Connecting Compact Star-forming and Extended Star-forming Galaxies at Low Redshift: Implications for Galaxy Compaction and Quenching

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Received 2018 May 23; revised 2018 August 16; accepted 2018 August 17; published 2018 September 20

Abstract

Previous findings show that the existence of dense cores or bulges is the prerequisite for quenching a galaxy, leading to a proposed two-step quenching scenario: compaction and quenching. In this scenario, galaxies first grow their cores to a stellar mass surface density threshold, and subsequently quenching occurs, suggesting that galaxies evolve from extended star-forming galaxies (eSFGs), through compact star-forming galaxies (cSFGs), to a quenched population. In this work, we aim at examining the possible evolutionary link between eSFGs and cSFGs by identifying the trends in star formation rate (SFR), gas-phase metallicity, and H1 content, since one would naturally expect that galaxies evolve along the track of cold gas consumption and metal enhancement. We select a volume-limited sample of 15,933 galaxies with stellar mass above $10^{10.5} M_\odot$ and redshift of 0.02 < z < 0.05 from the NASA Sloan Atlas catalog within the ALFALFA footprint. The cSFGs on average exhibit similar or slightly higher SFRs of ~0.06 dex and significantly higher gas-phase metallicity (up to 0.2 dex at low mass) with respect to the eSFGs, while the cSFGs dominate the galaxy population of the most intense star formation activities. More importantly, overall the median H1 content and gas depletion time of cSFGs are about half of eSFGs. Our result supports the compaction and quenching scenario that galaxies evolve and grow their cores along the track of cold gas consumption and metal enhancement. The environments of eSFGs and cSFGs are indistinguishable, suggesting that the compaction process is independent of any environmental effects at least for the low-redshift universe.

Key words: galaxies: general – Galaxy: evolution – methods: observational

1. Introduction

The bimodality of color or star formation rate (SFR) for galaxies has been found in decades by large imaging and spectroscopic surveys (e.g., Strateva et al. 2001; Baldry et al. 2004; Bell et al. 2004; Blanton et al. 2005; Faber et al. 2007; Wetzel et al. 2012). Galaxies thus are naturally separated into two populations: the star-forming (SF) galaxies and quenched galaxies (QGs). The typical SF galaxies are actively forming stars with prominent disk-like morphology, whereas the QGs usually have no on-going star formation with pronounced spheroid-like morphology (e.g., Strateva et al. 2001; Kauffmann et al. 2003; Baldry et al. 2004; Brinchmann et al. 2004; Li et al. 2006; Muzzin et al. 2013; Barro et al. 2017; Wang et al. 2018b). Deep narrow-field surveys show that this bimodality persists up to a redshift of 2.5 (e.g., Bundy et al. 2006; Brammer et al. 2009; Huang et al. 2013), and the prevalence of a quenched population has dramatically increased since a redshift of 1 (e.g., Muzzin et al. 2013; Tomczak et al. 2014), indicating that quenching is one of the major themes in galaxy evolution over the past 8 Gyr. However, how SF galaxies become quenched is still not well understood.

Many theoretical processes have been proposed to explain the star formation quenching, which can mainly be categorized into two classes: the internal processes and external processes. The feedback from starbursts and active galactic nuclei (AGNs; McNamara et al. 2000; Nulsen et al. 2005; McNamara & Nulsen 2007; Dunn et al. 2010; Fabian 2012; Cicone et al. 2014) belongs to the former class and acts to heat the surrounding gas and/or strip the cold gas away from host galaxies. Another example of an internal process is so-called “morphological quenching” (Martig et al. 2009), i.e., the presence of a dominant bulge stabilizes the gas disk against gravitational instabilities needed for star formation. The external processes include a series of the environmental effects, such as major/minor mergers (e.g., Conselice et al. 2003; Cox et al. 2006; Smethurst et al. 2015), tidal/ram pressure stripping (Gunn & Gott 1972; Moore et al. 1996; Abadi et al. 1999; Poggianti et al. 2017), shock-excited heating (e.g., Rees & Ostriker 1977; Birnboim & Dekel 2003; Kereš et al. 2005; Cattaneo et al. 2006), and strangulation (e.g., Weinmann et al. 2009; Peng et al. 2015; van de Voort et al. 2017), which act to either rapidly consume and/or expel the cold gas or prevent the cold gas accretion. However, some of these internal processes may be closely related to environmental effects, which makes the star formation cessation picture rather complicated. For instance, the AGN activities can be triggered by galaxy–galaxy interactions or mergers (Urrutia et al. 2008; Ellison et al. 2011; Kocevski et al. 2012; Satyaapal et al. 2014). Since all the quenching mechanisms are working on the cold gas of galaxies, understanding the cold gas content in galaxies is essential to uncovering the stage of galaxy evolution along the track of star formation quenching. Observationally, the link between quenching and structural properties has gained attention. Many works have proposed that a massive bulge is the key factor for quenching star formation in local galaxies (e.g., Bell et al. 2012; Cheung et al. 2012; Wake et al. 2012; Fang et al. 2013; Bluck et al. 2014, 2016). For instance, Fang et al. (2013) found that the existence of a dense bulge is necessary but not sufficient to
quench a galaxy by analyzing the stellar surface density profiles for SF and quenched central galaxies. More recently, by applying an artificial neural network approach for pattern recognition of quiescent systems on \( \sim 400,000 \) central galaxies taken from the Sloan Digital Sky Survey (SDSS), Teimoorinia et al. (2016) argued that the central velocity dispersion, bulge mass, and bulge-to-total stellar mass ratio are excellent quenching predictors, indicating that properties related to the central mass of the galaxy are most closely linked to the star formation cessation. The link between quenching and structural properties has also been established for high-redshift galaxies (e.g., Tacchella et al. 2015; Barro et al. 2017). The fundamental structural differences for SF and quiescent galaxies are presented in the mass–size relation of different redshifts (e.g., Toft et al. 2007; Williams et al. 2010; Newman et al. 2012; van der Wel et al. 2014; Shibuya et al. 2015), where quiescent galaxies always exhibit a much higher stellar surface density than SF galaxies. These suggest that SF galaxies must grow dense cores before quenching.

Recently, a two-step star formation quenching scenario has been proposed: compaction and quenching (e.g., Fang et al. 2013; Dekel & Burkert 2014; Tacchella et al. 2015, 2016a, 2016b; Barro et al. 2017). The term “compaction,” as used in the present work, can be caused by the shrinkage of galaxies with radial migration of stars and/or the growth of the cores or bulges without a significant change in overall radius (see Section 3.1 for details). Under this scenario, in the high-redshift universe, the extended SF galaxies first contract via a dissipative process to lose energy and angular momentum, such as a major merger, accretion of counterrotating streams, or recycled gas, usually associated with violent disk instability (Dekel & Burkert 2014; Zolotov et al. 2015), subsequently become compact SF galaxies, and then consume and/or lose their cold gas and turn into quiescent galaxies as a whole. In the low-redshift universe, the compaction of extended SF galaxies may be via a minor merger, interaction with neighboring galaxies, and/or bar-driven secular evolution to form the compact SF galaxies (e.g., Moore et al. 1996, 1998; Bournaud et al. 2007; Di Matteo et al. 2007; Wang et al. 2012; Barro et al. 2017; Lin et al. 2017). Observationally, there are indicative identifications of the progenitors of the compact quiescent galaxies in the form of compact SF galaxies, whose masses, kinematics, and morphologies resemble those of the compact quiescent galaxies (Barro et al. 2013, 2014; Bruce et al. 2014; Nelson et al. 2014; Williams et al. 2014) but appear to be different from other SF galaxies that have irregular or clumpy features. However, whether the extended SF galaxies are necessarily quenched through compaction, how the compaction process occurs, and what happens in this process are still poorly understood.

In this paper, we aim at testing the two-step quenching scenario, by comparing the extended SF galaxies and compact SF galaxies to find whether there are any clues for the supposed evolution from eSFGs and cSFGs under the two-step quenching scenario. Following the work of Fang et al. (2013), we use the stellar surface mass density within a radius of 1 kpc, \( \Sigma_{1kpc} \), to quantify the growth of bulges as galaxies evolve. They have presented the existence of a \( \Sigma_{1kpc} \) threshold, above which galaxies begin to shut down their star formation. This result persists up to at least a redshift of 3 (Barro et al. 2017; Mosleh et al. 2017; Whitaker et al. 2017). While there is also a significant fraction of SF galaxies with \( \Sigma_{1kpc} \) greater than the threshold, studying their properties and connecting them with extended SF galaxies would probably shed light on the process of compaction and quenching. Thus, in this work, we select the sample from the NASA Sloan Atlas and separate them into extended SF galaxies and compact SF galaxies\(^5\) according to the \( \Sigma_{1kpc} - M_\ast \) diagram. Although the sample galaxies we selected are limited to the low-redshift universe, this enables us to present a detailed investigation of the chemical abundance, the H\(\text{I}\) content, and the environment for eSFGs and cSFGs, and further to examine whether there is a trend for cold gas consumption and metal enhancement from eSFGs to cSFGs.

This paper is structured as follows. In Section 2, we present the details on sample selection and the definition of extended SF and compact SF galaxies, as well as the description of relevant physical parameters. In Section 3, we investigate the SFRs, gas-phase metallicities, H\(\text{I}\) detection rate, and environments as a function of stellar mass for extended SF and compact SF galaxies. In Section 4, we discuss the gas depletion time along the star formation main sequence, the prevalence of AGNs for the two populations, and the implications for our results. We summarize the results in Section 5. Throughout this paper, we assume a flat cold dark matter cosmology model with \( \Omega_m = 0.3, \Omega_\Lambda = 0.7, \) and \( h = 0.7 \) when computing distance-dependent parameters.

2. Data

2.1. Sample Selection

Our galaxy sample is selected from the NASA Sloan Atlas (NSA),\(^6\) which is a galaxy catalog constructed by Blanton et al. (2011) listing physical parameters for more than 640,000 local galaxies based on data from GALEX, SDSS, and the Two Micron All Sky Survey. We select the galaxy sample to locate in the ALFALFA\(^7\) (Arecibo Legacy Fast ALFA Survey; Giovanelli et al. 2005; Haynes et al. 2011) footprint. Thus, the H\(\text{I}\) mass of galaxies can be obtained. The left panel of Figure 1 shows the ALFALFA galaxy sample (small red dots) overlapped on the NSA footprint, indicated by all the individual galaxies (small black dots). Here we only use the galaxies of the northern galactic cap from the 70% ALFALFA catalog, since the southern galactic cap of ALFALFA has little overlap with the NSA footprint. The blue solid lines show the boundaries of the ALFALFA footprint, and 258,938 NSA galaxies are within the boundaries.

The right panel of Figure 1 presents the stellar mass and redshift relation for the NSA sample within the ALFALFA footprint. According to this relation, we select a volume-limited sample with a stellar mass greater than \( 10^{10.5} M_\odot \) and a redshift of \( 0.02 < z < 0.05 \) to avoid the Malmquist bias, denoted by blue lines. The upper limit of redshift is selected by considering the redshift range of ALFALFA (\( z < 0.06 \)), and the lower limit of the stellar mass is selected to include more galaxies. In addition, we exclude the highly inclined galaxies with a minor-to-major axis ratio of less than 0.5 to reduce the influence of the inclination effect on the measurements of \( \Sigma_{1kpc} \) (Fang et al. 2013). According to the above criteria, in total 17,609

\(^5\) This definition of compact SF galaxies differs from previous works, where “compact” is an absolute term to identify the smallest galaxies (e.g., van Dokkum et al. 2015).

\(^6\) http://www.nsatlas.org/

\(^7\) http://egg.astro.cornell.edu/index.php/
2.2. Physical Properties of Galaxies

The MPA-JHU catalog provides the measurements of the main physical parameters used in this work, including SFR, gas-phase metallicity, and the relevant emission-line fluxes. The SFRs are measured by an updated version of the method of Brinchmann et al. (2004) using the Kroupa initial mass function (Kroupa & Weidner 2003). The measurements of gas-phase metallicity are estimated using the Charlot & Longhetti (2001) model, taken from Tremonti et al. (2004). The stellar masses are drawn from the NSA catalog. The surface mass density within a circular aperture of radius 1 kpc, denoted as $\Sigma_{1\text{kpc}}$, is calculated by directly integrating the light profiles from the innermost point out to 1 kpc, adopting the relation between $M_g/L_i$ (stellar mass divided by $i$-band luminosity) and the rest-frame $g - i$ color from Fang et al. (2013): $\log M_g/L_i = 1.15 + 0.79 \times (g - i)$. In practice, we generate the cumulative flux profile at a series of radii and obtain the total flux within 1 kpc by the cubic spline interpolation for the two bands, based on the azimuthally averaged radial surface brightness profile (also known as $\text{ProfMean}$ in the output of the SDSS pipeline). The $i$-band luminosity and $g - i$ color are corrected to the rest frame (Blanton & Roweis 2007) considering the galactic extinction (Schlegel et al. 1998). Our sample is selected to have a redshift of less than 0.05, where the half-width at half-maximum of the SDSS point-spread function (0.7") is comparable to the aperture of 0.68 kpc. This indicates that the seeing should not heavily affect the reliability of measurements of $\Sigma_{1\text{kpc}}$ (see more details in Fang et al. 2013). Although the main result in this work is presented based on the $\Sigma_{1\text{kpc}}$, we have also adopted the stellar mass surface density within the effective radius to reproduce the main result and find that our result still holds (see Appendix A). This indicates that our result is not sensitive to the definition of the compactness of galaxies.

Since only the most H I-rich galaxies have been detected in 21 cm emission, we adopt an H I mass estimator for the galaxies unmatched with ALFALFA, using the formula of Catinella et al. (2010): $\log_{10} M_{\text{HI}}/M_\odot = -0.332 \times \mu_{b,z} - 0.240 \times (\text{NUV} - r) + 2.856$, where $M_{\text{HI}}$ is the H I mass of galaxies, $\mu_{b,z}$ is the stellar mass surface density, computed using the half-light radius of SDSS $z$-band images, and NUV $-r$ is the color between near-UV and SDSS $r$ band. This relation is calibrated using the GASS (the GALEX Arecibo SDSS Survey; Catinella et al. 2010) sample with a scatter of $\pm 0.3$ dex and suggests that galaxies with higher $\mu_{b,z}$ and redder NUV $-r$ color appear to be more H I deficient (Brown et al. 2015). Li et al. (2012) have found that this relation generally works well but underestimates the $M_{\text{HI}}$ mass for the most H I-rich galaxies with $\log_{10} M_{\text{HI}}/M_\odot > 0.0$. However, this should not be a concern, since the most H I-rich galaxies have the observed H I mass from ALFALFA and our purpose is to make a comparison of compact SF and extended SF galaxies.

We quantify the galaxy environment by using two independently derived parameters: the host halo mass and the local overdensity of galaxies. The host halo masses are derived from the SDSS DR7 (Abazajian et al. 2009) group catalog of Yang et al. (2007), which is based on a halo-based group-finding algorithm developed in Yang et al. (2005). The local overdensity ($\delta$) is defined as $\delta = \rho/\bar{\rho}$, where $\rho$ is the local matter density and $\bar{\rho}$ is the mean matter density. The local overdensity used here is drawn from the 3D reconstructed local mass density of SDSS DR7 (Abazajian et al. 2009) with a smoothed scale of 3 Mpc using the approach of a nonlinear, non-Gaussian full Bayesian large-scale structure analysis (Jasche et al. 2010).
2.3. Definition of cSFGs and eSFGs

Galaxies are bimodally distributed in the SFR–$M_*$ relation (e.g., Brinchmann et al. 2004; Peng et al. 2010; Woo et al. 2013; Bluck et al. 2016), which is widely used to separate SF and quenched populations. The left panel of Figure 2 shows the SFR–$M_*$ relation. As expected, the bimodal distribution of sample galaxies is clearly seen. We adopt the division line from Woo et al. (2013), $\log_{10}\text{SFR} = 0.64\log_{10}M_* - 7.22$ (indicated by the red solid line), to separate SF galaxies and QGs. Thus, 8442 galaxies are classified as SF galaxies, and 7491 galaxies are quenched ones. According to this definition, some so-called “green valley” galaxies are classified into SF type. We have checked our main result by shifting the demarcation line to avoid or largely reduce the mixing effect of green valley galaxies. The cSFGs and eSFGs are defined to have different inner stellar mass bins, indicated by black circles. We perform a linear fit to the data points, shown in the black solid line. This black solid line thus represents the normal SFMS of the sample galaxies.

The right panel of Figure 2 shows the $\Sigma_{1\text{kpc}}$–$M_*$ relation for SF galaxies (blue dots with gray contours) and QGs (red contours). As shown, linear correlations are clearly seen for both SF and QGs. The QGs reside in a narrow sequence on the $\Sigma_{1\text{kpc}}$–$M_*$ diagram, while SF galaxies appear to be more scatterly distributed with respect to the quenched population. Furthermore, the QGs appear to have higher $\Sigma_{1\text{kpc}}$ than SF galaxies across the whole stellar mass range. This is in good agreement with the previous finding that the existence of a mature bulge or a dense stellar core is a prerequisite to quench a galaxy (Cheung et al. 2012; Fang et al. 2013; Bluck et al. 2014; Barro et al. 2017). However, there is a significant fraction of SF galaxies that reside in the same region as QGs on the $\Sigma_{1\text{kpc}}$–$M_*$ diagram. These galaxies are likely in the transitional phase from normal SF galaxies to QGs according to the compaction and quenching scenario. Studying these galaxies would probably give instructions on galaxy compaction and star formation quenching. Thus, we separate SF galaxies into two subsamples: the compact SF galaxies (cSFGs) and extended SF galaxies (eSFGs). We emphasize that the definition of compact galaxies is not based on galaxy radius, but on the central surface mass density throughout this paper. The demarcation line is indicated by the black solid line, which is parallel to but 0.2 dex lower than the best-fit relation of $\Sigma_{1\text{kpc}}$–$M_*$ for QGs (the red solid line). This demarcation is determined to be in line with the bottom envelop of the red contour enclosing 75% of the quenched population. Although this demarcation is manually determined, it excellently distinguishes the Sérsic index of cSFGs and eSFGs (see details in Appendix B), suggesting that the classification is reasonable. Overall, the sample galaxies consist of three subsamples: 3452 cSFGs, 4990 eSFGs, and 7491 QGs.

3. Observational Results

The cSFGs and eSFGs are defined to have different inner stellar surface densities. According to the compaction and quenching scenario, the eSFGs are expected to assemble their inner stellar mass before becoming quiescent galaxies. However, the comparison of physical properties for eSFGs and cSFGs is not well investigated up to now, such as their locations on the SFMS and the mass–metallicity relation and their cold gas content and environments. In this section, we will study the properties of these two populations, which should shed light on the galaxy compaction (if any), and further examine the compaction and quenching scenario.

3.1. Two Approaches of Galaxy Compaction

The SF galaxies and QGs are found to have different sizes at both low and high redshift (e.g., Toft et al. 2007; Williams et al. 2010; Newman et al. 2012; van der Wel et al. 2014; Shibuya et al. 2015), suggesting the coevolution of the size and...
star formation status of galaxies. The left panel of Figure 3 presents the $\Sigma_{1kpc}$–$M_*$ diagram of SF galaxies with the color-coding of the Petrosian radius ($R_{r,90}$), defined as the radius containing 90% of the Petrosian luminosity based on the SDSS $r$-band image. Here we use $R_{r,90}$ rather than half-light radius because $R_{r,90}$ is better representative of the global size of galaxies. The black dashed curves indicate the contours of constant $R_{r,90}$ on the diagram. As expected, at fixed stellar mass, the $R_{r,90}$ is dramatically decreasing when galaxies are getting more compact, indicating that the cSFGs are much smaller in size than eSFGs at a given stellar mass. This result can be seen more clearly in the right panel of Figure 3, where the $R_{r,90}$ as a function of stellar mass for eSFGs (blue squares), cSFGs (green circles), and QGs (red triangles) are shown. The representative scatter of the $R_{r,90}$–$M_*$ relation is denoted in the lower right corner for each population. As shown, eSFGs have systematically higher $R_{r,90}$ than cSFGs (for up to 0.3 dex), while the cSFGs show a similar global size to QGs almost in the whole stellar mass range.

Assuming that eSFGs need to evolve to cSFGs before quenching, eSFGs are becoming more and more compact, mainly via two approaches: the in situ star formation in their central regions and/or the shrinkage of their sizes with the radial migration of stars. These two different approaches result in different evolution tracks of eSFGs on the $\Sigma_{1kpc}$–$M_*$ diagram. For a given eSF in the lower left corner of the $\Sigma_{1kpc}$–$M_*$ diagram, we naturally assume that it evolves with both increasing stellar mass and increasing $\Sigma_{1kpc}$ as time goes on. If the eSF assembles its stellar mass only via in situ star formation or mergers, it would evolve along a track that is steeper than the contours of constant $R_{r,90}$ (see the dashed curves in the left panel of Figure 3). If the eSF were getting compact mainly via the size shrinking (possibly along with in situ star formation or mergers), it would evolve along a track that is flatter than the contours of constant $R_{r,90}$. In the case the eSF evolves along a track flatter than the contours of constant $R_{r,90}$, which means that its stellar mass and size are growing without prominent growing of $\Sigma_{1kpc}$, which is in good agreement with the inside-out growth scenario (e.g., Pérez et al. 2013; Goddard et al. 2017; Wang et al. 2018a). Thus, although the cSFGs are defined by using $\Sigma_{1kpc}$, the compaction process discussed in this work includes the above two approaches of compaction.

3.2. The SFR and Gas-phase Metallicity

The SFR and gas-phase metallicity are two basic properties of SF galaxies. SFR reflects the present growth rate of the stellar mass of galaxies, while metallicity plays an important role in many fundamental physical processes that regulate galaxy evolution, including gas cooling, star formation, and dust formation. The tight SFMS established at both low and high redshift (e.g., Brinchmann et al. 2004; Daddi et al. 2007; Salim et al. 2007; Elbaz et al. 2011) suggests that the metallicity at the low stellar mass end is usually interpreted as evidence for the ubiquity of galactic winds and their feedback in removing metals from galaxy potential wells. Thus, investigating these two scaling relations for cSFGs and eSFGs would provide clues for the compaction process under the compaction and quenching scenario.

The left two panels of Figure 4 show the $\Sigma_{1kpc}$–$M_*$ relation for SF galaxies color-coded by SFR and gas-phase metallicity, respectively. At fixed stellar mass, the SFR appears to show no or very weak dependence on $\Sigma_{1kpc}$, suggesting that cSFGs and eSFGs appear to have similar SFRs at fixed stellar mass as a whole, given their different structural properties. In contrast, the gas-phase metallicity is sensitive to $\Sigma_{1kpc}$ at the low stellar mass end ($M_* < 10^{10.5} M_\odot$), with higher $\Sigma_{1kpc}$ corresponding to higher gas-phase metallicity. This indicates that cSFGs are more metal-rich than eSFGs at the low stellar mass end. We note that there is a lack of valid measurements of metallicity at the high-mass end (see the bottom left panel of Figure 4),
which is due to the fact that the computing of metallicities requires galaxies to have 5σ detection of the emission lines for H\(\alpha\), H\(\beta\), and [N II] (Tremonti et al. 2004).

These results can be more clearly seen in the right two panels of Figure 4, where the median SFR–\(M_\star\) and 12 + log(O/H)–\(M_\star\) relations are presented for cSFGs (green circles) and eSFGs (blue squares). As shown, the SFRs of cSFGs appear to be at most slightly higher than those of eSFGs (with an average of 0.06 dex), while we note that this result is preserved over the whole stellar mass range especially at the high stellar mass end. This indicates that under the compaction and quenching scenario, galaxies sustain or even slightly enhance their star formation activities during the evolution from eSFGs to cSFGs. In contrast, for the 12 + log(O/H)–\(M_\star\) relation, the pronounced differences between the two populations are shown. The differences become less significant with increasing stellar mass. Specifically, cSFGs are more metal-rich at \(M_\star \sim 10^9 M_\odot\) than eSFGs for \(\sim 0.19\) dex, while the gas-phase metallicities of the two become comparable to each other at \(M_\star \sim 10^{10.5} M_\odot\). This finding is consistent with the result of Ellison et al. (2008) that the gas-phase metallicity strongly depends on the galaxy half-light radius, in the sense that more compact galaxies are more metal-rich at fixed stellar mass.

Furthermore, the metallicity difference can be as large as 0.2 dex, which is roughly equal to what we find here. The dominated mechanism of this finding is still under debate (Ellison et al. 2008; Yabe et al. 2012; Sánchez Almeida et al. 2014; Wang et al. 2017; Sánchez Almeida & Dalla Vecchia 2018), which is likely a combined effect of metal-poor gas accretion, metal-rich gas outflow, and the metal enrichment from current star formation activities. However, the metallicity difference between cSFGs and eSFGs vanishes at stellar masses greater than \(10^{10.5} M_\odot\). This is likely due to the fact that the metallicities from the MPA-JHU catalog are measured based on the 3\(''\) fiber spectra, which could not represent the global metallicity for large galaxies. Considering that SF galaxies with a large stellar disk usually have a significant metallicity gradient (e.g., Sánchez et al. 2014; Carton et al. 2018), we suspect that the cSFGs likely have higher global metallicity than eSFGs even at high stellar mass if the metallicities are measured within the apertures that cover the whole galaxies (Wang et al. 2017).

Although the median SFRs of the two populations are similar at fixed stellar mass, the distribution of SFR of the two can be different. Indeed, we have checked the distribution of SFR for cSFGs and eSFGs at a given stellar mass and find that
the SFR of cSFGs is more broadly distributed at the high-SFR end with respect to that of eSFGs. This is also confirmed by the standard deviation of SFR for cSFGs and eSFGs, shown in Figure 7. We will discuss this in detail in Section 4.1.

3.3. The HI Properties

The cold gas in galaxies is the fuel to sustain their star formation (e.g., Sancisi et al. 2008; Conselice et al. 2013; Wang et al. 2013, 2015). Galaxies are usually quenched by exhausting or heating their cold gas, removing their cold gas, or stabilizing the gas disk against gravitational instabilities to suppress star formation. Thus, investigating the cold gas properties in galaxies is one of the most important keys to uncovering the process of star formation quenching. For instance, by using H I spectral stacking of a sample of early-type galaxies in the ALFALFA footprint, Fabello et al. (2011) did not find evidence that galaxies with a prominent bulge component are less efficient in turning their cold gas reservoirs into stars, which appears to be inconsistent with the “morphological quenching” picture (Martig et al. 2009). In this subsection, we will examine the H I properties of cSFGs and eSFGs and the possible evolution of gas content during the compaction process under the compaction and quenching scenario.

Since just a small fraction of the sample galaxies are matched with ALFALFA galaxies, we could not obtain the H I properties for each of the sample galaxies. This means that direct comparison of the observed H I content for all the cSFGs and eSFGs is not valid. Alternatively, we introduce a parameter, the H I detection rate, defined as the fraction of galaxies that are detected by the ALFALFA survey for a given subsample. Thus, for a given subsample of fixed stellar mass, the higher H I detection rate usually corresponds to the higher averaged H I content, since ALFALFA is a blind H I survey. Due to the detection limit of ALFALFA, there is a lack of H I sources with the H I mass below $10^{9.7} M_\odot$ at a redshift of 0.05, indicating that the detection limit of H I gas is $\sim 10^{9.7} M_\odot$ by this redshift. Thus, in order to reduce the effect of the detection limit, galaxies only with H I mass greater than $10^{9.7} M_\odot$ are treated as H I detected sources. In this way, there are in total 19.1% of cSFGs and 35.8% of eSFGs treated as H I detected sources.

The top left panel of Figure 5 shows the $\Sigma_{1\text{kpc}}-M_\star$ diagram with the color-coding of the H I detection rate. At fixed $\Sigma_{1\text{kpc}}$, the H I detection rate slightly increases with increasing stellar mass, which is consistent with the fact that more massive SF galaxies usually host more H I gas (Catinella et al. 2010; Wang et al. 2015). However, at fixed stellar mass, the H I detection rate shows a rapid decline with increasing $\Sigma_{1\text{kpc}}$. This result can
be clearly seen in the top right panel of Figure 5, where the H I detection rate as a function of stellar mass for cSFGs and eSFGs is presented. As shown, the eSFGs exhibit a higher H I detection rate with respect to cSFGs, suggesting that eSFGs are on average more gas-rich than cSFGs. The bottom left panel of Figure 5 presents the $\Sigma_{1kpc}$--$M_*$ diagram color-coded with the H I mass. The H I masses for galaxies with undetected 21 cm emission in ALFALFA are estimated by adopting the relation (see Section 2.2) from Catinella et al. (2010). As shown, the H I mass is strongly anticorrelated with $\Sigma_{1kpc}$, indicating that eSFGs tend to be more H I-rich than cSFGs. Indeed, as shown in the bottom right panel of Figure 5, the eSFGs have higher median H I mass than cSFGs for $\sim$0.3 dex, which confirms the result found in the top two panels of Figure 5.

We conclude that eSFGs are more H I-rich than cSFGs, which is consistent with the compaction and quenching scenario assuming that galaxies evolve along the direction of cold gas consumption.

3.4. The Environment of cSFGs and eSFGs

Galaxies residing in different environments have different prevalences of quenched populations (e.g., Peng et al. 2010; Woo et al. 2015; Wang et al. 2018c), indicating that environmental effects play an important role in quenching a galaxy. The fraction of QGs is found to be correlated with halo mass and anticorrelated with halo-centric radius (e.g., Weinmann et al. 2006; van den Bosch et al. 2008; Wetzel et al. 2012; Kauffmann et al. 2013; Wang et al. 2018a, 2018c), indicating that galaxies residing in the inner region of massive halos are more likely to be quenched with respect to galaxies in the outer region of similar halos or the inner region of less massive halos. Not only working on the star formation quenching, environmental effects are believed to effectively transform the morphology of galaxies from disk-like to spheroid-like. For instance, major mergers can efficiently transform the SF disk galaxies to quenched ellipticals. In addition, numerical simulations have shown that disk galaxies in a rich cluster would suffer from frequent encounters with member galaxies and the cluster’s tidal field (also known as galaxy harassment), along with a complete morphological transformation from disks to spheroids (e.g., Moore et al. 1996, 1998; Fujita 1998). However, it is still unclear what the role of environment is in the compaction process. In this subsection, we will examine the environment of cSFGs and eSFGs and try to find out whether the environment plays a key role in the compaction process under the scenario of compaction and quenching.

The left two panels of Figure 6 show the $\Sigma_{1kpc}$--$M_*$ relation for SF galaxies with the color-coding of the host halo mass and the local overdensity. As shown, the host halo mass of both cSFGs and eSFGs strongly depends on stellar mass, while the overdensity of the two populations shows no or very weak dependence on the stellar mass. Specifically, the halo mass of SF galaxies shows a dramatic drop at a stellar mass of $\sim 10^{10.5} M_\odot$. This is because satellite galaxies dominate the galaxy population at the low stellar mass end, while central galaxies dominate the population at the high stellar mass end (Yang et al. 2009). We note that most of central galaxies with log$_{10} M_*/M_\odot < 10.2$ do not have a valid value of halo mass. These galaxies are not included in generating the top right panel of Figure 6, leading to a boost of halo mass at the low stellar mass end. In contrast, the overdensity of SF galaxies is almost independent of stellar mass, which seems to be inconsistent with the dependence of halo mass on stellar mass. Actually, this discrepancy is due to the exclusion of central galaxies with invalid halo mass at the low stellar mass end when generating the stellar mass-halo mass relation. In the present work, we do not divide galaxies into centrals and satellites because centrals and satellites are found to exhibit similar quenching behaviors when both halo mass and stellar mass are controlled (Hirschmann et al. 2014; Knobel et al. 2015; Wang et al. 2018a, 2018c). More importantly, at fixed stellar mass, the halo mass and/or overdensity of SF galaxies exhibit no or very weak dependence on $\Sigma_{1kpc}$, indicating that cSFGs and eSFGs reside in halos of similar mass with similar overdensities. This result can be more clearly seen in the right panels of Figure 6, where the median halo mass and overdensity as a function of stellar mass for cSFGs, eSFGs, and QGs are shown. We find that the QGs more likely reside in more massive halos (or regions with higher matter densities) with respect to cSFGs or eSFGs at the low stellar mass end ($M_\star < 10^{10.5} M_\odot$), suggesting an environmentally driven quenching mechanism especially for less massive galaxies. However, we find that the environments of cSFGs and eSFGs do not show significant differences, suggesting that environmental effects do not play a major role in the compaction process under the scenario of compaction and quenching at least for the low-redshift universe.

4. Discussion

4.1. Gas Depletion Time along the SFMS

In Section 3.2, we find that cSFGs appear to have a slightly higher SFR than eSFGs. However, the SFR distribution of cSFGs and eSFGs can be different. We present the standard deviation of the SFR as a function of stellar mass for cSFGs and eSFGs in the left panel of Figure 7. The scatter of SFMS shown here is $\sim 0.3$ dex, which is broadly consistent with the previous findings of 0.2–0.3 dex (e.g., Noeske et al. 2007; Whitaker et al. 2012; Speagle et al. 2014). As one can see, the standard deviations of SFR for cSFGs are systematically higher than those of eSFGs almost over the whole stellar mass range, suggesting that cSFGs have wider SFR distribution than eSFGs at fixed stellar mass. Indeed, we check the distribution of the two populations on the SFR--$M_\star$ diagram and find that 288 ($\sim 8.3\%$) cSFGs lie above the normal SFMS for 0.5 dex, while only 86 ($\sim 1.7\%$) eSFGs lie above the normal SFMS for 0.5 dex, indicating that galaxies with the most intense star formation activities tend to be cSFGs, rather than eSFGs at a given stellar mass (see Figure 2). This result is confirmed by the normalized distribution of $\Delta$SFR, defined as the deviation from the normal SFMS in logarithmic space, for eSFGs and cSFGs. This result is also in good agreement with the cosmological simulations of Tacchella et al. (2016b), who found that galaxies in the upper envelope of the SFMS tend to be compact at a redshift of $>1$. We have checked the morphologies of these cSFGs with $\Delta$SFR $> 0.5$ dex by visual inspection and find that only a few of them ($< 10\%$) exhibit clear features of an ongoing major merger.

In the right panel of Figure 7, we present the SFR--$M_\star$ relation for SF galaxies with the color-coding of H I depletion time. The H I depletion time is computed assuming that

\[ \text{H}_\text{i} \text{ masses of H}_\text{i} \text{ nondetected galaxies in ALFALFA are estimated using the relation from Catinella et al. (2010).} \]
(1) galaxies sustain their current SFR and (2) the replenishment of cold gas is negligible (Tacchella et al. 2016b). We do not consider the contribution of helium and the molecular gas in the calculation. As shown, the H I depletion time for galaxies with the most intense star formation activities can be as low as 1 Gyr. These galaxies are dominated by cSFGs and have strong star formation activities, suggesting that they likely suffer from the ongoing compaction along with the rapid buildup of their stellar cores (or bulges) and the rapid cold gas consumption.

In addition, we examine the median gas depletion time for cSFGs and eSFGs with the above assumptions. We find that the H I depletion time only weakly depends on stellar mass, with the median H I depletion time of ~4 Gyr for cSFGs and ~8 Gyr for eSFGs. This suggests that cSFGs are statistically closer to the quenched population than eSFGs along the evolution track. However, in computing H I depletion time, we assume that SF galaxies sustain their current SFR, which is not true in the real universe. Indeed, by investigating the simulated SF galaxies of high redshift (z > 1), Tacchella et al. (2016b) proposed that SF galaxies go up and down across the normal SFMS before quenching their star formation. Observationally, we find a small but significant fraction of cSFGs that lies above the normal SFMS by 0.5 dex. This suggests that the fraction of the lifetime for a cSFG during which it lies significantly above the normal SFMS is small but significant, assuming that lying significantly above the normal SFMS is a period of a SF galaxy during its lifetime. If this is the case, the cSFGs consume a bulk of their cold gas and build their stellar cores in a short timescale when they lie significantly above the normal SFMS, and subsequently they are back to the normal SFMS or even lower. Thus, it is not necessary to take 4–8 Gyr to quench a galaxy, because a bulk of its cold gas can be consumed in a short timescale when it lies significantly above the normal SFMS.

Assuming that galaxies evolve from eSFGs, through cSFGs, to the quenched population, the relative number of eSFGs and cSFGs would give instructions on the timescale of compaction and quenching. The fraction of cSFGs takes the proportion of ~21.6% of the whole sample and ~40.9% of all the SF galaxies, indicating that cSFGs are a non-negligible galaxy population. This suggests that the star formation quenching is likely not dominated by rapid processes at the local universe. This is different from the case of high redshift, where major mergers and cold gas accretions are believed to much more frequently occur than in the local universe (e.g., Rodriguez-Gomez et al. 2015; Tacchella et al. 2016a, 2016b), suggesting a different compaction and quenching timescale with respect to the low-redshift universe.
4.2. The Prevalence of AGN Activities

The AGN activities have been brought in to explain the link between inner structural properties of galaxies and star formation quenching (e.g., Croton et al. 2006; Fabian 2012; Ciccone et al. 2014; Henriques et al. 2015), acting to expel/deplete the preexisting cold gas supply and/or prevent gas cooling and further star formation by strong feedback from central massive black holes. Since the buildup of stellar cores of cSFGs is probably connected to the growth of central massive black holes, the prevalence of AGNs in cSFGs and eSFGs is likely to be different. Indeed, by examining the fraction of massive cSFGs that host an AGN at a redshift of \( z \approx 2 \), Kocevski et al. (2017) found that \( \sim 40\% \) of compact SF galaxies host an X-ray-detected AGN, which is 3.2 times higher than the incidence of AGNs in extended SF galaxies of similar masses and similar redshifts, based on the combination of Hubble WFC3 imaging and Chandra X-ray observations. In low-redshift universe, Wang et al. (2017) have identified a sample of galaxies with “outside-in” assembly mode from MaNGA (Mapping Nearby Galaxies at Apache Point Observatory; Bundy et al. 2015), which are selected to have a lower 4000 Å break in the inner region than in the outer region. They found that these galaxies are likely in the transitional phase from normal SF galaxies to QGs, given their smaller size, higher SFR, and higher gas-phase metallicity with respect to normal SF galaxies of similar stellar mass. The properties of these galaxies resemble the properties of cSFGs investigated in this work, although the two populations are defined in totally different ways. In addition, the galaxies with outside-in assembly mode are more likely to host an AGN than normal SF galaxies, although with a limited sample size (Wang et al. 2017; Liu et al. 2018), suggesting a higher prevalence of AGNs in cSFGs than in eSFGs.

Figure 8 shows the fraction of optical AGNs for cSFGs and eSFGs as a function of stellar mass. The optical AGNs have been brought in to explain the link between inner structural properties of galaxies and star formation quenching (e.g., Croton et al. 2006; Fabian 2012; Ciccone et al. 2014; Henriques et al. 2015), acting to expel/deplete the preexisting cold gas supply and/or prevent gas cooling and further star formation by strong feedback from central massive black holes. Since the buildup of stellar cores of cSFGs is probably connected to the growth of central massive black holes, the prevalence of AGNs in cSFGs and eSFGs is likely to be different. Indeed, by examining the fraction of massive cSFGs that host an AGN at a redshift of \( z \approx 2 \), Kocevski et al. (2017) found that \( \sim 40\% \) of compact SF galaxies host an X-ray-detected AGN, which is 3.2 times higher than the incidence of AGNs in extended SF galaxies of similar masses and similar redshifts, based on the combination of Hubble WFC3 imaging and Chandra X-ray observations. In low-redshift universe, Wang et al. (2017) have identified a sample of galaxies with “outside-in” assembly mode from MaNGA (Mapping Nearby Galaxies at Apache Point Observatory; Bundy et al. 2015), which are selected to have a lower 4000 Å break in the inner region than in the outer region. They found that these galaxies are likely in the transitional phase from normal SF galaxies to QGs, given their smaller size, higher SFR, and higher gas-phase metallicity with respect to normal SF galaxies of similar stellar mass. The properties of these galaxies resemble the properties of cSFGs investigated in this work, although the two populations are defined in totally different ways. In addition, the galaxies with outside-in assembly mode are more likely to host an AGN than normal SF galaxies, although with a limited sample size (Wang et al. 2017; Liu et al. 2018), suggesting a higher prevalence of AGNs in cSFGs than in eSFGs.

![Figure 7. Left panel: standard deviation of SFR as a function of stellar mass for cSFGs (green) and eSFGs (blue). The normalized distributions of \( \Delta SFR \) for cSFGs (green histogram) and eSFGs (blue histogram) are also presented in the inset. Right panel: SFR–\( M_\star \) relation for SF galaxies with the color-coding of gas depletion time. The solid gray line is the best-fit relation of the SFMS taken from Figure 2, and the dashed gray line is the 0.5 dex above this relation.](image)

![Figure 8. Seyfert galaxy fraction as a function of stellar mass for eSFGs (blue squares) and cSFGs (green circles).](image)
Similarly, we use the deviation of SFR from the normal SFMS, $\Delta_{\text{SFR}}$, to quantify the star formation status of galaxies, which is independent of stellar mass. The left panel of Figure 9 presents the $\Delta_{\text{SFR}}$–$\Delta_{1kpc, S}$ diagram for all the sample galaxies color-coded with the H I detection rate. Galaxies on this diagram are mainly distributed in two branches, denoted by the gray contours. Galaxies in the upper branch are SF galaxies, whereas galaxies in the lower branch are quenched ones. Almost all the QGs have high inner surface stellar mass densities, indicated by the lack of galaxies in the lower left corner of Figure 9. This agrees with the previous finding that a compact stellar core is the requisite for quenching a galaxy (e.g., Fang et al. 2013; Bluck et al. 2014; Barro et al. 2017). More importantly, from eSFGs to cSFGs, and from cSFGs to the quenched population, the H I detection rate is significantly decreasing, which is consistent with the compaction and quenching scenario that the gas reservoirs for sustaining star formation become less and less along the quenching track. Moreover, we have checked the $\Delta_{\text{SFR}}$–$\Delta_{1kpc, S}$ diagram with color-coding of the HI mass and find that the result strengthens the above statement.

In the right panel of Figure 9, we present the sketch for galaxy evolution on the $\Delta_{\text{SFR}}$–$\Delta_{1kpc}$ diagram under the scenario of compaction and quenching.
along with metal enhancement (for less massive galaxies) and central stellar mass assembly (see Figures 4 and 11). From cSFGs to the quenched population, galaxies appear to exhaust almost all their cold gas and shut down their star formation along with the buildup of their dense stellar cores or bulges (see Figures 9 and 11).

Thus, we propose a simple picture under the scenario of compaction and quenching to string the results together, where eSFGs first contract via a series of possible physical processes. The dominated processes for compaction are likely to be different at redshifts of less than 1. In the high-redshift universe ($z > 1$), major mergers and the accretion of counterrotating tidal streams occur more frequently than in the local universe (e.g., Conselice 2006; Bertone & Conselice 2009; Zolotov et al. 2015; Tacchella et al. 2016b). These processes are usually associated with violent disk instabilities, subsequently leading to the collapse of gaseous and/or stellar disks and the enhancement of star formation. However, the physical processes of compaction in the local universe are much gentler and have a longer timescale than those in the high-redshift universe. Minor mergers, interactions with close companions, and/or the bar-driven gas inflow in secular evolution are thought to play a role in enhancing star formation and contributing to the buildup of stellar cores or bulges for low-redshift galaxies (e.g., Moore et al. 1998; Bournaud et al. 2007; Di Matteo et al. 2007; Wang et al. 2012; Lin et al. 2017). This intense star formation could only be sustained for 1 Gyr or less (see the right panel of Figure 7), but it is efficient to consume the cold gas and assemble the stellar mass by in situ star formation in the inner regions of galaxies along with the metal enhancement. The major role of compaction is to transform an extended SF galaxy with a sufficient H1 reservoir to a compact SF but H1-deficient galaxy (see Figures 5 and 11). Then this galaxy can be quenched by either the feedback of its central massive black hole or stabilizing the gaseous disk against collapse from forming stars because of the existence of a dominant core (or bulge), although the morphological quenching picture appears to be inconsistent with the fact that quenching inevitably invokes the loss of cold gas (see Figure 9). Alternatively, this galaxy can be quenched by the environmental effects, such as tidal stripping or strangulation if it is a less massive galaxy of a big cluster. We note that the cSFGs and eSFGs appear to reside in a similar environment, suggesting that the compaction process is independent of environmental effects.

We also remind the readers that there is no necessity for invoking the evolution from eSFGs and cSFGs to explain our result. It is also possible that the eSFGs and cSFGs are formed differently, owing to different formation and gas accretion histories. By investigating 100 simulated galaxies of various morphologies with Milky-Way-like halo mass drawn from the Galaxies–Intergalactic Medium Interaction Calculation (GIMIC), Sales et al. (2012) found that the coherent alignment of the angular momentum of accreted gas over galaxy formation is the key to galaxy morphology: spheroids more likely form when the spin of newly accreted gas is misaligned with that of the extant galaxy, whereas disk galaxies form usually with the similar alignment of angular momentum for the accreted gas and the earlier accreted material. Furthermore, under this scenario, the accreted gas flows more easily into the galactic center for spheroids than disk galaxies, associated with the enhancement of central star formation activities (Davis et al. 2011; Chen et al. 2016; Jin et al. 2016) and the possible feeding of central massive black holes (see Figure 8). This naturally leads to the cSFGs being more H1 deficient than eSFGs owing to the rapid cold gas consumption in cSFGs, and the structural dependence of metallicity can be caused by either the metal-poor gas accretion of eSFGs or the metal enhancement of rapid star formation activities in the center of cSFGs (Yabe et al. 2012; Wang et al. 2017; Sánchez Almeida & Dalla Vecchia 2018). However, it is also possible that eSFGs accrete cold gas and/or dwarf galaxies with misaligned angular momentum and subsequently turn into cSFGs.

5. Summary and Conclusion

In this work, we select a volume-limited galaxy sample to have $0.02 < z < 0.05$, $\log_{10}(M_*/M_\odot) > 9.5$, and a minor-to-major axis ratio greater than 0.5 from NSA galaxies located in the ALFALFA footprint. We then match the selected galaxies with the MPA-JHU catalog, which results in 15,933 galaxies as our final sample. Further, we classify the galaxy sample into SF and quenched populations according to the SFR–$M_*$ relation, and we classify the SF galaxies into cSFGs and eSFGs based on the $\Sigma_{\text{H1}}$–$M_*$ diagram. We investigate and compare the properties of cSFGs and eSFGs, including the SFR, gas-phase metallicity, H1 content, and environment. This is helpful to
examine the possible evolution from eSFGs to cSFGs while naturally assuming that galaxies evolve along the track of cold gas consumption and metal enhancement. The main results are listed below.

1. The cSFGs on average exhibit similar or slightly higher SFRs with respect to eSFGs at fixed stellar mass, while the compact SF galaxies dominate the galaxy population with the most intense star formation activities (0.5 dex above the normal SFMS).

2. The cSFGs appear to have higher gas-phase metallicity at the low stellar mass end than eSFGs, while the metallicity difference between the two populations vanishes at stellar mass higher than $\sim10^{10.5} M_\odot$.

3. The H I detection rate of cSFGs is significantly lower than that of eSFGs at a given stellar mass, implying that cSFGs are more H I deficient than eSFGs. Indeed, this result is confirmed by adopting the estimated H I mass for H I undetected galaxies in ALFALFA.

4. The cSFGs and eSFGs of similar stellar mass appear to reside in a similar environment, quantified by the host halo mass and local overdensity.

5. The cSFGs more frequently host an AGN than eSFGs at a given stellar mass, suggesting that the feeding of a central massive black hole is more efficient in cSFGs than in eSFGs.

We examine the H I depletion time of cSFGs and eSFGs and find that cSFGs are closer to being quenched than eSFGs assuming the current SFR and neglecting the replenishment of cold gas. All these findings support the compaction and quenching scenario, when assuming that galaxies evolve following the track of cold gas consumption and metal enhancement. Under this scenario, the compaction is essential to the buildup of stellar cores (or bulges) along with a strong cold gas consumption and metal enhancement. In addition, the environmental effects appear to not play a key role in the compaction process. We also note that there is no necessity of the evolution from eSFGs and cSFGs, since the two populations can be formed differently owing to different formation and gas accretion histories.

We thank the anonymous referee for constructive suggestions. This work is supported by the National Basic Research Program of China (973 Program, 2015CB857004), the National Natural Science Foundation of China (NSFC, nos. 11320101002, 11522324, 11421303, 11703092, and 11433005), and the Fundamental Research Funds for the Central Universities. E.W. acknowledges the support from the Youth Innovation Fund by the University of Science and Technology of China (no. BK2030000040). Z.P. acknowledges the support from the Natural Science Foundation of Jiangsu Province (no. BK20161097).

Appendix A
Using $\Sigma_*$ to Define Samples

In the main text, we use the surface mass density within a radius of 1 kpc to quantify the compactness of galaxies and to classify the cSFGs and eSFGs. However, one may worry that the aperture of 1 kpc corresponds to a different relative size of different galaxies. Here we present another parameter, the stellar mass surface density within the effective radius, $\Sigma_{Re}$, to reproduce the main result of this work. In Figure 10, we present the $\Sigma_{Re} - M_*$ relation with the color-coding of SFR, gas-phase metallicity, H I detection rate, H I mass, host halo mass, and local overdensity. As shown, galaxies in the $\Sigma_{Re} - M_*$ diagram show broader distribution than in the $\Sigma_{1kpc} - M_*$ diagram, which is consistent with previous studies (e.g., Fang et al. 2013; Barro et al. 2017). We find that the SFR and environmental properties show weak or no dependence on $\Sigma_{Re}$, while the H I content and gas-phase metallicity show significant dependence on $\Sigma_{Re}$.

This is in good agreement with our result, indicating that the result is not sensitive to the definition of cSFGs and eSFGs.

Appendix B
$\Sigma_{1kpc} - M_*$ Diagram with Color-coding of the Sérsic Index

Previous results have shown that the Sérsic index is increasing from the eSFGs, through cSFGs, to QGs (Barro et al. 2017). Here we present the $\Sigma_{1kpc} - M_*$ for SF galaxies with the color-coding of the Sérsic index in the left panel of Figure 11. The Sérsic indices are taken from the NSA catalog (Blanton et al. 2011). As shown, the Sérsic index strongly depends on $\Sigma_{1kpc}$, with higher $\Sigma_{1kpc}$ corresponding to higher Sérsic index. In addition, the demarcation line of cSFGs and eSFGs appears to perfectly distinguish the Sérsic index of sample galaxies, in the sense that galaxies below and above the demarcation line show clearly different Sérsic indices. This confirms that our classifications of cSFGs and eSFGs are reasonable. The right panel of Figure 11 shows the Sérsic index as a function of stellar mass for cSFGs, eSFGs, and QGs. The Sérsic indices of cSFGs are between those of eSFGs and QGs almost over the whole stellar mass range. This is consistent with the compaction and quenching scenario that the structural properties evolve from eSFGs, through cSFGs, to QGs, along with the morphological transformation from disk-like to spheroid-like.

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References
Abadi, M. G., Moore, B., & Bower, R. G. 1999, MNRAS, 308, 947
Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, ApJS, 182, 543
Baldry, I. K., Glazebrook, K., Brinkmann, J., et al. 2004, ApJ, 600, 681
Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5
Barro, G., Faber, S. M., Koo, D. C., et al. 2017, ApJL, 840, 47
Barro, G., Faber, S. M., Pérez-González, P. G., et al. 2013, ApJ, 765, 104
Barro, G., Faber, S. M., Pérez-González, P. G., et al. 2014, ApJ, 791, 52
Bell, E. F., van der Wel, A., Papovich, C., et al. 2012, ApJ, 753, 167
Bell, E. F., Wolf, C., Meisneren, K., et al. 2004, ApJ, 608, 752
Bertone, S., & Conselice, C. J. 2009, MNRAS, 396, 2345
Birnboim, Y., & Dekel, A. 2003, MNRAS, 345, 349
Blanton, M. R., Eisenstein, D., Hogg, D. W., Schlegel, D. J., & Brinkmann, J. 2005, ApJ, 629, 143
Blanton, M. R., Kazin, E., Muna, D., Weaver, B. A., & Price-Whelan, A. 2011, AJ, 142, 31
Blanton, M. R., & Roweis, S. 2007, AJ, 133, 734
Blau, A. F. L., Mendel, J. T., Ellison, S. L., et al. 2014, MNRAS, 441, 599
Blau, A. F. L., Mendel, J. T., Ellison, S. L., et al. 2016, MNRAS, 462, 2559
Bournaud, F., Jog, C. J., & Combes, F. 2007, A&A, 476, 1179
Brammer, G. B., Whitaker, K. E., van Dokkum, P. G., et al. 2009, ApJL, 706, L173
Brinchmann, J., Charlot, S., White, S. D. M., et al. 2004, MNRAS, 351, 1151
Brown, T., Catinella, B., Cortese, L., et al. 2015, MNRAS, 452, 2479
