New Astronomy 51 (2017) 99–104

Contents lists available at ScienceDirect

New Astronomy

journal homepage: www.elsevier.com/locate/newast

Corrigendum

Compact star forming galaxies as the progenitors of compact quiescent galaxies: Clustering result

Xiaozhi Lin[a], Lulu Fan[b,a,*], Xu Kong[a], Guanwen Fang[c]

[a] Department of Astronomy, University of Science and Technology of China, Hefei, 230026, China
[b] Shandong Provincial Key Lab of Optical Astronomy and Solar-Terrestrial Environment, Institute of Space Sciences, Shandong University, Weihai, 264209, China
[c] Institute for Astronomy and History of Science and Technology, Dali University, Dali, 671003, China

ARTICLE INFO

Article history:
Received 4 January 2016
Revised 17 August 2016
Accepted 20 August 2016
Available online 22 August 2016

Keywords:
Galaxies: high-redshift
Galaxies: evolution
Galaxies: structure

ABSTRACT

We present a measurement of the spatial clustering of massive compact galaxies at $1.2 \leq z \leq 3$ in CANDELS/3D-HST fields. We obtain the correlation length for compact quiescent galaxies (cQGs) at $z \sim 1.6$ of $r_0 = 7.1^{+2.3}_{-2.6}$ h^{-1} Mpc and compact star forming galaxies (cSFGs) at $z \sim 2.5$ of $r_0 = 7.7^{+2.7}_{-2.9}$ h^{-1} Mpc assuming a power-law slope $\gamma = 1.8$. The characteristic dark matter halo masses M_H of cQGs at $z \sim 1.6$ and cSFGs at $z \sim 2.5$ are $\sim 7.1 \times 10^{12}\ h^{-1}M_\odot$ and $\sim 4.4 \times 10^{12}\ h^{-1}M_\odot$, respectively. Our clustering result suggests that cQGs at $z \sim 1.6$ are possibly the progenitors of local luminous ETGs and the descendants of cSFGs and SMGs at $z > 2$. Thus an evolutionary connection involving SMGs, cSFGs, QSOs, cQGs and local luminous ETGs has been indicated by our clustering result.

1. Introduction

Massive ($M_\star \geq 10^{10}M_\odot$), quiescent galaxies (QGs) at high redshift ($z \sim 2$) have been found to have $3-5$ times smaller effective radii than their local counterparts (e.g., Daddi (2005), Trujillo (2006), van der Wel (2008), van Dokkum (2008), Damjanov (2009), Newman (2012), Szomoru et al. (2012), Zirm et al. (2012), Fan et al. (2013a, 2013b)). Since massive compact quiescent galaxies (thereafter cQGs) in the local Universe are rare (e.g., Poggianti (2013)), a significant structural evolution has been required. Therefore, there raised two questions: (1) how do these cQGs evolve into local luminous early-type galaxies (ETGs) with larger size? and (2) how did these cQGs form at higher redshift?

There are two physical mechanisms which have been proposed to explain the observed structural evolution of cQGs at $z \geq 1$. One is dissipationless (dry) minor mergers (Naab et al., 2009; Oser et al., 2012; Oogi et al., 2016). The other is "puff-up" due to the gas mass loss by AGN (Fan et al., 2008; 2010) or supernova feedback (Damjanov, 2009). The recent evidence has shown the inside-out growth of massive cQGs at $z > 2$, which indicates that dry minor mergers may be the key driver of structural evolution (Patel, 2013). However, whether dry minor mergers are sufficient for the size increase, especially at $z \geq 1.5$, is still under debate (Newman, 2012; Belli, 2014).

Possible mechanisms for the formation of cQGs include gas rich mergers (Hopkins, 2008), violent disk instability fed by cold stream, or both (Ceverino, 2015). Whatever mechanism governs the formation of cQGs, their precursors should be expected to experience a compact and active phase: compact star forming galaxies (cSFGs) or compact starburst galaxies (i.e, sub-millimeter galaxies, SMGs). Faber et al. (2013)) found a population of massive cSFGs at $z \sim 2$. They proposed that cSFGs could be the progenitors of cQGs at lower redshift, suggested by the comparison of their masses, sizes, and number densities. Toft (2014) showed that SMGs at $z > 3$ are consistent with being the progenitors of $z \sim 2$ cQGs by matching their formation redshifts and their distributions of sizes, stellar masses, and internal velocities. They suggested a direct evolutionary connection between SMGs, through compact quiescent galaxies to local ETGs. In this evolutionary scenario, star formation quenching has been proposed to be either due to gas exhaustion or quasar (QSO) feedback. The latter is essential in many models of the evolution of massive galaxies (e.g., Granato (2004), Hopkins (2010)).

In this paper, we analyze the clustering properties of cQGs and cSFGs at $1.2 \leq z \leq 3$ and compare them to other populations: high-z QSOs, SMGs and local ETGs in order to investigate the possible connection between cQGs, cSFGs, SMGs, QSOs and local ETGs. All our data come from the CANDELS and 3D-HST programs (Grogin, 2011; Koekemoer, 2011; Skelton, 2014). The CANDELS/3D-HST programs have provided WFC3 and ACS images, spectroscopy and photometry covering ≈ 900 arcmin^2 in five fields: AEGIS, COSMOS, GOODS-North, GOODS-South and the UDS. The large survey

* Corresponding author. Fax: +866315679507.
E-mail addresses: llfan@sdu.edu.cn (L. Fan), xkong@ustc.edu.cn (X. Kong).

http://dx.doi.org/10.1016/j.newast.2016.08.013
1384-1076/

areas and the depth of the HST WFC3 camera enable us to make more accurate clustering measurement than in narrower, shallower fields. We emphasize that it is essential to use the high-resolution HST WFC3 imaging to investigate the compact structure of massive galaxies at high redshift. Throughout this paper, we adopt a flat cosmology (see Komatsu et al., 2011) with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 70$ km s^{-1} Mpc^{-1}. We assume a normalisation for the matter power spectrum of $\sigma_8 = 0.84$. All quoted uncertainties are 1 σ (68% confidence). All magnitudes are in the AB magnitude system.

2. Data and sample selection

We select our massive compact galaxies at $1.2 \le z \le 3$ from HST WFC3-selected photometric catalogs in the five CANDELS/3D-HST fields (Grogin, 2011; Koekemoer, 2011; Skelton, 2014)[1,2]. The five fields cover a total science area of 896 arcmin^2 after excluding the areas surrounding bright stars and field edge regions. For galaxies with $H_{F160W} < 23$ and having WFC3/G141 grism coverage, redshifts are measured using a modified version of the EAZY code (Brammer, 2013) from a combination of the $U - IRAC$ photometric data and the WFC3/G141 grism spectra. An accuracy of 0.003 – 0.005 in $\Delta z/(1+z)$ can be reached by comparing to available spectroscopic redshifts. For the remaining galaxies, which are either faint or without grism spectra, photometric redshifts have been used instead. Probability distribution functions (PDFs) of redshift, or equivalently, the comoving line-of-sight distance χ is derived by minimising the chi-square in the photometric analysis using EAZY (Brammer et al., 2008). PDF for each galaxy is defined as $f(\chi)$, such that $\int f(\chi)d\chi = 1$. The galaxy physical properties, such as stellar masses ($M_\star$), luminosity-weighted ages and rest-frame colors, are derived using FAST (Kriek, 2009), adopting Bruzual and Charlot (2003) models assuming a Chabrier (2003) IMF, solar metallicity, exponentially declining star formation histories (SFHs) and Calzetti extinction law (Calzetti et al., 2000). For the measurement of effective radius r_e, we use the result in van der Wel (2012)[3], which is based on best-fitting of Sérsic model.

In Fig. 1, we show our selection criteria of massive compact galaxies at $1.2 \le z \le 3$ on mass-size plane. We select compact galaxies at $1.2 \le z \le 2$ by using the same criterion as presented by Faber et al. (2013)) and the lower mass limit of $1.0 \times 10^{10} M_\odot$ (dotted line):

$$log(\Sigma_{1.5}) \equiv log(M_\star/r_e^{1.5}) > 10.3\ M_\odot \cdot kpc^{-1.5} \quad (1)$$

Similarly, we select compact galaxies at $2 < z \le 3$ by using the same criterion as that in Barro and Faber (2014) (dashed line):

$$log(\Sigma_{1.5}) \equiv log(M_\star/r_e^{1.5}) > 10.45\ M_\odot \cdot kpc^{-1.5} \quad (2)$$

Here we also impose a lower mass limit of $1.0 \times 10^{10} M_\odot$.

The rest-frame UVJ color diagram has been used to classify our compact sample into two classes: cSFGs and cQGs. This method has weak dependence on dust extinction and works well up to redshift 3 (e.g., Wuyts, 2007; Williams, 2009).

For the cross-correlation analysis, we also need two comparison galaxy samples at $1.2 \le z \le 2$ and $2 < z \le 3$ in the same fields. We take ≈ 14000 and ≈ 13000 galaxies with mass range $10^9 M_\odot \le M_\star \le 10^{10} M_\odot$ within the redshift range $1.2 \le z \le 2$ and $2 < z \le 3$, respectively.

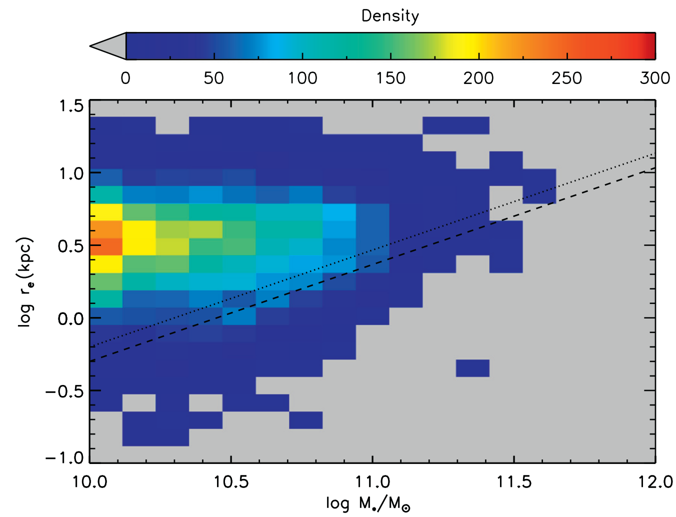

Fig. 1. The density distribution of massive galaxies at $1.2 \le z \le 3$ on the mass-size plane in CANDELS/3D-HST fields. The dotted and dashed lines mark the selection criteria of compact galaxies at $1.2 \le z \le 2$ and $2 < z \le 3$, respectively. The top color bar shows the galaxy number density.

3. Clustering analysis

Our clustering analysis is identical to the QSO-galaxy and SMGs-galaxy cross-correlation study presented in Hickox (2011) and Hickox (2012). Here we summarize some key details.

The two-point correlation function $\xi(r)$ is defined by:

$$dP = n[1 + \xi(r)]dV \quad (3)$$

where dP is the probability above Poisson of finding a galaxy in a volume element dV at a physical separation r from another randomly chosen galaxy, and n is the mean space density. In the linear halo-halo regime, the correlation function is well-described by a power law

$$\xi(r) = (r/r_0)^{-\gamma} \quad (4)$$

where r_0 is the real-space correlation length and γ has a typical value of 1.8 (e.g. Peebles, 1980).

By integrating $\xi(r)$, we can obtain the projected correlation function $\omega_p(R)$:

$$\omega_p(R) = 2\int_0^{\pi_{max}} \xi(R,\pi)d\pi \quad (5)$$

where R and π are the radial and perpendicular projected comoving distances between the two galaxies in the view of the observer. By averaging over all line-of-sight peculiar velocities, $\omega_p(R)$ can be re-written as:

$$\omega_p(R) = R\left(\frac{r_0}{R}\right)^{\gamma} \frac{\Gamma(1/2)\Gamma((\gamma-1)/2)}{\Gamma(\gamma/2)} \quad (6)$$

By weighing the PDFs of comparison galaxies overlapped with the redshift distribution of compact galaxy samples in matched pairs, we derive the real-space projected cross-correlation function using the method in Myers et al. (2009).

$$\omega_p(R) = N_R N_C \sum_{i,j} c_{i,j} \frac{D_C D_G(R)}{D_C R_G(R)} - \sum_{i,j} c_{i,j} \quad (7)$$

where $c_{i,j} = f_{i,j}/\sum_{i,j} f_{i,j}^2$ and $f_{i,j}$ is defined as the average value of the radial PDF $f(\chi)$ for each comparison galaxy i, in a comoving distance window (100 h^{-1} Mpc) around each compact galaxy j. R is the projected comoving distance from each galaxy in our compact galaxy sample to that in the comparison galaxy sample or

[1] http://candels.ucolick.org/
[2] http://3dhst.research.yale.edu/Data.php
[3] http://www.mpia.de/homes/vdwel/candels.html