Saizonova et al. (2020) find that the member galaxies in two of four clusters at $z \sim 1.45$ possess structural parameters indistinguishable from the galaxies in fields. But more bulge-dominated galaxies are found in the other two clusters at $z \sim 1.2$ and 1.8, compared with the galaxies in fields. This points out that the morphology–density relationship happens at $z = 1.75$ although there is a significant degree of intracluster variance. Recently, it was concluded that stellar mass is a stronger predictor of galaxy structure and morphology than local density from the VIMOS Spectroscopic Survey of a Supercluster (VISCO) at $z \approx 0.84$ (Paulino-Afonso et al. 2019). They re-produced the overall trend of $n$-density relation by $f_{G}$–density relation which suggests that the environmental effects mainly control quiescent fraction (e.g., Darvish et al. 2016). In this work, no significant mass dependence of $n$ is found at higher redshift ($1.5 < z < 2.5$), but for the quiescent galaxies in dense environments at lower redshifts ($0.5 < z < 1.5$), it is striking that the median of Sérsic indices tends to increase with stellar mass. There is only weak evidence at $0.5 < z < 1.0$ that massive QGs (or SFGs) in the highest-density environments have larger Sérsic indices, which is also reported by Kawinwanichakij et al. (2017). Beyond that, there is no statistically significant difference of Sérsic indices between SFGs (or QGs) in two different environments.

As to the environmental influence on galaxy size, the results are also highly disputed due to the limited numbers of (proto-) clusters and member galaxies over $z > 1$ (Overzier 2016). It is reported that cluster QGs at $z \sim 1.6$ have larger average effective sizes than field galaxies at fixed mass (Papovich et al. 2012; Bassett et al. 2013). However, Newman et al. (2014) find that the quiescent member galaxies at $z = 1.8$ follow the size–mass relation in fields with a systematic difference $\sim 0.01$. Allen et al. (2016) report that the observed effective radii of SFGs in the field are 16% larger than those in the cluster center, but find no significant difference for QGs. This comparison between field and cluster galaxies with 0.5 virial radius at $z = 0.92$ is shown panel (e) of Figure 6. It is also reasonable since the environmental effects on galaxy morphologies may only happen in the centers of clusters. In this work, our work is limited to the two density quarters (the highest and the lowest). There is only weak evidence that the effective radii of QGs in the highest quartile are larger than those in the lowest quartile, compared with the mass dependence of sizes for QGs. Thus, we conclude that there is no significant evidence showing a difference in effective radii between QGs (and SFGs) in two different environments. But the median radius of galaxies in the highest quartile is found to be slightly smaller than those in the lowest quartile in Figure 5. In the bottom panels of Figure 6, the different size–mass relations for QGs and SFGs show that the sizes of SFGs are larger than those of QGs. Meanwhile, the quiescent fraction of the galaxies in the highest quarter are found to be slightly larger than those in the lowest quarter. Considering QGs having smaller sizes systematically, this “trap” should be caused by a higher quiescent fraction in denser environment.

It can be seen that the galaxy morphological parameters ($n$ and $r_{e}$) as functions of stellar mass are distinctly largely different between SFGs and QGs. SFGs usually have larger sizes and are dominated by disk structures, whereas QGs are bulge-dominated and have smaller sizes (e.g., Lang et al. 2014; van der Wel et al. 2014). Considering the intrinsic difference in morphology between SFGs and QGs, the overall distributions of Sérsic indices ($n$) and effective radii ($r_{e}$) should be naturally contributed by two major galaxy populations (SFGs and QGs) at different redshifts.

For QGs and SFGs separately, no significant dependence of morphologies on environmental density is found at $0.5 < z < 2.5$ compared with the intrinsic difference. In other words, there is no obvious evidence that the morphological differences are caused by environmental processes. There is also evidence that morphological transformation is accompanied by star formation quenching, which is consistent with the results in Pandya et al. (2017) and Gu et al. (2018). Thus, we conclude that galaxy morphologies are primarily relevant to the status of star formation quenching. Stellar mass is also an important factor relevant to the sizes of galaxies at $0.5 < z < 2.5$, which is in agreement with previous work (Lang et al. 2014; van der Wel et al. 2014). For the Sérsic indices of galaxies, we only find that the mass dependence at $0.5 < z < 1.5$. At $1.5 < z < 2.5$, Sérsic indices are not sensitive to stellar mass. There is no obvious evidence that the morphological differences are influenced by some environmental processes. Statistically, the quiescent fraction in a sample is conclusive for the distributions of size and Sérsic index.

### 7. Conclusion

In this paper, we present a robust estimation of local galaxy overdensity using a density estimator within the Bayesian probability framework. We build up a map of environmental overdensity in five CANDELS fields across the redshift range $0.5 < z < 2.5$. Then we explore the mass and environmental dependence of quiescent fractions and galaxy structural parameters of the galaxies.

The main conclusions are the following.

1. Stellar mass is the dominant factor driving star formation quenching of massive galaxies at higher redshifts ($z > 1$) while environmental quenching tends to be more effective for low-mass galaxies $\log(M_{*}/M_{\odot}) < 10.0$ at lower redshifts ($z < 1$).
2. For the most massive galaxies with $\log(M_{*}/M_{\odot}) > 10.8$, the effect of environmental quenching is still significant up to $z \sim 2.5$.
3. It is also found that galaxy morphologies are primarily correlated with star formation status. There is no significant evidence that morphologies are dependent on environmental density.
4. The distributions of quiescent fractions and Sérsic indices along with stellar mass are generally similar. We consider that the quiescent fraction is conclusive for the distributions of galaxy sizes and Sérsic indices. This indicates that morphological transformation is accompanied by star formation quenching.

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Appendix

Derivation of Environmental Overdensity

In order to normalize the estimator within the Bayesian probability framework, $\Sigma'_{N}$, into a dimensionless environment indicator, we define the overdensity as

$$1 + \delta'_{N} = \Sigma'_{N} / \langle \Sigma'_{N} \rangle_{\text{uniform}},$$

(A1)

where $\Sigma'_{N}$ is the Bayesian indicator of environmental density, and $\langle \Sigma'_{N} \rangle_{\text{uniform}}$ represents its standard in the uniform condition. It is important to establish the conversion relation between $\langle \Sigma'_{N} \rangle_{\text{uniform}}$ and the surface number density $\Sigma_{\text{surface}}$ for the five CANDELS fields.

A simple simulation is made to realize that the galaxies just follow a uniform distribution with a given surface density. For each field of CANDELS, we randomly drop the galaxies into real sky coverage, and the galaxies are uniformly distributed. In practice, we make 8 different uniform maps containing different numbers of galaxies, ranging from 300 to 1700, for each field of CANDELS survey. The Bayesian density estimator, $\Sigma'_{N}$, is then calculated for each galaxy in the simulated uniform map. The median value of the Bayesian densities $\Sigma'_{N}$ of all simulated galaxies can be adopted as the typical value of the overall density indicator in the uniform condition, $\langle \Sigma'_{N} \rangle_{\text{uniform}}$. Figure A1 shows the relations between the surface number density $\Sigma_{\text{surface}}$ and the typical degree of environmental indicator $\langle \Sigma'_{N} \rangle_{\text{uniform}}$, with variable numbers of the nearest neighbors adopted ($N=3, 5, 7, 10$). There is a clear trend that the typical value of the density estimator in the uniform condition is proportional to the given surface number density, i.e., $\langle \Sigma'_{N} \rangle_{\text{uniform}} \propto \Sigma_{\text{surface}}$. We introduce a scale factor, $k'_{N}$, and the best-fitting relation can be simply formalized as $\langle \Sigma'_{N} \rangle_{\text{uniform}} = k'_{N} \times \Sigma_{\text{surface}}$.

Based on the above intrinsic linear relation, we propose a new method to estimate the overdensity at a given redshift bin. For each galaxy, we can convert the Bayesian density estimator into the dimensionless overdensity by

$$1 + \delta'_{N} = \Sigma'_{N} / k'_{N} \Sigma_{\text{surface}},$$

(A2)

where $\Sigma_{\text{surface}}$ is the surface number density for the given redshift slice. For each galaxy, we can easily derive the typical value of the Bayesian density indicator, $\langle \Sigma'_{N} \rangle_{\text{uniform}}$, from the surface number density of the given redshift slice.

It has been proven that our determination of overdensity, based on the Bayesian density estimator, is competent to trace the structures at high redshifts. Recently, Galametz et al. (2018) presented a large-scale galaxy structure Cl J021734-0513 at $z \sim 0.65$, containing ~20 galaxy groups and clusters, which is located in the CANDELS/UDS field. The cluster candidates (“C”, followed by a numerical index) are listed in Galametz et al. (2018), (e.g., C1, which is the main component of a reported large-scale structure). The cluster candidates are well detected in Figure A2. Compared to the other cluster candidates, the component C6 exhibits the relative lowest signal of overdensities. Although this large-scale structure is mainly composed of fainter galaxies which are excluded by the magnitude cut, its overdensity value (C6), denoted by the leftmost arrow, is still perceptible. In addition, there is an well known structure, CIG 0218.3-0510, at $z = 1.62$ in the UDS fields, reported by Papovich et al. (2010). As shown in the right panel, our overdensity map has a good performance in tracing the high-$z$ clusters.
Figure A2. Top: distribution of $1 + \delta'_0$ in the typical redshift slice. The red arrow shows the peak value of the overdensity $1 + \delta'_0$ in these known structures. Bottom: spatial distribution of the galaxy sample in two typical redshift slices. Points are color-coded by their overdensity. The rough locations of the known structures (groups/clusters) in the CANDLES/UDS field (Left: CIJ01734-0513 at $z \sim 0.65$; Galametz et al. (2018); Right: CIJ02182-0510 at $z \sim 1.62$, Papovich et al. 2010) are highlighted with red circles. Notice that the size of these circles is $1'$ and has nothing to do with the scale of the known structures.

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