GALAXY FORMATION AT z > 3 REVEALED BY NARROWBAND-SELECTED [O III] EMISSION LINE GALAXIES

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ABSTRACT

We present the physical properties of [O III] emission line galaxies at z > 3 as the tracers of active galaxies at 1 Gyr before the peak epoch at z ~ 2. We have performed deep narrowband imaging surveys in the Subaru/XMM-Newton Deep Survey Field with the Multi-object InfraRed Camera and Spectrograph on the Subaru Telescope and have constructed coherent samples of 34 [O III] emitters at z = 3.2 and 3.6, as well as 107 Hα emitters at z = 2.2 and 2.5. We investigate their basic physical quantities, such as stellar masses, star formation rates (SFRs), and sizes, using the publicly available multiwavelength data and high-resolution images from the Hubble Space Telescope. The stellar masses and SFRs show a clear correlation known as the “main sequence” of star-forming galaxies. It is found that the location of the main sequence of the [O III] emitters at z = 3.2 and 3.6 is almost identical to that of the Hα emitters at z = 2.2 and 2.5. Also, we investigate their mass–size relation and find that the relation does not change between the two epochs. When we assume that the star-forming galaxies at z = 3.2 grow simply along the same main sequence down to z = 2.2, galaxies with $M_\star = 10^9$–$10^{11} M_\odot$ increase their stellar masses significantly by a factor of 10–2. They climb up the main sequence, and their SFRs also increase a lot as their stellar masses grow. This indicates that star formation activities of galaxies are accelerated from $z > 3$ toward the peak epoch of galaxy formation at $z \sim 2$.

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

1. INTRODUCTION

The activities of star formation in galaxies and those of active galactic nuclei (AGNs) are very high at $z \sim 1$–3, corresponding to about 8–10 billion years ago (e.g., Fan et al. 2004; Hopkins & Beacom 2006). Physical states of galaxies are expected to change dramatically during this epoch, and it is critical to investigate galaxy properties in detail at this epoch in order to understand physical processes of galaxy formation. With the near-infrared (NIR) photometric and spectroscopic observations with ground-based and space telescopes, studies of high-z galaxies have advanced substantially in recent years, and our knowledge of physical states of those galaxies has been expanded significantly by many previous studies (e.g., Erb et al. 2006a; van Dokkum et al. 2008; Förster Schreiber et al. 2009; Kriek et al. 2009a; Wuys, et al. 2011).

An example is the discovery of the relationship between stellar mass and star formation rate (SFR) of star-forming galaxies at both low and high redshifts. Many previous studies have revealed that these two quantities show a tight correlation, called the “main sequence” of star-forming galaxies (e.g., Daddi et al. 2007; Elbaz et al. 2007; Noeske et al. 2007; Whitaker et al. 2012; Kashino et al. 2013). Using galaxy samples across a wide redshift range, the evolution of this relation has been investigated (e.g., Whitaker et al. 2012; Koyama et al. 2013; Tasca et al. 2014). These studies have shown that the $M_\star$–SFR relation does evolve strongly with redshift at least up to $z \sim 2.5$, in the sense that SFR increases monotonically with redshift at a given stellar mass.

Another example is the discovery of compact, massive, and quiescent galaxies at $z \sim 2$ (“red nuggets”; Daddi et al. 2005; Damjanov et al. 2009) and their likely progenitors, namely, compact star-forming galaxies at $z \geq 2$. The compact star-forming galaxies are thought to be formed by gas-rich processes such as mergers or disk instabilities that invoke starbursts in the central compact regions. They would then become compact, quiescent galaxies when their star formation activities are quenched (Barro et al. 2013). We can search for such compact star-forming galaxies based on the stellar mass versus size diagram. The redshift evolution of the mass–size relation is crucial for identifying the evolutionary paths from star-forming galaxies to quiescent galaxies, and it has been investigated up to $z \sim 3$. It is found that the sizes of early-type galaxies depend more strongly on their stellar masses as compared to late-type galaxies and that the average size evolution at a fixed stellar mass of late-type galaxies is very slow, while the average size of the early-type galaxies increases rapidly with the cosmic time (e.g., Shen et al. 2003; van der Wel et al. 2014).

The studies of physical properties of galaxies are now being expanded to the more distant universe beyond the highest peak of the star formation activities at $z \sim 2$–3. The epoch of $z \sim 3$–3.7, corresponding to about 1–2 Gyr before the peak epoch, is especially crucial to reveal how galaxy formation activities are activated toward its peak. At $z > 2.5$, the ultraviolet (UV) light is often used to construct star-forming galaxy samples. Using the UV-selected galaxies, such as the Lyman break galaxies (LBGs), the redshift evolution of star formation activities has been investigated (e.g., Stark et al. 2009, 2013; González et al. 2010; Reddy et al. 2012; Tasca et al. 2014).
Stark et al. (2013) investigate the evolution of the specific SFR (sSFR = SFR/$M_\star$) for the spectroscopically confirmed LBG sample at $3.8 < z < 5$. Their result indicates that the sSFR at the fixed stellar mass increases by a factor of 5 from $z \sim 2$ to $z \sim 7$. Based on the i-band-selected and spectroscopically confirmed galaxy sample, Tasca et al. (2014) investigate the evolution of the $M_\star$-sSFR and $M_\star$-sSFR relations up to $z \sim 5$. Their conclusion is that the sSFR increases very slowly from $z \sim 3$ up to $z \sim 5$. These two galaxy samples have some small differences in the sample selection (see the papers for details). Moreover, both of the samples are likely to be biased to less dusty star-forming galaxies since the samples are selected at the rest-frame far-UV. Up to $z \sim 2.5$, the H$\alpha$ emission line is a good tracer of star formation activity, due to its lower sensitivity to the dust extinction as compared to the UV light. However, since the H$\alpha$ line comes to longer wavelength than $K$ band at $z > 3$, we are no longer able to use the H$\alpha$ line as the tracer of star-forming galaxies at $z > 3$ in the observations with ground-based telescopes. Recent NIR spectroscopic observations have revealed that the high-$z$ star-forming galaxies show strong [O iii] emission lines (e.g., Holden et al. 2014; Masters et al. 2014; Shimakawa et al. 2014; Steidel et al. 2014). Such a strong [O iii] emission line indicates extreme interstellar medium (ISM) conditions of high-$z$ star-forming galaxies. Nakajima & Ouchi (2014) have shown that the lower metallicities and higher-ionization parameters contribute to their extreme ISM conditions. Therefore, we argue that the [O iii] emission line is one of the best tracers of star-forming galaxies at $z > 3$. We should note, however, that the [O iii] emission line originates from ionized regions not only by hot young massive stars but also by AGNs.

We have conducted a systematic narrowband (NB) imaging survey with the Subaru Prime Focus Camera (Suprime-Cam) and Multi-object InfraRed Camera and Spectrograph (MORIRCS) on the Subaru Telescope. The project is called “MAHALO-Subaru” (MApping HAlpha and Lines of Oxygen with Subaru; Kodama et al. 2013). The imaging observations with NB filters allow us to obtain emission-line galaxies in particular redshift slices. By targeting high-density regions, such as clusters or protoclusters, as well as the lower-density blank fields, we have constructed a coherent NB-selected galaxy sample across various environments and cosmic times. Tadaki et al. (2013) carried out NB imaging observations with MORIRCS at the Subaru/XMM-Newton Deep survey Field (SXDF; Furusawa et al. 2008) and have constructed the H$\alpha$ emitter sample at $z = 2.2$ and 2.5. They found that the H$\alpha$ emitters constitute the star-forming main sequence and that galaxies with high SFRs located above the main sequence tend to be dustier. They also investigated the structural properties of the H$\alpha$ emitters using the Hubble Space Telescope (HST) images (Tadaki et al. 2014). They found two classes of objects: star-forming galaxies with extended disks, and massive and compact star-forming galaxies. The latter class of objects are likely to evolve to the red nuggets seen at similar or lower redshifts after quenching their star formation activities and eventually to massive elliptical galaxies today after significant size growth by minor mergers (e.g., van Dokkum et al. 2010). In order to make such evolutionary links further, it is important to explore those possible progenitors (massive and compact star-forming galaxies) at higher redshifts, $z > 3$, in a systematic way.

In this study, we construct an NB-selected [O iii] emitter sample at $z > 3$ based on the NB imaging survey data at SXDF taken through the MAHALO-Subaru project (Tadaki et al. 2013). We investigate their physical properties to reveal galaxy formation at the epoch shortly before the highest peak of activities. In this field, a range of multiband photometric data and high-resolution images by HST are available. Combining those data with our NB imaging data, we investigate stellar masses, SFRs, and sizes of the [O iii] emitters. We then compare their properties with those of the H$\alpha$ emitters at lower redshifts ($2.2 < z < 2.5$) in the same field to track the evolution of star-forming galaxies between the two epochs.

This paper is organized as follows: In Section 2, we briefly introduce our NB imaging observations and the publicly available observational data in SXDF and explain the selection method of emission-line galaxies. In Section 3, we present the measurements of basic physical quantities of the [O iii] emitters, such as stellar masses, SFRs, and sizes, and show the relations between these physical quantities. We also compare our galaxy sample with the H$\alpha$ emitters at lower redshifts in the same field. In Section 4, we discuss any possible selection bias arising from our use of the [O iii] emission line as the tracer of star-forming galaxies at $z > 3$. We also discuss the mass growth and star formation histories (SFHs) of galaxies from $z = 3.2$ to $z = 2.2$ with a simple model. Finally, we summarize our study in Section 5. We assume the cosmological parameters of $\Omega_m = 0.27$, $\Omega_{\Lambda} = 0.73$, and $H_0 = 71$ [km s$^{-1}$ Mpc$^{-1}$]. Through this paper, unless otherwise noted, all the magnitudes are given in the AB magnitude system (Oke & Gunn 1983), and the Salpeter initial mass function (IMF; Salpeter 1955) is adopted for the estimations of stellar masses and SFRs.

2. OBSERVATIONAL DATA AND SAMPLE SELECTION

2.1. Narrowband Imaging Surveys

We summarize below our NB imaging observations performed at SXDF, and further details of the observations and data reduction are described in Tadaki et al. (2013).

The NB imaging at SXDF was carried out with the NIR camera and spectrograph called MORIRCS (Suzuki et al. 2008) on the Subaru Telescope. MORIRCS is equipped with two HAWAI-2 detectors (2048 × 2048 pixels). The pixel scale is 0.117 arcsec pixel$^{-1}$, and the field of view is 4′ × 7′. Two NB filters were used, namely, NB 209 ($\lambda_c = 2.093$ μm, FWHM = 0.026 μm) and NB 2315 ($\lambda_c = 2.317$ μm, FWHM = 0.026 μm). The NB 209 and NB 2315 filters can probe H$\alpha$ emission lines at $z = 2.191 \pm 0.019$ and $z = 2.525 \pm 0.021$ and also [O iii]λ5007 emission lines at $z = 3.174 \pm 0.025$ and $z = 3.623 \pm 0.027$, respectively. Figure 1 shows the transmission curves of these two NB filters. The data were obtained over several observing runs from 2010 October, November, and 2011 September. The total observed areas were 91 arcmin$^2$ and 93 arcmin$^2$ for NB 209 and NB 2315, respectively. The survey areas are slightly different between the two NB filters, but both are overlapped with the CANDELS-UDS field observed by HST/Advanced Camera for Surveys (ACS) and WFC3 (see Figure 2 of Tadaki et al. 2013). The exposure times were 140–186 minutes, and the seeing sizes were 0.5″–0.7″ (FWHM). The 5σ limiting magnitudes with 1″ diameter aperture were 23.6 and 22.88 mag in NB 209 and NB 2315, respectively. The observed data were reduced with
the MOIRCS imaging pipeline software (MCSRED);\(^6\) Tanaka et al. (2011). The point-spread functions (PSFs) were smoothed to 0\(^\prime\)7 when combining all the images.

### 2.2. Public Data

In our survey field, SXDF, the multiwavelength data from UV to mid-infrared are all available. We use the public photometric catalog provided at the Rainbow Database\(^7\) (Galametz et al. 2013). It contains \(u\)-band data from Canada–France–Hawaii Telescope (CFHT)/Megacam (O. Almaini et al. 2015, in preparation); \(B\), \(V\), \(R\), \(i\), \(z\), and \(\text{z}^\prime\)-band data from Subaru/Prime-Cam (SXDS; Furusawa et al. 2008); \(Y\) and \(K\)-band data from VLT/HAWK-I (HUGS; Fontana et al. 2014); \(J\), \(H\), and \(K\)-band data from UKIRT/WFCAM (UKIDSS; Lawrence et al. 2007); 3.6, 4.5, 5.8, and 8.0 \(\mu\)m data from Spitzer/IRAC; and 24 \(\mu\)m data from Spitzer/MIPS (SpUDS; PI: J. Dunlop and SEDS; Ashby et al. 2013).

Our survey areas are also mostly covered by the HST/ CANDELS (Grogin et al. 2011; Koekemoer et al. 2011), and the photometric catalog and the high-resolution images of \(V\)\(^{F606W}\) and \(I\)\(^{F814W}\) band from ACS and \(J\)\(^{F125W}\) and \(H\)\(^{F160W}\) band from WFC3 are all publicly available. All the publicly available multwavelength data used in this study are summarized in Table 1.

### 2.3. Selection of [O \(\text{III}\)] Emitters at \(z > 3\)

First of all, we extract sources from the NB images taken with MOIRCS and the broadband (BB; \(H\) and \(K\) bands) images taken with WFCAM, using the public software SExtractor (Bertin \\& Arnouts 1996). The pixel scales and PSF sizes of the BB images are matched to those of the NB images. We perform aperture photometries on the NB and BB images with a 1\(\prime\)6 diameter aperture. Source extraction and photometries are carried out with the double image mode of SExtractor. Those aperture photometry data are used to select line emitters based on the color–magnitude diagrams (Figure 2) and to measure NB fluxes. On the other hand, the template-fitting photometry data from the public catalog (see Galametz et al. 2013 for more details) are used for the color–color selections (Figure 3), the spectral energy distribution (SED) fitting, and the SFR measurements from UV luminosities (in \(R\)\(^c\) band).

The objects that have large excesses in NB fluxes as compared to BB fluxes are selected as the NB emitters. Since the effective wavelengths of the NB filters and the \(K\) band are slightly different, we estimate BB fluxes at the exact effective wavelengths of the NB 209/NB 2315 filters by interpolating fluxes between \(H\) and \(K\) bands as follows (Tadaki et al. 2013):

\[
\begin{align*}
\text{HK} (\lambda = 2.09 \, \mu\text{m}) &= 0.8 \, K + 0.2 \, H - 0.015, \\
\text{HK} (\lambda = 2.315 \, \mu\text{m}) &= 1.2 \, K - 0.2 \, H + 0.011.
\end{align*}
\]

We select NB excess sources using \(\text{HK}–\text{NB} 209\) or \(\text{HK}–\text{NB} 2315\) color–magnitude diagrams (Figure 2). We use a parameter \(\Sigma\), which determines the significance of an NB excess relative to a 1\(\sigma\) photometric error (Bunker et al. 1995). The relation between \(\Sigma\) and the color of \(m_{\text{BB}} - m_{\text{NB}}\) is obtained from

\[
m_{\text{BB}} - m_{\text{NB}} = -2.5 \log_{10} \left[ 1 + \frac{\Sigma \sqrt{\sigma^2_{\text{BB}} + \sigma^2_{\text{NB}}}}{f_{\text{NB}}} \right],
\]

where \(f_{\text{NB}}\) is an NB flux density, and \(\sigma^2_{\text{BB}}\) and \(\sigma^2_{\text{NB}}\) are the sky noises in the BB and NB images measured within an aperture, respectively (Tadaki et al. 2013). We set the criterion of \(\Sigma = 3\) to sample secure emitters, and it is represented as the solid curve in Figure 2. We also set the criteria that the NB magnitude excess with respect to the \(HK\) magnitude, \(HK-\text{NB}\), is larger than 0.4 mag, and that the NB magnitude is brighter than the 5\(\sigma\) limiting magnitude (the horizontal red line and the vertical dashed line in Figure 2, respectively). With these selection criteria, we obtain 101 and 58 NB excess sources in NB 209 and NB 2315, respectively.

The NB 209 (NB 2315) filter captures different emission lines from galaxies at different redshifts, such as \(\text{H}\alpha\) emission.

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\(^6\) http://www.naoj.org/staff/ichi/MCSRED/mcsred.html

\(^7\) https://arcoiris.ucolick.org/Rainbow_navigator_public/
lines at \( z = 2.19(2.53) \) and [O iii] emission lines at \( z = 3.17(3.62) \). In order to construct a sample of [O iii] emitters at \( z > 3 \), we need to separate [O iii] emitters from Hα emitters at \( z < 3 \). The conspicuous spectral features such as the Balmer and/or 4000 Å breaks can be used for this purpose. Since the break feature is redshifted to a different wavelength in the observed frame according to the redshift of a galaxy, if we choose an appropriate combination of passbands that can neatly straddle the spectral break feature, we are able to disentangle those various possible solutions for different line emitters at different redshifts. Tadaki et al. (2013) use an \( i' - J \) versus \( J - K \) diagram for NB 209 emitters and \( i' - H \) versus \( H - K \) diagram for NB 2315 emitters. They have shown that [O iii] emitters at \( z > 3 \) and Hα emitters at \( z < 3 \) can be well separated by the dividing lines as shown in Figure 3. We follow their selection method, and here the contribution from the emission line is subtracted from the \( K \)-band magnitude. Our NB emitter sample may also contain some Pα emitters at low redshifts (\( z = 0.1-0.2 \)). However, since the Pα emitters should appear in the same regions as the Hα emitters on these diagrams, they should not be major contaminants for our [O iii] emitters. We have thus finally obtained strong candidates for [O iii] emitters: 27 at \( z = 3.17 \) and 7 at \( z = 3.62 \).

Figure 4 shows the relation between stellar masses and dust-extinction-uncorrected SFRs measured from [O iii] line luminosities for the [O iii] emitters in order to verify our sample selection. We will explain our method of measuring stellar masses and SFRs in the following sections. Our criteria of determining NB flux excesses, namely, \( \Sigma > 3 \) and \( HK - NB 209 > 0.4 \) [mag] as shown in Figure 2, correspond to the limits of SFR \( > 4.5 \) [\( M_\odot \) yr\(^{-1}\)] and EW\(_{\text{rest}}\) > 30 [Å], respectively. We draw a line corresponding to the EW cut on the \( M_{\star} - \text{SFR} \) diagram by establishing a relation between stellar mass and SFR along the threshold of \( HK - NB 209 = 0.4 \). As proxies of the \( H - K \) and \( J - K \) colors along this boundary line, we use the averaged colors of the three objects that are located nearest to the boundary of \( HK - NB 209 = 0.4 \). Then, for a given NB magnitude, we assign a \( K \)-band magnitude using \( HK - NB 209 = 0.4 \) and the above \( H - K \) color. A
stellar mass is then estimated from the $K$-band magnitude and the above $J - K$ color. $J - K$ color is used to correct for the mass-to-light ratio based on the stellar population synthesis model of Kodama et al. (1998, 1999). Also a dust-extinction-uncorrected SFR$_{[O II]}$ is calculated from each NB magnitude. Figure 4 shows that our EW cut is located well below the actual observed data points, and our selected galaxy sample is not biased to any particular galaxies on the main-sequence diagram.

3. PHYSICAL PROPERTIES OF [O II] EMITTERS

3.1. AGN Contribution

Not only hot young massive stars in star-forming regions but also AGN activities can contribute to the [O II] line intensity. Therefore, it is important for us to verify the presence of AGN candidates in our sample.

We use a photometric redshift code EAZY (Brammer et al. 2008) to obtain the rest-frame $U$-, $V$-, and $J$-band magnitudes for our sample. Note that derived photometric redshifts are mostly consistent with the expected redshifts, $z = 3.2$ and 3.6. The rest-frame $U-V$ and $V-J$ colors allow us to distinguish between two galaxy populations, namely, old quiescent galaxies and young, dusty star-forming galaxies, by capturing the Balmer/4000 Å breaks between $U$ and $V$ bands (e.g., Wuyts et al. 2007; Williams et al. 2009; Whitaker et al. 2011). Figure 5 shows the rest-frame $UVJ$ color–color diagram for our [O II] emitters. We find that one object is marginally classified as a quiescent galaxy, indicating that its [O II] emission is likely to be dominated by the AGN activity rather than the star formation. However, we cannot discriminate between the contribution from AGNs and that from star-forming regions for all the other emitters classified as star-forming galaxies.

For further investigation, we inspect the X-ray image from XMM-Newton (Ueda et al. 2008). None of our [O II] emitters are detected in X-ray, and thus our sample does not seem to contain any bright unobscured AGNs. We also look into the Spitzer/MIPS 24 μm catalog and find that three objects are detected with MIPS. A fraction of them might be obscured AGNs with warm dust components that emit strong IR emissions.

Spectroscopic observations are necessary to confirm the presence of AGNs, and we do not exclude these objects in the following analyses.

3.2. SED Fitting

We perform the SED fitting for our [O II] emitters using the public code FAST (Kriek et al. 2009b). We use 18 bands, $u$, $B$, $V$, $R_c$, $i'$, $z'$, $F606W$, $F814W$, $F125W$, $F160W$, $Y$, $J$, $H$, $K_s$, 3.6, 4.5, 5.8, and 8.0 μm. For the NB 209-selected [O II] emitters, emission-line fluxes are subtracted from the $K_s$-band fluxes before the SED fitting is performed, while no correction is required for the NB 2315-selected ones as the NB 2315 has little overlap with the $K_s$ band in wavelength. The redshifts of the NB 209- and NB 2315-selected [O II] emitters are fixed to $z = 3.17$ and 3.62, respectively, for the SED fitting. We use the stellar population synthesis model of Bruzual & Charlot (2003), the Salpeter IMF (Salpeter 1955), and the dust attenuation law of Calzetti et al. (2000). We assume the exponentially declining SFH in the form of SFR $\sim \exp(-t/\tau)$, with $\log(\tau/{\hbox{year}}) \approx 7.0-10.0$ in steps of 0.5, and the solar metallicity. The output physical quantities from the FAST code are star formation timescale $\tau$, age, dust extinction $A_V$, stellar mass, SFR, specific SFR, and age/τ ratio.

The stellar masses and dust extinctions ($A_V$) used in the following analyses are all estimated by the SED fitting.
3.3. Star Formation Rates

We estimate SFRs of the [O\text{III}] emitters with two different indicators, namely, the UV continuum luminosities (tracing hot young stars) and the [O\text{III}] emission line intensities (tracing star-forming H\text{ii} regions). In the former case, we adopt the following equation from Madau et al. (1998):

\[
\text{SFR} \left( M_\odot \text{yr}^{-1} \right) = \frac{4\pi D_L^2 f_\nu}{(1+z)8 \times 10^{27}} \left( \text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1} \right)
\]

\[
= \frac{L_{1600} \text{Å}}{8 \times 10^{27} \text{ erg s}^{-1} \text{Hz}^{-1}},
\]

(4)

where \(D_L\) is the luminosity distance and \(f_\nu\) is the flux density derived from the \(R_c\)-band magnitude (\(\lambda_c = 6498.1 \text{ Å}\)). The dust extinction at 1600 Å is estimated from the SED-based \(A_V\) value and the extinction curve for starburst galaxies of Calzetti et al. (2000):

\[
E(B-V)_{\text{stellar}} = A_V/R_V^c,
\]

\[
A'(\lambda) = k'(\lambda)E(B-V)_{\text{stellar}},
\]

(5)

and

\[
k'(\lambda) = 2.659(-2.156 + 1.509/\lambda
- 0.198/\lambda^2 + 0.011/\lambda^3)
+ R_V^c, \quad \text{at } 0.12 \mu \text{m} \leq \lambda \leq 0.63 \mu \text{m}.
\]

(7)

\(E(B-V)_{\text{stellar}}\) indicates the amount of reddening in the stellar continuum, and \(R_V^c\) is 4.05 for starburst galaxies (Calzetti et al. 2000). The intrinsic flux density \(f_\nu(\lambda)\) is then obtained as

\[
f_\nu(\lambda) = f_\nu^c(\lambda)10^{0.4A'(\lambda)},
\]

(8)

and the dust-extinction-corrected SFRs (SFR\text{UV}) are derived using Equation (4).

In Maschietto et al. (2008), they derive an SFR from an [O\text{III}] emission line strength by assuming an [O\text{III}]/H\alpha ratio of \(\sim 2.4\), which is the maximum value for local star-forming galaxies (Moustakas et al. 2006). Considering the fact that high-z star-forming galaxies show very high [O\text{III}]/H\beta ratio due to the high excitation states (e.g., Holden et al. 2014; Masters et al. 2014; Shimakawa et al. 2014; Steidel et al. 2014), this assumption seems to be reasonable for our sample, although this ratio has a large dispersion among individual galaxies (Moustakas et al. 2006). We adopt this maximum ratio to derive the relation between the SFR and H\alpha luminosity of Kennicutt (1998b):

\[
\text{SFR}_{H\alpha} \left( M_\odot \text{yr}^{-1} \right) = 7.9 \times 10^{-42} \frac{L_{H\alpha}}{\text{erg s}^{-1}},
\]

(9)

The lower limit of SFR\text{OIII} is thus obtained by

\[
\text{SFR}_{[\text{OIII}]} \left( M_\odot \text{yr}^{-1} \right) > 0.33 \times 10^{-41} \frac{L_{\text{OIII}}}{\text{erg s}^{-1}}.
\]

(10)

The luminosity of the [O\text{III}] emission line, \(L_{\text{OIII}}\), is obtained by measuring the [O\text{III}] line flux from the NB and BB flux densities. The NB and BB flux densities are defined as

\[
f_{\text{NB}} = f_c + F_{\text{line}}/\Delta_{\text{BB}},
\]

(11)

\[
f_{\text{BB}} = f_c + F_{\text{line}}/\Delta_{\text{BB}},
\]

(12)

where \(f_c\) is a continuum flux density, \(F_{\text{line}}\) is a line flux intensity, and \(\Delta_{\text{NB}}\) and \(\Delta_{\text{BB}}\) are FWHMs of the NB and BB filters, respectively (Tadaki et al. 2013). The continuum flux density, the line flux intensity, and the equivalent width (EW) in the rest frame are given by the following equations, respectively:

\[
f_c = \frac{f_{\text{BB}} - f_{\text{NB}} \left( \Delta_{\text{NB}}/\Delta_{\text{BB}} \right)}{1 - \Delta_{\text{NB}}/\Delta_{\text{BB}}},
\]

(13)

\[
F_{\text{line}} = \Delta_{\text{NB}} \frac{f_{\text{BB}} - f_{\text{NB}}}{1 - \Delta_{\text{NB}}/\Delta_{\text{BB}}},
\]

(14)

\[
\text{EW}_{\text{rest}} = \frac{F_{\text{line}}}{f_c}(1 + z)^{-1}.
\]

(15)

The line flux \(F_{\text{line}}\) is converted to the [O\text{III}] luminosity with \(L_{[\text{OIII}]} = 4\pi D_L^2 F_{\text{line}}\). The dust extinction at 5007 Å is estimated in the same manner as used for the dust extinction at 1600 Å based on the SED fitting. We assume that there is no extra extinction for the nebula emissions compared to the stellar extinction, i.e., \(E(B-V)_{\text{stellar}} = E(B-V)_{\text{nebula}}\).

In Figure 6, we compare SFRs derived from the two different indicators. The ratios of SFR\text{OIII}/SFR\text{UV} range from 0.25 to 3 for most of the objects. On the other hand, the object classified as a quiescent galaxy on the UVJ diagram (Figure 5) shows a slightly higher ratio of SFR\text{OIII}/SFR\text{UV} \(\sim 5.3\). It suggests that this object has an extra contribution from an AGN to its [O\text{III}] emission, as expected in Section 3.1.

3.4. M*–SFR Relation

We investigate the relation between stellar masses and SFRs (the “main sequence” of star-forming galaxies) for the [O\text{III}] emitters at \(z > 3\). The dust-extinction-corrected SFRs (SFR\text{UV}) of most of the [O\text{III}] emitters at SXDF range from a
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3.5. Sizes

Our NB imaging survey areas are covered by the HST/CANDELS fields, and high spatial resolution images in the rest-frame UV–optical wavebands (ACS and WFC3) are available for the [O iii] emitters.

We use the structural parameters measured by van der Wel et al. (2012) on the HFI160W-band-selected objects in CANDELS. We briefly summarize below their methods to obtain the structural parameters. They perform a Sérsic model fit to the HFI160W-band–selected objects using the software GALAPAGOS (Barden et al. 2012) and GALFIT (Peng et al. 2010). The parameters that are used for the fit are the total magnitude, half-light radius measured along the major axis, Sérsic index, axial ratio, position angle, and central position. The initial guesses of these parameters are given by SExtractor. The best-fit GALFIT parameters for all the objects are publicly available in the Rainbow Database (Galametz et al. 2013). A flag number between 0 and 3 is assigned for each object. We reject objects with flag $\geq 2$ because the fitting result with a Sérsic model becomes increasingly unreliable. They note that resultant structural parameters have systematic and random uncertainties and that such uncertainties depend on the brightness of objects and become larger for fainter objects. At $HFI160W = 25$, systematic and random uncertainties of the half-light radius ($r_e$ in arcsec) are $0".04$ and $0".18$, respectively, when $r_e$ is less than $0".3$, while they are $-0".09$ and $0".33$ when $r_e$ is greater than $0".3$. At $HFI160W = 26$, those uncertainties become as large as $0".12/0".42$ ($r_e < 0".3$) and $-0".11/0".63$ ($r_e > 0".3$), respectively.

Using the GALFIT parameters from van der Wel et al. (2012), we estimate the effective radius $r_e$ [kpc] in the rest-frame U band for the [O iii] emitters. We use only the bright objects ($HFI160W < 25$) with flag values of 0 or 1. Based on the magnitude cut and the flag values, 10 and 9 objects, respectively, are excluded from the [O iii] emitter sample.

3.6. $M_*$–Size Relation

Figure 8 shows the relation between stellar masses and sizes for the [O iii] emitters at $z > 3$. The HFI emitters at $z = 2.2$ and 2.5 are also shown. Their sizes are estimated in the HST $J_{125W}$-band images so that they can be directly compared to those of our [O iii] emitters at the same rest-frame wavelength. The size measurements are also limited to the bright objects ($J_{125W} < 25$) with flag = 001. In Figure 8, the solid and dashed lines represent the mass–size relations of late- and early-type galaxies at $2.5 < z_{\text{phot}} < 3.5$, respectively, derived from the 3D-HST/CANDELS group (van der Wel et al. 2014). We find that the size distribution of the [O iii] emitters with respect to the stellar mass is similar to that of the HFI emitters, and that they follow the mass–size relation of late-type galaxies at $z \sim 2.75$ from van der Wel et al. (2014). In van der Wel et al. (2014), galaxy sizes are estimated at a rest-frame wavelength of 5000 Å, slightly longer than in the rest-frame U band, where our galaxy sizes are measured. To verify a possible effect due to wavelength mismatch, we also apply their same correction method to our sample, and we confirm that there is no systematic difference between the two measurements at different wavelengths.

While most of the [O iii] emitters have sizes consistent with the mass–size relation of late-type galaxies at $z \sim 2.75$, there is a massive [O iii] emitter for its size ($M_\odot \sim 3 \times 10^{10} M_\odot$ and

Figure 7. Stellar mass and SFR relation (main sequence of star-forming galaxies) for the [O iii] emitters (filled circles for $z = 3.2$, and open circles for $z = 3.6$) and the HFI emitters at $z = 2.2$ and 2.5 from Tadaki et al. (2013; filled triangles). SFRs are derived from UV luminosities and corrected for dust extinction. Errors in SFRs for the [O iii] emitters are estimated from 1σ photometric errors of the $R_c$-band magnitudes. The solid line represents the best-fit line to the HFI emitters: SFR$_{\text{UV}} = 129 M_{\odot} \text{yr}^{-1} (M_{\text{125}}/10^9 M_\odot)$. Top and right histograms show the stellar mass and SFR distributions of the [O iii] emitters at $z = 3.2$ and 3.6 (red hatched histograms) and the HFI emitters at $z = 2.2$ and 2.5 (blue open histograms) with an arbitrary scale.

Few to $\sim 30 M_\odot$ yr$^{-1}$. Figure 7 shows an $M_*–$SFR relation for the [O iii] emitters at $z = 3.2$ and 3.6, together with the HFI emitters at $z = 2.2$ and 2.5 in the same field (Tadaki et al. 2013). We re-estimate stellar masses and dust-extinction-corrected SFRs (SFR$_{\text{UV}}$) of the HFI emitters in the same manner as in this study by using the FAST code (Section 3.2).

We find that stellar masses and SFRs of the [O iii] emitters show a clear correlation, as seen in other studies of star-forming galaxies across a wide redshift range (e.g., Daddi et al. 2007; Elbaz et al. 2007; Whitaker et al. 2012; Kashino et al. 2013; Koyama et al. 2013; An et al. 2014; Tasca et al. 2014). The normalization of the $M_*–$SFR relation for the [O iii] emitters at $z = 3.2$ and 3.6 looks almost identical to that of the HFI emitters at $z = 2.2$ and 2.5. We confirm that the best-fit line to the [O iii] emitters is consistent with the fit to the HFI emitters within 1σ errors in both the slopes and the intercepts. Importantly, however, the distributions of galaxies along the main sequence are systematically different in the sense that the stellar masses of the [O iii] emitters at $z \sim 3.2$ and 3.6 are much (nearly by a factor of 10) lower than those of the HFI emitters at $z \sim 2.2$ and 2.5. We can simply interpret the difference in two ways: (1) the evolution of galaxies from $z = 3.2$, 3.6 to $z = 2.2$, 2.5, and (2) the selection bias between [O iii] and HFI emitters. In Section 4.1, we refer to option 2, and in Section 4.2, we assume that the difference between stellar mass distributions is only due to the evolution of galaxies from $z = 3.2$, 3.6 to $z = 2.2$, 2.5, and we discuss how their stellar masses and SFRs grow in this time interval.
Massive and compact star-forming galaxies are expected to evolve to massive and compact quiescent galaxies when their star formation is quenched (e.g., Barro et al. 2013; Tadaki et al. 2014). We confirm the presence of such massive and compact star-forming galaxies at $z = 3.2$.

4. DISCUSSIONS

4.1. Selection Bias

We note here a possible selection bias introduced by our use of the [O III] emission line as an indicator of star-forming galaxies. When we use the [O III] line, the galaxy sample tends to be biased toward galaxies with more extreme ISM conditions. It has been found that high-$z$ star-forming galaxies tend to have much higher excitation states (e.g., Holden et al. 2014; Masters et al. 2014; Shimakawa et al. 2014; Steidel et al. 2014). Shimakawa et al. (2014) perform the NIR spectroscopic observations of the Hα emitters at $z = 2.2$ and 2.5 associated with the two protocluster fields and have shown that the [O III]/Hα ratios measured from the stacked spectra are $\sim$1.0–3.0 in the stellar mass range of $10^{9}$–$10^{11} M_\odot$. The extreme ISM condition is expected to be a common feature among high-$z$ star-forming galaxies, and we expect that the [O III] emission line is an appropriate tracer of normal star-forming galaxies at high redshifts.

The [O III] emitters may also be biased to less dusty galaxies compared to the Hα emitters, since the [O III] emission line (5007 Å) is located at a slightly shorter wavelength than the Hα emission line (6563 Å) and hence more strongly affected by dust extinction. However, adopting the extinction curve of Calzetti et al. (2000), the dust extinction at the wavelength of the [O III] line is only $\sim$1.3 times larger than that at the wavelength of the Hα line. Considering that high-$z$ star-forming galaxies tend to have high [O III]/Hα ratios as mentioned above, the effect of dust extinction for the [O III] line would not introduce a strong bias to less dusty galaxies.

Moreover, the metallicity of galaxies may also affect the strength of [O III] emission. Since lower metallicity leads to higher stellar temperature, the [O III] line becomes stronger. Given the well-known mass–metallicity relation of star-forming galaxies (e.g., Erb et al. 2006), this metallicity effect may result in a possible bias toward lower stellar masses for [O III] emitters as compared to Hα emitters.

In order to verify those selection biases, HiZELS (the High-redshift(Z) Emission Line Survey; Best et al. 2010; Sobral et al. 2013, 2014) offers a very unique sample of dual emitters. They used a pair of NB filters to capture [O III] and Hα emission lines at the same redshift, and they constructed the samples of [O III] emitters and Hα emitters at $z = 2.23$ (D. Sobral, private communication). We will address the selection biases between the two samples based on this unique data set in a forthcoming paper (D. Sobral 2015, private communication).

4.2. Galaxy Growth from $z = 3.2$ to $z = 2.2$

In Section 3.4, we show that there is no significant change in the location of the main sequence of star-forming galaxies between $z = 3.2$ (3.6) and $z = 2.2$ (2.5), but the galaxy distributions on the sequence are different between the two epochs. In this section, we assume that the differences in galaxy distributions on the $M_\ast$–SFR plane between the [O III] emitters and Hα emitters is simply due to the evolution of star-forming galaxies between the two epochs, and we discuss the stellar mass growth of galaxies from $z = 3.2$ to $z = 2.2$. From our result that the location of the main sequence is unchanged during this time interval (1 Gyr), which is represented by SFR = $129 M_\odot^{0.705} L_{\odot}$ as defined for the Hα emitters at $z = 2.2$ and 2.5 (Figure 7), we can put some constraints on the history of star formation and thus that of the stellar mass growth. In order to stay on the same main sequence, the simplest evolutionary path would be that the individual star-forming galaxies evolve along the main sequence. This assumption should be valid if the galaxies keep forming stars at the rates above our threshold of the Hα NB imaging, i.e., SFR > $4 [M_\odot yr^{-1}]$ (dust-uncorrected) and EW_{[O III]} > 40 Å.

The stellar mass growth between $z = 3.2$ and $z = 2.2$ can be approximately tracked by the following derivative equation:

$$\frac{dM_\star}{dt} = (1 - R) \times \text{SFR} = (1 - R) \times 129 M_\odot^{0.705} L_{\odot},$$

where the return mass fraction $R$ is $\sim 0.3$ for the Salpeter IMF. Using this equation, a galaxy with $M_\star = 10^9 M_\odot$ at $z = 3.2$ can increase its stellar mass by a factor of 10 to $\sim 1.1 \times 10^{10} M_\odot$. The extreme ISM condition is expected to be a common feature among high-$z$ star-forming galaxies, and we expect that the [O III] emission line is an appropriate tracer of normal star-forming galaxies at high redshifts.
pre-peak epoch of galaxy formation. In order to achieve such an increasing star formation activity, an increasing rate of gas infall from outside is required, since otherwise the quick gas consumption would lower the SFR as time progresses. In order to verify the presence of such continuous gas infall more quantitatively, we estimate the gas mass for the [O III] emitters from their SFR surface densities by assuming the Schmidt–Kennicutt relation (Kennicutt 1998a). SFR surface densities ($\Sigma_{\text{SFR}} = \text{SFR}/\pi r_e^2$) are estimated by using SFRs derived from UV luminosities in Section 3.3 and the effective radius $r_e$ in Section 3.5. We then calculate the gas depletion timescale of $t_{\text{dep}} = M_{\text{gas}}/\text{SFR}$. The depletion timescale of the [O III] emitters is mostly in the range of 0.2–0.4 Gyr, and shorter than 1 Gyr. This means that the [O III] emitters at $z = 3.2$ would consume all the remaining gas and terminate the star formation before $z = 2.2$ if there is no gas supply from the outside of galaxies.

We have to mention that we have assumed the exponentially declining SFH in the form of $\text{SFR} \sim \exp(-t/\tau)$ in the SED fitting, while we now claim that the SFR increases with time from $z = 3.2$ to $z = 2.2$. In order to verify the impact of assumed SFHs on the resulting physical quantities in the SED fitting, we re-estimate the stellar masses and SFRs of the [O III] emitters by assuming the exponentially increasing SFH. In the case of the increasing SFH, the estimated stellar masses vary by only a factor of 0.9–1.3 for most of our sample, while the SFRs derived with $A_V$ values from the SED fitting can increase by a factor of $\sim 1.4$. However, such a modest offset would be systematic and would apply to both the H$\alpha$ and [O III] emitter samples. Therefore, it should not change our results significantly.

In reality, some galaxies would stop their star formation and evolve to quiescent galaxies by $z = 2.2$, although this quenching process should happen on a relatively short timescale so that they do not significantly appear on the lower side of the main sequence and break its clear sequence. Also, we have ignored the effect of galaxy–galaxy mergers, which can also increase the stellar mass of galaxies. Moreover, some galaxies would pop out all of a sudden on the main sequence with $M_9 > 10^{10} M_\odot$ sometime between $z = 3.2$ and $z = 2.2$, which were below $M_9 \ll 10^9 M_\odot$ at $z = 3.2$ or somewhere off the main sequence. Those galaxies should form stars at even higher rates such as in a starburst mode, and the fraction of stars that are formed between the two epochs can be larger than 90%.

The presence of those missing galaxies that are not considered in the simple model above is indicated by the comparison of number densities of the [O III] emitters at $z = 3.2$ and the H$\alpha$ emitters at $z = 2.2$. The number density of the [O III] emitters at $z = 3.2$ with $M_9 \gtrsim 10^9 M_\odot$ is $1.7 \times 10^{-3}$ [Mpc$^{-3}$], while that of the H$\alpha$ emitters at $z = 2.2$ with $M_9 \gtrsim 10^{10} M_\odot$ is $2.7 \times 10^{-3}$ [Mpc$^{-3}$]. Here we have taken into account the mass growth predicted by the above simple model. The latter number is $\sim 1.6$ times larger. It suggests that some galaxies may actually appear on the main sequence suddenly between $z = 3.2$ and $z = 2.2$, if we consider that there is no selection bias between the [O III] emitters and the H$\alpha$ emitters (see Section 4.1).

In any case, it is likely that star-forming galaxies grow at an accelerated pace during this time interval, assuring that this epoch is critically important for galaxy formation.

We also investigate the size growth of galaxies from $z = 3.2$ to $z = 2.2$ by assuming that the mass–size relation is unchanged between $z = 3.2$ and $z = 2.2$, as suggested in Section 3.6. Using the mass–size relation of late-type galaxies at $z \sim 2.75$ from van der Wel et al. (2014), the effective radius of a galaxy with $M_b = 10^8 M_\odot$ at $z = 3.2$ would grow in size by a factor of $\sim 1.5$ by $z = 2.2$, and the size growth ratio does not depend much on the initial stellar mass of galaxies at $z = 3.2$. The size growth is not so strong from $z = 3.2$ to $z = 2.2$ as compared to the mass growth that we just discussed above. Considering the growth of the stellar mass and the size of galaxies from $z = 3.2$ to $z = 2.2$ together, we can also estimate the evolution in stellar mass surface density. It is predicted to grow by a factor of 5 for a galaxy with $M_b = 10^9 M_\odot$ at $z = 3.2$.

5. SUMMARY

In this study, we construct an [O III] emitter sample at $z > 3$ in SXDF from the NB imaging data taken with MOIRCS on the Subaru Telescope (Tadaki et al. 2013). We identify 27 and 7 [O III] emitters at $z = 3.2$ and 3.6, respectively. Some objects in our [O III] emitter sample might be contributed by AGNs based on the rest-frame UVJ diagram and the Spitzer/MIPS detections. The spectroscopic observation is required to confirm the presence of AGNs, and we do not exclude these objects in this study. Using the multiwavelength data and HST high-resolution images, we investigated their basic physical properties and compared them with those of the H$\alpha$ emitters at $z = 2.2$ and 2.5 in the same field.

1. The stellar mass and the dust-extinction-corrected SFR$_{UV}$ of the [O III] emitters show a clear correlation, as seen in other previous studies over a wide redshift range. Comparing our [O III] emitters at $z = 3.2$ and 3.6 with the H$\alpha$ emitters at $z = 2.2$ and 2.5 in the same field from Tadaki et al. (2013), the location of the $M_{*}$–SFR relation of the [O III] emitters at $z = 3.2$ and 3.6 is almost the same as that of the H$\alpha$ emitters at $z = 2.2$ and 2.5.

2. Although the location of the relation is almost the same between the [O III] and H$\alpha$ emitters, the galaxy distributions on the $M_{*}$–SFR plane are different in the sense that the [O III] emitters at $z = 3.2$ and 3.6 tend to have lower stellar masses and SFRs as compared to the H$\alpha$ emitters at $z = 2.2$ and 2.5.

3. If we assume that the different galaxy distributions on the main sequence are due to the evolution of star-forming galaxies from $z = 3.2$ to $z = 2.2$, and that star-forming galaxies simply evolve along the constant star-forming main sequence in this time interval, galaxies with $M_b = 10^9$–$10^{10} M_\odot$ can obtain $\sim 90\%$–$50\%$ of their stellar masses within just a Gyr from $z = 3.2$. Galaxies climb up the main sequence, and their SFRs also increase a lot as their stellar masses grow. Although we consider only the simple model without outflows or mergers, we infer that galaxy formation activities at $z > 3$ are accelerated toward its peak epoch at $z \sim 2$.

4. We investigate the sizes of the [O III] emitters measured from the HST H-band images (van der Wel et al. 2012). The size distribution of the [O III] emitters at $z = 3.2$ and 3.6 with respect to the stellar mass is similar to that of the H$\alpha$ emitters at $z = 2.2$ and 2.5 and to that of the late-type galaxies at $z \sim 2.75$ from van der Wel et al. (2014). When the size of a galaxy grows from $z = 3.2$ to $z = 2.2$ along the mass–size relation at $z \sim 2.75$ from van der Wel et al. (2014), the effective radius would become 1.5
times larger at $z = 2.2$, and the size growth ratio does not depend much on the stellar mass of galaxies at $z = 3.2$. We conclude that the size evolution is not strong from $z = 3.2$ to $z = 2.2$.

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