THE STRUCTURE OF MASSIVE QUIESCENT GALAXIES AT $z \sim 3$ IN THE CANDELS-COSMOS FIELD

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ABSTRACT

In this Letter, we use a two-color ($J - L$) versus ($V - J$) selection criterion to search massive quiescent galaxy (QG) candidates at $2.5 \lesssim z \lesssim 4.0$ in the CANDELS-COSMOS field. We construct an $H_{\text{F160W}}$-selected catalog and complement it with public auxiliary data. We finally obtain 19 passive $VJL$-selected (hereafter $pVJL$) galaxies as the possible massive QG candidates at $z \sim 3$ by several constrains. We find the sizes of our $pVJL$ galaxies are on average three to four times smaller than those of local early-type galaxies (ETGs) with analogous stellar mass. The compact size of these $z \sim 3$ galaxies can be modeled by assuming their formation at $z_{\text{form}} \sim 4$–6 according to the dissipative collapse of baryons. Up to $z < 4$, the mass-normalized size evolution can be described by $r_e \propto (1+z)^{-1.9}$. Low Sérsic index and axis ratio, with median values $n \sim 1.5$ and $b/a \sim 0.65$, respectively, indicate that most of the $pVJL$ galaxies are disk-dominated. Despite large uncertainty, the inner region of the median mass profile of our $pVJL$ galaxies is similar to those of QGs at $0.5 < z < 2.5$ and local ETGs. It indicates that local massive ETGs have been formed according to an inside-out scenario: the compact galaxies at high redshift make up the cores of local massive ETGs and then build up the outskirts according to dissipationless minor mergers.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift – galaxies: structure

Online-only material: color figures

1. INTRODUCTION

Early-type galaxies (ETGs) are the most massive objects in the local Universe, containing the bulk of the stellar mass, which are predominantly old with mass-weighted ages of $\geq 8$–9 Gyr (Renzini 2006). This indicates that most of the stars in ETGs were formed at redshift $z \geq 1.5$. ETGs are characterized by homogeneous stellar populations with a lot of observational scaling relations. Amongst these, a remarkably tight luminosity–size/mass–size correlation has been confirmed (e.g., Shen et al. 2003).

Recent observations have evidenced that massive quiescent galaxies (QGs) at high redshift are more compact compared to local ETGs with similar stellar mass (Daddi et al. 2005; Trujillo et al. 2006; Toft et al. 2007; van der Wel et al. 2008; van Dokkum et al. 2008; Damjanov et al. 2009; Ryan et al. 2012; Papovich et al. 2012; Zirm et al. 2012). Physical mechanisms have been proposed to explain the smaller size at high redshift and the resulting size evolution with redshift, such as major merger, dissipationless (dry) minor merger (e.g., Naab et al. 2009), and “puff-up” due to the gas mass loss by active galactic nucleus (AGN; Fan et al. 2008) or supernova feedback (Damjanov et al. 2009).

So far, most studies on the structural evolution of passive galaxies focus on the redshift range $0 < z < 3$. Although the massive QGs are rarely selected at $z \geq 3$, the discovery of these galaxies is quite exciting. Several methods (such as morphological, color–color, or specific star formation rate (sSFR); Cassata et al. 2013; Bruce et al. 2012; Szomoru et al. 2012) for selecting high-redshift QGs have been used. For instance, the rest-frame $UVJ$ color has been shown to effectively separate QGs from star-forming galaxies (SFGs; e.g., Williams et al. 2009; Patel et al. 2013). Anyway, the rest-frame $UVJ$ color and sSFR are dependent on the determination of photometric redshift. Although photometric redshift now can be measured with relatively small error (e.g., Ilbert et al. 2009), the measurement of photometric redshift may vary from person to person, depending on the adopted spectral energy distribution (SED) fitting codes and SED libraries. Guo et al. (2012) proposed a new set of color selection criteria analogous with the $BzK$ method (Daddi et al. 2004) to select both SFGs and QGs at $z \sim 3$. They extended the successful $BzK$ method from $z \sim 2$ to $z \sim 3$ by replacing the selection bands with the observed $V, J$, and IRAC 3.6 μm band (hereafter $L$ band), according to the relative shift of galaxy spectra between the two redshifts. Unlike photometric redshift selections, the bias of color selection can be fairly explicitly determined and the results are robust.

In this Letter, we will search for massive quiescent at $z \sim 3$ using the new $VJL$ color selection method. We will use recent Hubble Space Telescope (HST)/WFC3 imaging on the central region of the Cosmic Evolution Survey (COSMOS) as part of CANDELS multi-cycle treasury program (Grogin et al. 2011; Koekemoer et al. 2011) to study the structure of the two-color-selected massive QGs at $z \sim 3$. We will try to extend our knowledge on size distribution and evolution with redshift beyond $z \sim 3$. Throughout this Letter, we assume a concordance ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. All magnitudes are in the AB systems.

2. DATA AND $VJL$ COLOR SELECTION

We focus our study on the central region of the COSMOS survey (Scoville et al. 2007) which has been imaged with HST/WFC3 as part of CANDELS multi-cycle treasury program (Grogin et al. 2011; Koekemoer et al. 2011). The CANDELS data consist of a contiguous mosaic of $4 \times 11$ HST WFC3/IR tiles covering a total area of $\sim 210$ arcmin$^2$, along with a...
contemporaneous mosaic of Advanced Camera for Surveys (ACS) parallel exposures. The exposure times are 1650, 3450, 1000, and 1600 s for F606W (V F606W band), F814W (H F814W band), F125W (J F125W band), and F160W (H F160W band) filters, reaching 5σ point-source sensitivity of 28.1, 28.0, 26.8, and 26.5 (AB mag), respectively. The HST WFC3/IR and ACS images are prepared by drilling the individual exposures onto a grid with rescaled pixel sizes of 60 mas and 30 mas, respectively (Koekemoer et al. 2011). We use the latest data release v1.0 of CANDELS-COSMOS field.6

We construct an H F160W-selected catalog using SExtractor (Bertin & Arnouts 1996) v2.8.6. We run SExtractor in dual mode using H F160W-band mosaics as the detection images and ACS V F606W, J F125W, and WFC3 F160W bands as the measurement images. We use the same set of SExtractor detection parameters as the so-called “hot” setup in van der Wel et al. (2012), which is chosen for optimally detecting small, faint objects. We use a Gaussian smoothing kernel with an FWHM of 4 pixels and select objects with 10 adjacent pixels with 0.7σ fluxes. Deblending is done with a minimum contrast of 0.001 and 64 logarithmic sub-thresholds. Finally, we obtain an H F160W-selected catalog of 34,963 objects with H F160W ≤ 26.5.

We complement the H F160W-selected catalog with Subaru BVgriz (Capak et al. 2007), UltraVISTA YJHKs photometry (McCracken et al. 2012), and deep Spitzer/IRAC 3.6 μm, 4.5 μm, 5.8 μm, and 8.0 μm data taken from S-COSMOS survey (Sanders et al. 2007). The H F160W-selected catalog has been cross-matched with these photometric catalogs, with a matching radius of 1″. The final catalog includes multi-wavelength photometry spanning from the B band to 8.0 μm. The photometric redshifts are determined using EAZY code (Brammer et al. 2008). The galaxy physical properties, such as stellar masses (M*), SFRs, and luminosity-weighted ages, are derived using FAST (Kriek et al. 2009). We adopt a grid of Bruzual & Charlot (2003) models assuming a Chabrier (2003) initial mass function, solar metallicity, exponentially declining star formation histories (SFHs), and Calzetti extinction law (Calzetti et al. 2000). We find that the derived M* do not significantly depend on the assumed SFH.

between the derived M* using exponentially declining and truncated SFH is only 0.06 dex.

We use pVIL color selection criteria given by Guo et al. (2012):

$$J - L \geq 2.5 \, \bigwedge \, J - L < 1.2 \times (V - J) + 0.2,$$

where $\bigwedge$ means the logical and. In Figure 1, we plot the galaxies of our master catalog in two-color ($J - L$) versus ($V - J$) diagram with small black dots. The black lines mark the adopted pVIL color selection criteria (upper right region). 276 galaxies fulfill the color selection criteria. However, just as mentioned in Guo et al. (2012), several possible contaminations can enter the pVIL selection window. The main contamination may be the highly obscured SFGs from both lower ($z \lesssim 2.0$) and higher ($z \gtrsim 4.0$) redshifts. AGNs could also contaminate our pVIL sample. We therefore choose several conditions to constrain and clean our pVIL sample for the purpose of studying the structure of massive QGs at $z \sim 3$: (1) stellar mass $M_* > 10^{10.5} \, M_\odot$; (2) photometric redshift ($2.5 \leq z \leq 4.0$); (3) Spitzer MIPS 24 μm undetected (we cross-match our pVIL sample with the deep Spitzer MIPS 24 μm catalog by Le Floc’h et al. 2009); (4) sSFR = (SFR/$M_*$) < $10^{-9.5}$ yr$^{-1}$; (5) X-ray undetected by C-COMSOS (Civano et al. 2012); (6) effective radius $r_e < 1''$. For the structural parameters of our pVIL galaxies, we use the results of a public catalog including the structural parameters of the best-fitting Sérsic models of galaxies in CANDELS, given by van der Wel et al. (2012).7 Throughout this Letter, we use the structural parameters measured using H F160W-band images. (7) H F160W ≤ 24.5. Finally, we obtain 19 galaxies fulfilling all the conditions (see the filled points in Figure 1). We take them as our massive QG candidates at $z \sim 3$ for further analysis.

3. THE STRUCTURE OF MASSIVE pVIL GALAXIES AT $z \sim 3$

In Figure 2, we plot the distribution of effective radius versus stellar mass for our pVIL sample at $2.5 \lesssim z \lesssim 4.0$. We compare with the local relation (Shen et al. 2003) and find

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6 http://candels.ucolick.org/data_access/Latest_Release.html

7 ftp://cndsarc.u-strasbg.fr/pub/cats/J/ApJS/203/24/
that these galaxies are on average $\sim$3–4 times smaller than the local counterparts with similar stellar masses. In Figure 2, we overplot a massive QG with spectroscopic redshift $z_{\text{spec}} = 2.99$, which is serendipitously discovered by Gobat et al. (2012). This spectroscopic-confirmed QG has very similar size as the median value of our pVJL galaxies. The compact size of these $z \sim 3$ galaxies can be modeled by assuming their formation according to the dissipative collapse of baryons. The dotted lines illustrate the outcomes of our model prediction for reasonable values of the relevant parameters $f_\sigma$ and $z_{\text{form}}$, where $z_{\text{form}}$ is the redshift when the collapse of baryons begins, and $f_\sigma$ is a factor relating the halo rotational velocity to the three-dimensional stellar velocity dispersion (see more details in Fan et al. 2010). For our pVJL galaxies at $z \sim 3$ with luminosity-weighted ages $\geq 0.5$ Gyr, we expect their formation redshift should be $z_{\text{form}} \sim 4$–6.

In Figure 3, we explore the size evolution with redshift for our pVJL sample at $z \sim 3$. We detect the ratio between the measured effective radius of our pVJL galaxy ($r_e$) and the average size with the same stellar mass expected by the local size–mass relation ($r_e$ (SDSS)). We adopt the local size–mass relation $r_e \propto M^\alpha$, where $\alpha$ equals 0.56 by Shen et al. (2003). The relation $r_e \propto (1 + z)\beta$ is used to describe the mass-normalized size evolution with redshift. Combined with local Sloan Digital Sky Survey (SDSS) data and CANDELS-GOODS-South data at $0.5 < z < 2.5$ (Szomoru et al. 2013), the mass-normalized size evolution can be described well with $\beta \sim -1.0$ up to $z \sim 4$. The 1σ size scatter ($\sigma_{\text{logr}}$) of our pVJLs sample is large ($\sigma_{\text{logr}} \sim 0.27$). These results are consistent with the previous findings based on the data at $z \leq 2.5$ (e.g., Newman et al. 2012; Szomoru et al. 2012; Fan et al. 2013). The Sérsic indices can determine the distribution of light and can be suggestive of a bulge or disk component. The axis ratio distribution provides a better constraint on the shapes of galaxies. We examine Sérsic index of our pVJL galaxies taken from van der Wel et al. (2012). The Sérsic indices of our pVJL galaxies at $z \sim 3$ are relatively lower compared to the $z \sim 2$ QGs. The median Sérsic index $n$ is 1.5. Out of 19 galaxies, 13 have $n < 2.0$. The large fraction with low $n$ indicates that the structure of our pVJL galaxies at $z \sim 3$ may be mostly disk-dominated, same as the situation at $z \sim 2$ (van der Wel et al. 2011). We also examine the axis ratios of our pVJL galaxies at $z \sim 3$. The median axis ratio is $b/a \sim 0.65$. Nine out of 19 pVJL galaxies have $b/a < 0.6$, also indicating a disk-like structure.

4. STELLAR MASS SURFACE DENSITY PROFILES OF MASSIVE pVJL GALAXIES AT $z \sim 3$

In this section, we will estimate the stellar mass surface density profiles of our pVJL galaxies at $z \sim 3$ and compare it with those at lower redshift. For simplicity, we neglect the radial gradients in the mass-to-light ratio and use the best-fitting Sérsic profile representing the mass profile for each galaxy. A Sérsic function is written as

$$\Sigma(r) = \Sigma_0 \exp(-b_n[(r/r_e)^{1/n} - 1]). \quad (2)$$

Here $\Sigma(r)$ is the surface brightness at radius $r$, $r_e$ is the effective radius, $\Sigma_0$ is the surface brightness at radius $r_e$, and $n$ is the Sérsic index. The constant $b_n$ can be determined from the condition that the luminosity inside $r_e$ is half the total luminosity, which has a numerical solution (see Prugniel & Simien 1997):

$$b_n = 2n - \frac{1}{3} + 0.009876/n. \quad (3)$$

Neglecting the radial gradients in the mass-to-light ratio, the stellar mass inside radius $r$ can be written as

$$M(<r) = \gamma(2n, b_n r^{1/n} - 1) \times M_\star, \quad (4)$$

where $x = r/r_e$, $M_\star$ is the stellar mass of the whole galaxy, $\gamma(a, b) = \int_0^b \frac{e^{-t} t^{a-1} dt}{(1 + t)^b}$ is the incomplete gamma function. Thus, basically we can compute the stellar mass surface density profile if having only effective radius $r_e$, Sérsic index $n$, and stellar mass $M_\star$. For 19 pVJL galaxies at $z \sim 3$, we compute the individual stellar mass surface density profiles and the corresponding median profile at each radius. Our result is plotted in Figure 4 with solid lines (thick line: median profile; thin lines: individual profiles). We compare the median mass profile of our pVJL galaxies with those of QGs at $z \sim 1$ and $z \sim 2$ (Szomoru et al. 2013) and local ETGs (Huang et al. 2013). For the sake of comparison, we recalculate the mass profiles of QGs in Szomoru et al. (2013) by neglecting radial gradients in the mass-to-light ratio. In Figure 4, we can find that the median mass profiles at different redshifts are very similar in the inner region (within $r < 1–2$ kpc). Anyway, we must note that the median mass profiles are very uncertain at $r < 0.7$ kpc, which is the approximate point-spread function (PSF) half-width at half maximum (HWHM) at $z \sim 3$. Despite the similarity, the median mass profiles at different redshifts already show some difference at 1–2 kpc. This difference is likely due to the large uncertainty of the median profiles in the small samples at $z \geq 1$. The difference is greater at larger radii ($r \geq 4$ kpc). Figure 4 clearly shows that the surface mass density increases with decreasing redshift at $r \geq 4$ kpc. The effective radii (marked with the colorful arrows) also increase with decreasing redshift. One possible indication is that most of the stars in the inner region of local massive ETGs have been presented in place even since $z \sim 3$. This result is consistent with the inside-out formation scenario in which the compact galaxies at high redshift make up the cores of local massive ETGs and then build up the outskirts according to dissipationless minor mergers (e.g., Loeb & Peebles 2003; Hopkins et al. 2009). Patel et al. (2013) also studied the evolution in the surface mass density profiles by using CANDELS HST WFC3 imaging in
the UKIDSS-UDS. They confirmed that most of the mass at \( r < 2 \) kpc was in place by \( z \sim 2 \) and that most of the new mass growth occurred at larger radii. However, they found that the stellar mass appears to grow in the inner part of the galaxy from \( z \sim 3 \) to \( z \sim 2 \). The difference of the evolution in the surface mass density profiles from \( z \sim 3 \) to \( z \sim 2 \) may be due to the different sample selection methods. We compare the median mass profiles at different redshifts with equal stellar mass (\( M_\star \sim 10^{11} M_\odot \)), while Patel et al. (2013) selected the massive galaxies at constant cumulative number density. Their subsample at \( z > 2.5 \) has a stellar mass of \( 10^{10.7} M_\odot \), which is two times less massive than ours.

5. SUMMARY AND DISCUSSION

In this Letter, we try to use a two-color ((\( J - L \)) versus (\( V - J \)) selection criterion (the so-called \( pVLJ \) selection; Guo et al. 2012) to select massive QG candidates at \( 2.5 \leq z \leq 4 \) in the CANDELS-COSMOS field. The preliminary \( pVLJ \) sample contains a lot of contaminations, which are mostly the highly obscured SFGs from both lower (\( z \leq 2.0 \)) and higher (\( z > 4.0 \)) redshifts. AGNs are another possible contamination, though they can only contribute a tiny fraction. Following the work of Guo et al. (2012), we use several conditions to clean our \( pVLJ \) sample. Finally, 19 \( pVLJ \) galaxies have been selected fulfilling all our massive QG conditions at \( z \sim 3 \). The caveat is that there may be the remaining contamination from dusty SFGs in our \( pVLJ \) sample. Though we try to clean the sample by using available data, such as \textit{Spitzer} 24 \( \mu \)m detection, specific SFR based on the SED best-fitting result, it is still not adequate due to the poor limit of shallower 24 \( \mu \)m on SFR and the age-attenuation degeneracy of SED fitting. Further deeper submillimeter/millimeter observation may help purify the quiescent sample.

By comparing our \( pVLJ \) galaxies with local ETGs in the mass–size plane, we find that the sizes of our \( pVLJ \) galaxies are on average three to four times smaller than those of the local ETGs with analogous stellar mass. The compact size of these \( z \sim 3 \) galaxies can be modeled by assuming their formation at \( z_{\text{form}} \sim 4–6 \) according to the dissipative collapse of baryons. We extend our knowledge on the size evolution with redshift for massive QGs beyond \( z \sim 3 \). The effective radius seems to gradually decrease with increasing redshift. Up to \( z < 4 \), the mass-normalized size evolution can be described by \( r_e \sim (1 + z)^{-1} \). The large scatter of size distribution \( \sigma_{\text{size}} \), is also present in our \( pVLJ \) sample at \( z \sim 3 \). The remaining contamination from dusty SFGs may be also possibly corresponding to the large size scatter at \( z \sim 3 \). Alternatively, repeated AGN feedback may help explain the increasing size scatter with redshift (e.g., Fan et al. 2013). By examining the Sérsic index and axis ratios, we find that a significant fraction of our \( pVLJ \) galaxies is disk-dominated. We must mention that the size comparison between massive QGs with equal stellar mass at \( z \sim 3 \) and at \( z \sim 2 \) may not be straightforward here. The progenitors of \( z \sim 2 \) massive compact galaxies are compact SFGs at \( z \sim 3–4 \) (Barro et al. 2013; Stefanon et al. 2013), which are excluded in this work according to the sSFR selection criteria. Our \( pVLJ \) galaxies could be the possible progenitors of even more massive QGs at \( z \sim 2 \).

We compare the median stellar mass surface density profile of our \( pVLJ \) galaxies with those of QGs at \( z \sim 1 \) and \( z \sim 2 \) and local ETGs. An important result is that most of the stars in the inner region (\( r < 1–2 \) kpc) of local massive ETGs have been presented in place as early as \( z \sim 3 \). The result favors the inside-out formation scenario in which the compact galaxies at high redshift make up the cores of local massive ETGs and then build up the outskirts according to dissipationless minor mergers.

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