ENVELOPMENT EFFECTS ON STAR FORMATION ACTIVITY AT $z \sim 0.9$ IN THE COSMOS FIELD

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ABSTRACT

We investigated the fraction of [O\textsc{ii}] emitters in galaxies at $z \sim 0.9$ as a function of the local galaxy density in the Hubble Space Telescope (HST) COSMOS 2 deg$^2$ field. [O\textsc{ii}] emitters are selected by the narrowband excess technique with the NB711-band imaging data taken with Suprime-Cam on the Subaru telescope. We carefully selected 614 photo-$z$-selected galaxies with $M_{\text{UV}} < -19.31$ at $z = 0.901 - 0.920$, which includes 195 [O\textsc{ii}] emitters, to directly compare the results with our previous study at $z \sim 1.2$. We found that the fraction is almost constant at $0.3$ Mpc$^{-2} < \Sigma_{\text{gal}} < 10$ Mpc$^{-2}$. We also checked the fraction of galaxies with blue rest-frame colors of $U-V < 2$ in our photo-$z$-selected sample, and found that the fraction of blue galaxies does not significantly depend on the local density. On the other hand, the semi-analytic model of galaxy formation predicted that the fraction of star-forming galaxies at $z \sim 0.9$ decreases with increasing projected galaxy density even if the effects of the projection and the photo-$z$ error in our analysis were taken into account. The fraction of [O\textsc{ii}] emitters decreases from $\sim 60\%$ at $z \sim 1.2$ to $\sim 30\%$ at $z \sim 0.9$ independent of galaxy environment. The decrease of the [O\textsc{ii}] emitter fraction could be explained mainly by the rapid decrease of star formation activity in the universe from $z \sim 1.2$ to $z \sim 0.9$.

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

Online-only material: color figures

1. INTRODUCTION

It is known that star formation activity in galaxies strongly depends on the environment in the present universe. High-density regions such as clusters of galaxies are dominated by passively evolving early-type galaxies, while there are many star-forming late-type galaxies in field (low-density) environments (e.g., Dressler 1980; Goto et al. 2003; Bamford et al. 2009). The fraction of star-forming galaxies systematically decreases with increasing local galaxy density (e.g., Gómez et al. 2003; Balogh et al. 2004; Kauffmann et al. 2004; Tanaka et al. 2004). From these findings, we consider that galaxies’ star formation history in general depends on environment.

In order to understand how the star formation history of galaxies depends on environment, it is important to investigate the star formation activity of galaxies as a function of environment in the early universe. Several such environmental studies have been carried out at $z > 1$, when the cosmic star formation rate (SFR) density reached its peak. Hayashi et al. (2010) studied the fraction of narrowband-selected [O\textsc{ii}] emitters as a function of the local galaxy density around a cluster at $z \sim 1.5$, and found that the fraction of such star-forming galaxies is nearly independent of the local density and does not decrease even in the core of a cluster. Tran et al. (2010) also found that the fraction of actively star-forming galaxies with bright IR luminosity slightly increases with the local galaxy density in a cluster at $z = 1.62$. Ideue et al. (2009) similarly investigated the fraction of [O\textsc{ii}] emitters in more general environments at $z \sim 1.2$ and found that the fraction is almost constant from low-density to medium-density environments. These results suggest that the relation between the star formation activity and the galaxy environment changed between $z > 1$ and $z \sim 0$. Since the cosmic SFR density decreases from $z \sim 1$ to the present by about an order of magnitude (e.g., Hopkins & Beacom 2006; Shioya et al. 2008; Westra et al. 2010), the change of the environmental dependence of star formation activity might be directly related with the decrease of global SFR density in the universe. Therefore, it is interesting to investigate star formation activity as a function of environment in detail at $z \sim 1$, when the cosmic SFR density started to decrease.

At $z \sim 1$, several studies in general environments claimed that the average SFR of galaxies increases with the local galaxy density (e.g., Elbaz et al. 2007; Cooper et al. 2008), while some studies around clusters of galaxies reported that the fraction of star-forming galaxies decreases with local density (e.g., Poggianti et al. 2008; Patel et al. 2009, 2011; Koyama...
et al. 2010). Recently, Sobral et al. (2011) carried out a wide-field near-infrared narrowband survey in the COSMOS and UKIDSS UDS fields. They found that the fraction of narrowband-selected Hz emitters is nearly constant or slightly increases with local galaxy density from low-density to medium-density environments, and then the fraction decreases toward the highest-density regions such as rich clusters, which is consistent with previous studies in both general fields and clusters regions. Such somewhat complicated environmental dependence of star formation activity might be considered to be intermediate between those at $z > 1$ and at the present.

The next important step is to investigate the evolution of star formation activity as a function of environment by directly comparing those in different epochs. For example, Elbaz et al. (2007) and Cooper et al. (2008) made comparisons between $z \sim 1$ and $z \sim 0$ in general fields, while Poggianti et al. (2008) compared the results in groups and clusters at $z = 0.4$–0.8 with those at $z \sim 0$. In this paper, we focus on the evolution between $z \sim 1.2$ and $z \sim 0.9$, when the cosmic SFR density began to decrease. Using the optical narrowband imaging data in the COSMOS survey (Scoville et al. 2007) obtained with Suprime-Cam on the Subaru Telescope, we investigated a fraction of narrowband-selected [O iii] emitters in galaxies at $z \sim 0.9$ as a function of the local galaxy density. The combination of the wide area of the COSMOS survey and the [O iii] emitter selection allows us to construct a large sample of star-forming galaxies with a secure redshift identification. By carefully choosing the selection criteria for our sample and adopting the same method for the estimate of the local galaxy density as our previous study at $z \sim 1.2$ in the COSMOS field (Ideue et al. 2009), we directly compare star formation activities as a function of environment between $z \sim 0.9$ and $z \sim 1.2$. Section 2 describes the data and the methods for the sample selection and the environment estimate. In Section 3, we show the fraction of [O iii] emitters in galaxies at $z \sim 0.9$ as a function of the environment and compare it with that at $z \sim 1.2$, and then check the robustness of the results. In Section 4, we compare our results with previous studies, and then discuss the evolution of the fraction in the redshift interval and its relation to the decrease of the star formation activity in the universe.

Throughout this paper, magnitudes are given in the AB system. We adopt a flat universe with $\Omega_{\text{matter}} = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. SAMPLE AND ANALYSIS

2.1. Samples

In this study, we use a sample of galaxies with photometric redshifts of $z = 0.901$–0.920 from the COSMOS photometric redshift catalog (Ilbert et al. 2009). We can select [O iii] emitters using the NB711 narrowband data for the redshift interval. In order to directly compare with our previous results at $z \sim 1.2$ (Ideue et al. 2009, hereafter I09), we need to match the magnitude limit of the sample to that at $z \sim 1.2$. In I09, we used a sample of galaxies with $i' < 24$ at $z \sim 1.2$, which corresponds to the rest-frame 3500 Å absolute magnitude of $M_{U3500} < -19.71$. Therefore, we constructed a sample of galaxies with $M_{U3500} < -19.71$ at $z = 0.901$–0.920 (hereafter Sample A). The rest-frame 3500 Å absolute magnitude was calculated from the best-fit spectral energy distribution template derived in the photo-$z$ calculation (Ilbert et al. 2009) for each galaxy.

In addition to Sample A, we also construct another sample of galaxies at $z = 0.901$–0.920 using the different magnitude limit, for which the luminosity evolution at the rest-frame 3500 Å between $z \sim 1.2$ and $z \sim 0.9$ is taken into account. In order to measure the strength of the luminosity evolution, we derived the rest-frame 3500 Å luminosity functions (LFs) for the $z \sim 0.9$ and $z \sim 1.2$ samples, and fitted these LFs with the Schechter function. The estimated Schechter parameters are $M_* = -19.55$ and $\log \phi_* = -2.01$ for the $z \sim 0.9$ sample and $M_* = -19.95$ and $\log \phi_* = -1.94$ for the $z \sim 1.2$ sample. The faint-end slope was fixed to $\alpha = -1.0$ in the fitting for both redshifts. Therefore, we assumed that galaxies become fainter by 0.4 mag at the rest-frame 3500 Å from $z \sim 1.2$ to $z \sim 0.9$, and used $-19.71 + 0.4 = -19.31$ as another magnitude limit. The sample of galaxies with $M_{U3500} < -19.31$ at $z = 0.901$–0.920 is referred to as Sample B.

For the redshift range, we can almost completely sample galaxies even with $M_{U3500} < -19.31$ (Figure 1). All galaxies in the samples have $i' < 24$, and the photometric redshift accuracy is the same as in our previous study at $z \sim 1.2$. Sample A has 373 galaxies and Sample B has 733 galaxies. The effective survey area is 5540 arcmin$^2$ and the redshift interval of $z = 0.901$–0.920 corresponds to the comoving depth of 50 Mpc. Our effective survey volume is $2.28 \times 10^5$ Mpc$^3$ given the assumed cosmology.

2.2. [O iii] Emitter Selection

We select [O iii] emitters from the samples mentioned above as star-forming galaxies using the narrowband excess technique. In order to select the [O iii] emitter, we use the $r'$, $i'$, and NB711 bands photometry from the COSMOS photometric catalog (Capak et al. 2007). NB711 is a narrow band with a central wavelength of 7119.6 Å and a FWHM of 72.5 Å, which covers the redshifted [O iii] $\lambda 3727$ emission lines for galaxies at $z = 0.901$–0.920. We used the 3″ diameter aperture magnitudes in three bands. We adopted the correction for the photometric zero point presented by Ilbert et al. (2009), which is calculated by comparing the observed multi-broadband photometry for galaxies with spectroscopic identification with the best-fit model.
templates. The zero-point corrections are 0.003, 0.019, and 0.014 mag for $r'$, $i'$, and NB711 bands, respectively. The limiting magnitudes are $r'_\text{lim} = 26.6$, $i'_\text{lim} = 26.1$, and NB711\text{lim} = 24.6, for a 3σ detection on a 3′ diameter aperture. Note that we use the Canada–France–Hawaii Telescope (CFHT) $i'$-band magnitude instead of the Subaru/Suprime-Cam $i'$-band one for galaxies brighter than $i' = 21$ because such bright galaxies appear to be affected by the saturation effect in the Suprime-Cam data. Details of the imaging data and the photometry are given in Taniguchi et al. (2007) and Capak et al. (2007).

In order to select NB711-band excess objects, we calculated a continuum magnitude at the wavelength of NB711 from $r$- and $i$-band magnitudes as $f_{ri} = 0.32 f_{r} + 0.68 f_{i}$, where $f_{r}$ and $f_{i}$ are the $r'$ and $i'$ flux densities, respectively. Its 3σ limiting magnitude is $ri \simeq 26.5$ in a 3′ aperture. For the bright galaxies with $i' < 21$, the $r$ continuum is calculated as $fr = 0.32 fr' + 0.68 fi'$, where $fi'$ is the CFHT $i'$-band flux density. Then, we select NB711-band excess objects using the following criteria:

\[
ri - NB711 \geq 0.285
\]  
\[
ri - NB711 > 3\sigma_{ri-NB711},
\]

where

\[
3\sigma_{ri-NB711} = -2.5 \log \left(1 - \sqrt{(f3\sigma_{NB711})^2 + (f3\sigma_{ri})^2/fNB711} \right).
\]

The former criterion corresponds to the rest-frame equivalent width $EW_{0}(O\text{\textsc{ii}})) \geq 12$ Å, which is the same as that in our previous study at $z \sim 1.2$ (I09). Figure 2 shows the color–magnitude distribution for galaxies at $z = 0.901$–0.920. The red symbols represent galaxies with $M_{U3500} < -19.71$ (Sample A), and the blue ones show galaxies with $-19.71 < M_{U3500} < -19.31$. The narrowband and broadband data are deep enough to almost completely sample galaxies with $EW_{0}(O\text{\textsc{ii}})) \geq 12$ Å. Here we exclude X-ray sources as active galactic nuclei (AGNs) based on the X-ray information given in the COSMOS photo-z catalog (Ilbert et al. 2009). Finally, we select 118 [O\text{\textsc{ii}}] emitters out of the 373 galaxies in Sample A and 233 [O\text{\textsc{ii}}] emitters out of the 733 galaxies in Sample B.

We also examine how many AGNs are included in our sample using Spitzer IRAC mid-infrared colors. Lacy et al. (2004) and Stern et al. (2005) pointed out that AGNs can be distinguished from star-forming galaxies using Spitzer IRAC colors, e.g., [3.6] – [4.5]. While the ultraviolet to mid-infrared ($\lambda < 5 \mu m$) continuum of star-forming galaxies is the composite stellar continuum that peaks at $\sim 1.6 \mu m$, an AGN continuum is well fit by a power law. The infrared colors of AGNs tend to be systematically redder than star-forming galaxies. As in I09, we select objects with a mid-infrared color of [3.6] – [4.5] $> 0$ as AGN. We apply this criterion for the 207 [O\text{\textsc{ii}}] emitters detected in both 3.6 and 4.5 μm. We find that 2 out of the 207 [O\text{\textsc{ii}}] emitters in our sample satisfy this criterion; the fraction of possible AGNs is 2/207 = 1.0% at most. Therefore, we consider that AGN contamination does not affect our discussion below.

2.3. Local Surface Density

As in I09, we use the 10th nearest neighbor method to estimate the local surface density of galaxies as a measurement of galaxy environment. The projected surface density is calculated as

\[
\Sigma_{10n} = \frac{11}{\pi r_{10}^2},
\]

where $r$ is the distance to 10th nearest neighbor. We calculate this distance for galaxies within the redshift $z \pm \sigma$, taking into account the error of the photometric redshift ($\sigma_z = 0.023$ at $z \sim 0.9$). The redshift slice of $z \pm \sigma$ corresponds to the comoving depth of 118 Mpc, while that in our previous study at $z \sim 1.2$ is 114 Mpc (I09). Therefore, the comoving depth for the estimate of the projected surface density in this study is similar to that in I09. We consider that such a small difference in the depth of the redshift slice does not affect our results shown in the next section. We discard the galaxies near the edge of our field of view, i.e., those whose $r$ is larger than the distance to the edge of the field. This procedure reduces the number of galaxies in our samples to 291 (95 [O\text{\textsc{ii}}] emitters) for Sample A and 614 (195 [O\text{\textsc{ii}}] emitters) for Sample B. We summarize our samples in Table 1.

3. RESULTS

3.1. Fraction of [O\text{\textsc{ii}}] Emitters at $z \sim 0.9$ as a Function of Local Density

Figure 3 shows the fraction of [O\text{\textsc{ii}}] emitters in galaxies at $z \sim 0.9$ as a function of local galaxy density. The results for Samples A and B are shown as solid circles and open squares, respectively. For comparison, we also show the results for galaxies at $z \sim 1.2$ from I09.

In Figure 3, we cannot find a significant environmental dependence of the fraction of [O\text{\textsc{ii}}] emitters in both Samples A and B. The fraction of [O\text{\textsc{ii}}] emitters is nearly constant ($\sim 0.3$) between $\Sigma_{10n} \sim 0.3$ Mpc$^{-2}$ and $\sim 10$ Mpc$^{-2}$. Even if we take the effect of luminosity evolution of galaxies into account, the flat distribution holds. The fraction of [O\text{\textsc{ii}}] emitters at $z \sim 1.2$ also shows no significant environmental dependence, but the fraction is $\sim 0.6$ over a wide range of the local density, which is significantly higher than that at $z \sim 0.9$. The fraction of [O\text{\textsc{ii}}]
emitters decreases from \( \sim 0.6 \) to \( \sim 0.3 \) between \( z \sim 1.2 \) and \( z \sim 0.9 \) in all environments we investigated.

We check the effects of the projection and the photometric redshift error on these results in the following sections.

### 3.2. Fraction of Galaxies with Blue NUV – R Color

In the analysis of the previous section, we mainly used the sample of galaxies with \( 0.901 \leq z_{\text{phot}} \leq 0.920 \) (i.e., \( \Delta z = 0.019 \)) to select [O\II] emitters as the star-forming population, while the local galaxy density was calculated with galaxies within a redshift slice of \( z \pm \sigma_z \) (i.e., \( \Delta z = 0.046 \)) taking into account the photo-z error. Thus the density measurement includes galaxies outside the main sample. Furthermore, as we show in Section 3.4, [O\II] emitters selected by the NB711-band excess tend to have higher photo-z accuracy than the other galaxies without narrowband excess.

In order to check whether they affect the environmental dependence of the fraction of star-forming galaxies, we selected star-forming galaxies by the rest-frame NUV – R color estimated from the COSMOS multi-band photometric data instead of \( \text{EW}_0([\text{O}\II]) \). \( \text{EW}_0([\text{O}\II]) \) is the ratio of the line luminosity \( L([\text{O}\II]) \) and the continuum luminosity at the rest-frame 3727 Å. While \( L([\text{O}\II]) \) mainly depends on SFR, the continuum luminosity at 3727 Å depends on both SFR and stellar mass. Therefore, we believe that the rest-frame NUV – R color is more suitable for a substitute for \( \text{EW}_0([\text{O}\II]) \) than the simple rest-frame UV luminosity. If we ignore the effect of the dust reddening, star-forming galaxies with large \( \text{EW}_0([\text{O}\II]) \) are expected to have blue NUV – R colors. Since the rest-frame NUV – R selection is not limited to the narrow redshift range of \( z_{\text{phot}} = 0.901–0.920 \), we can estimate the fraction of blue star-forming galaxies and the local galaxy density with the same sample within a redshift slice of \( \Delta z = 0.046 \).

Figure 4 shows the two color diagrams of NUV – R versus \( R – J \) for galaxies at \( 0.901 \leq z_{\text{phot}} \leq 0.920 \). It is seen that [O\II] emitters tend to show blue NUV – R colors as expected. Since more than 90\% of [O\II] emitters have NUV – R < 2, we use NUV – R < 2 as the selection criterion for blue star-forming galaxies. The average fraction of galaxies with NUV – R < 2 is 47\% in Sample A, which is slightly larger than that of [O\II] emitters. Figure 5 shows the fraction of galaxies with NUV – R < 2 in Sample A as a function of local galaxy density. We first used galaxies at \( z_{\text{phot}} \leq 0.901 \) as the main sample and measured the local density for each sample galaxy by using galaxies within a redshift slice of \( z \pm \sigma_z \) centered on its redshift, as in the case of [O\II] emitters (solid circles in Figure 5). Then we estimated both the fraction of blue galaxies and the local galaxy density from the same galaxies at \( 0.91–0.923 \leq z_{\text{phot}} \leq 0.91 + 0.023 \) (open circles in the figure). The fractions of galaxies with NUV – R < 2 in both cases agree within the uncertainty at each density. The fraction does not significantly depend on the local density in both cases, although the fraction could be slightly smaller at the highest-density bin in the latter case. If we use Sample B instead of Sample A, we obtain similar results. Therefore, we argue that the difference in the redshift range between the main sample and the sample used for the density measurement does not significantly affect our results.

| Sample | Redshift Range | Limiting Magnitude | Total Number (\( \Sigma_{10th} \) Available) | No. of [O\II] Emitters (\( \Sigma_{10th} \) Available) |
|--------|----------------|-------------------|---------------------------------------------|-----------------------------------------------|
| Sample A | 0.901–0.920 | \( M_{\text{F}3500} < -19.71 \) | 373 (291) | 118 (95) |
| Sample B | 0.901–0.920 | \( M_{\text{F}3500} < -19.31 \) | 733 (614) | 233 (195) |

**Table 1** Summary of the Samples

**Figure 3.** Fraction of [O\II] emitters as a function of the galaxy local density. The filled circles show the result for Sample A and the open squares show that for Sample B. The small open circles represent the result at \( z \sim 1.2 \) updated from 109 with the newest version of the COSMOS photometric redshift catalog.

**Figure 4.** Rest-frame NUV – R vs. \( R – J \) diagram for Sample B (\( M_{\text{F}3500} < -19.31 \)). The blue circles show [O\II] emitters selected by the NB711-band excess. The red circles represent bright Spitzer/MIPS 24 μm sources with \( f_{24 \mu m} \gtrsim 150–200 \) μJy at \( z_{\text{phot}} = 0.901–0.920 \), which include those objects with \( M_{\text{F}3500} > -19.31 \).
projected densities become slightly larger simply because of the increase of the number of galaxies in the sample. We confirmed that these results do not depend on a choice of the direction of the slice in the simulation box.

We also checked the environmental dependence of the fraction of [O II] emitters in the simulation by calculating \( \text{EW}_{0}(\text{O II}) \) of model galaxies from their \( L(\text{O II}) \) and \( M_U \) in the mock catalog. Figure 7 shows the fraction of galaxies with \( \text{EW}_{0}(\text{O II}) > 12 \) Å as a function of the three-dimensional density (left panel) and the two-dimensional projected density with the photometric redshift error (right panel). Since the overall fraction is slightly larger than the observed fraction of [O II] emitters, we also show the fraction of model galaxies with \( \text{EW}_{0}(\text{O II}) > 36 \) Å for comparison. It is seen from the left panel that the fraction of star-forming galaxies selected by the \( \text{EW}_{0}(\text{O II}) \) criteria clearly decreases with local galaxy density in the semi-analytic model as previous studies have already reported (e.g., Elbaz et al. 2007). Even if we use the projected density with the photometric redshift error, the fraction of [O II] emitters clearly depends on density, although the environmental dependence of the fraction becomes slightly weaker. This suggests that the effects of the projection and photometric redshift error in our density measurement do not smear out the relation between the fraction of [O II] emitters and local density. The observed fraction in Figure 3 does not seem to decrease with local density, which is different from the semi-analytic model, although the relatively large statistical error in our analysis prevents us from completely rejecting the model.

We note that the above simulation of the fraction of [O II] emitters with the semi-analytic model does not consider the fact that [O II] emitters are selected by the narrowband excess within a narrower redshift width of \( \Delta z = 0.019 \). As seen in the previous subsection, however, we obtained the same result (no significant environmental dependence) when we selected galaxies with blue rest-frame NUV – R colors as the star-forming population within the same redshift width of \( \Delta z = 0.046 \) as in the local density measurement. Therefore, we argue that it does not affect the comparison between our result and the model prediction.

3.4. Incompleteness and Contamination due to the Photometric Redshift Error

We here check the incompleteness and contamination due to the photometric redshift error in our sample by using spectroscopic redshifts from the zCOSMOS redshift survey (Lilly et al. 2007, 2009). Since the NB711 data are used in the photometric redshift measurement (Ilbert et al. 2009), the photometric redshifts of [O II] emitters with narrowband excess are expected to be more accurate than the other galaxies without narrowband excess (hereafter, non-[O II] emitters) in our sample. Therefore, we investigated the incompleteness and contamination for [O II] emitters and non-[O II] emitters separately.

We first examined the spectroscopic redshift distribution for the photo-z-selected galaxies with \( M_U < -19.71 \) (Sample A) in order to estimate the fraction of the contamination from outside the redshift range in the photo-z-selected sample. There are 24 [O II] emitters and 65 non-[O II] emitters with spectroscopic identification in Sample A, and we can use these galaxies for our purpose. Out of 24 [O II] emitters, 19 have spectroscopic redshifts of 0.901 \( \leq z_{\text{spec}} \leq 0.920 \), and the other 5 objects have spectroscopic redshifts outside of the redshift range (i.e., \( z_{\text{spec}} < 0.901 \) or \( z_{\text{spec}} > 0.920 \)). If we consider these five objects as the contaminants from outside the redshift range,
the fraction of contamination from outside the redshift range is $5/24 = 21\%$. Actually, four of these five objects have slightly lower redshifts of $z_{\text{spec}} = 0.893-0.899$, for which the [O II] emission enters into the short-wavelength wing of the NB711 filter, while one object is an [O III] emitter at $z_{\text{spec}} = 0.422$. Thus if we include four objects with $z_{\text{spec}} = 0.893-0.899$ into the [O II] emitter sample, the contamination rate becomes $1/24 = 4\%$. On the other hand, 39 of 65 non-[O II] emitters in Sample A lie within $0.901 \leq z_{\text{spec}} \leq 0.920$, and the other 26 objects have spectroscopic redshifts of $z_{\text{spec}} < 0.901$ or $z_{\text{spec}} > 0.920$. Therefore, the contamination rate for non-[O II] emitters is $26/65 = 40\%$. 

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure6}
\caption{Left: comparison between the three-dimensional (true) local galaxy density and the projected two-dimensional density for $\sim 550,000$ mock galaxies with $M_U < -19.71$ at $z \sim 0.9$ in the semi-analytic model by Font et al. (2008). Both densities are estimated by the 10th nearest neighbor method. The two-dimensional projected density is calculated from model galaxies within a slice of 60 Mpc in physical scale, which corresponds to $\Delta z = 0.046$ at $z \sim 0.9$. The solid line shows the median value of the projected density as a function of the three-dimensional density, while the dashed lines represent the 16th and 84th percentiles. Right: the same as the left panel but the projected density is calculated from model galaxies within a slice of 60 Mpc after galaxies are randomly shifted with a offset of the Gaussian distribution with $\sigma = 30$ Mpc in order to account for the photometric redshift error (see the text). (A color version of this figure is available in the online journal.)}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure7}
\caption{Left: fraction of [O II] emitters in mock galaxies with $M_U < -19.71$ at $z \sim 0.9$ in the semi-analytic model by Font et al. (2008) as a function of the three-dimensional local galaxy density. The solid line shows the fraction of galaxies with $\text{EW}_{0}(\text{[O II]}) > 12$ Å, and the dashed line shows that of galaxies with $\text{EW}_{0}(\text{[O II]}) > 36$ Å. Right: the same as the left panel but as a function of the two-dimensional projected density with a photometric redshift error of $\sigma_z = 0.023$. (A color version of this figure is available in the online journal.)}
\end{figure}
Next, we checked the photometric redshift distribution of galaxies with $z_{\text{spec}} = 0.901-0.920$ and $M_{V,3500} < -19.71$ to estimate the incompleteness due to the photo-$z$ error for Sample A. From the spectroscopic catalog, we could use 97 objects with $z_{\text{spec}} = 0.901-0.920$ and $M_{V,3500} < -19.71$, and found that 58 out of 97 have photometric redshifts of $0.901 \leq z_{\text{phot}} \leq 0.920$. While these 58 objects are included into our photo-$z$-selected sample, the other 39 objects were missed by the photo-$z$ selection. Out of 97 objects with $z_{\text{spec}} = 0.901-0.920$, 20 objects show a significant NB711-band excess and satisfy the criteria for [O II] emitters, and the other 77 objects are non-[O II] emitters. Similarly, out of 58 objects with $z_{\text{spec}} = 0.901-0.920$ and $z_{\text{phot}} = 0.901-0.920$, 19 objects satisfy the criteria for [O II] emitters, and the other 39 objects are non-[O II] emitters. Therefore, for [O II] emitters, 19 out of 20 galaxies with $z_{\text{spec}} = 0.901-0.920$ are selected from Sample A, and the completeness is 19/20 = 95%. On the other hand, 39 out of 77 non-[O II] emitters with $z_{\text{spec}} = 0.901-0.920$ are included in the sample. Therefore, the completeness for non-[O II] emitters is 39/77 = 51%.

By adopting these contamination and completeness rates, which are estimated from the spectroscopic sample, for all the photo-$z$-selected sample, we examined the effects of contamination and incompleteness due to the photo-$z$ error on the fraction of [O II] emitters in the photo-$z$-selected sample. Since the contamination and completeness rates for [O II] emitters are 21% and 95%, respectively, we select 95% of the real [O II] emitters and also pick up contaminants that account for 21% of the observed number. Therefore, the number of [O II] emitters is expected to be overestimated by $\sim 20\%$; i.e., $0.95/(1-0.21) \sim 1.20$. Similarly, from the contamination rate of 40% and the completeness rate of 51%, we can calculate that the observed number of non-[O II] emitters is underestimated by $\sim 15\%$; i.e., $0.51/(1-0.40) \sim 0.85$. Since the observed numbers of [O II] emitters and non-[O II] emitters are 95 and 196, respectively, the number of all photo-$z$-selected galaxies is expected to be underestimated by $\sim 6\%$; i.e., $(95+196)/(95/1.21 + 196/0.85) \sim 0.94$. As a result, the number of [O II] emitters is overestimated by $\sim 20\%$, while the number of the all photo-$z$ sample is underestimated by $\sim 6\%$. Therefore, the fraction of [O II] emitters could be overestimated by $\sim 28\%$; i.e., $1.20/0.94 \approx 1.28$. If we do not consider the four [O II] emitters with $z_{\text{spec}} = 0.893-0.899$ as the contaminants, the contamination rate for [O II] emitters decreases from 21% to 4% as mentioned above, and the overestimation of the fraction of [O II] emitters becomes $\sim 5\%$. Since Ideue et al. (2012) estimated that the fraction of [O II] emitters at $z \sim 1.2$ could be overestimated by $\sim 17\%$ due to the photo-$z$ error, the fractions of non-[O II] emitters at $z \sim 1.2$ and $z \sim 0.9$ might be similarly overestimated.

4. DISCUSSION

4.1. Comparison with Other Studies

We here compare our results in the COSMOS field with previous studies of the environmental dependence of star formation activity in galaxies at similar redshifts. Elbaz et al. (2007) investigated the average SFR of galaxies with $M_B < -20$ at $0.8 \leq z \leq 1.2$ as a function of the local galaxy density in the GOODS fields. They found that the average SFR increases with density and seems to peak around a density of $\sim 2-3$ Mpc$^{-2}$. Our results seem to be consistent with their results in that the fraction of actively star-forming galaxies does not decrease with the local density on average, which is different from the SFR-density relation seen in the present universe and from the predictions by semi-analytic models of galaxy formation. However, the fraction of [O II] emitters at $z \sim 0.9$ in the COSMOS field does not significantly depend on density and does not seem to peak around a density of several Mpc$^{-2}$. In order to examine the environmental dependence of the average SFR in our sample, we plot $L([\text{O II}])$ of [O II] emitters as a function of the local density in Figure 8. $L([\text{O II}])$ is estimated from the $ri$ and NB711 magnitudes (see the Appendix for details). It is seen that the $L([\text{O II}])$ of [O II] emitters is also independent of density. Therefore, we expect that the average $L([\text{O II}])$ also does not significantly depend on local density.

A possible origin of the different behaviors in the SFR-density relation between Elbaz et al. (2007) and this study is the effect of the dust extinction. We selected star-forming galaxies with the [O II] emitter selection, while Elbaz et al. (2007) estimated SFRs of galaxies from the Spitzer/MIPS 24 $\mu$m fluxes. Although we correct $L([\text{O II}])$ for the dust extinction assuming $A_{\text{H}_\alpha} = 1$ mag, the [O II] emitter selection itself could miss dusty star-forming galaxies. In order to check this, we cross-matched the 24 $\mu$m source catalog from the S-COSMOS survey (Sanders et al. 2007) to galaxies at $0.901 \leq z_{\text{phot}} \leq 0.920$ in our sample. The flux limit of the 24 $\mu$m catalog is $\sim 150-200$ $\mu$Jy. We plot the 24 $\mu$m sources as red circles in Figure 4. These bright 24 $\mu$m sources tend to show red rest-frame $NUV - R$ and $R - J$ colors, and the overlap between these 24 $\mu$m sources and [O II] emitters is relatively small. Since star-forming galaxies are expected to be distributed over a diagonal region from $(R - J \sim 0$, $NUV - R \sim 1)$ to $(R - J \sim 1.5$, $NUV - R \sim 4.5)$ (e.g., Bundy et al. 2010), the [O II] selection seems to miss star-forming galaxies with relatively red $NUV - R$ colors such as the bright 24 $\mu$m sources. We also compare the stellar mass of [O II] emitters with that of the bright 24 $\mu$m sources in Figure 9. The stellar mass of each galaxy is estimated by fitting the multi-band photometric data from UV to MIR wavelength with the population synthesis model by Bruzual & Charlot (2003; Ilbert et al. 2010). Chabrier’s (2003) initial mass function is assumed. Figure 9 shows that most [O II] emitters have relatively low stellar masses of $M_{\text{star}} \lesssim 10^{10} M_\odot$, while the all photo-$z$-selected galaxies are distributed over $10^9 M_\odot \lesssim M_{\text{star}} \lesssim 10^{11} M_\odot$.
$M_{\text{star}} \lesssim 10^{11} M_{\odot}$. On the other hand, the bright 24 $\mu$m sources show systematically larger stellar masses of $\sim 10^{10}$–$10^{11} M_{\odot}$. The 24 $\mu$m selected star-forming galaxies in Elbaz et al. (2007) are also distributed over $10^{9} M_{\odot} \lesssim M_{\text{star}} \lesssim 10^{11} M_{\odot}$. Therefore, the [O ii] emitter selection seems to miss massive (dusty) star-forming population. Since star-forming galaxies with $10^{10}$–$10^{11} M_{\odot}$ have a large contribution to the cosmic SFR density at $z \sim 1$ (e.g., Kajisawa et al. 2010), these massive star-forming galaxies could significantly contribute the average SFR in each environment. The contribution from these massive galaxies might cause the peak of the average SFR around a local density of $\sim 2$–3 $M_{\text{pc}}^{-2}$ as seen in Elbaz et al. (2007). However, we note that the fraction of star-forming galaxies in our sample does not significantly depend on the density, even if we include the bright 24 $\mu$m sources into the star-forming population.

Another possible origin of the different results is the different scales of the local density measurement. Elbaz et al. (2007) measured the density with a box of $1.5 \text{ Mpc} \times 1.5 \text{ Mpc} \times 40 \text{ Mpc}$ in comoving scale, while we used the 10th nearest neighbor method with galaxies within a comoving depth of 118 Mpc. In the 10th nearest neighbor method, a radius used in the density measurement depends on the local density itself. For example, the local density of $\Sigma_{10\text{th}} = 1 \text{ Mpc}^{-2}$ corresponds to a radius of $r_{10\text{th}} \sim 3.6 \text{ Mpc}$ in comoving scale ($\sim 1.9 \text{ Mpc}$ in physical scale). When the local density is 10 $M_{\text{pc}}^{-2}$, a radius becomes 1.1 Mpc in comoving scale. Since we typically investigate galaxies with $\Sigma_{10\text{th}} \sim 1$–10 $M_{\text{pc}}^{-2}$ (Figure 3), the local density in our analysis is measured with a radius of 1.1–3.6 Mpc, which corresponds to a diameter of 2.2–7.2 Mpc. This scale is larger than that in (Elbaz et al. 2007; 1.5 Mpc), especially for low-density environments. The depth of 118 Mpc used in our density measurement is also a diameter of 2.2–7.2 Mpc. This scale is larger than that in (Elbaz et al. 2007; 1.5 Mpc), especially for low-density environments. If this is the case, the galaxy interactions might not play a important role in star formation activity of most field galaxies.

As a result, the evolution of star formation activity in these galaxies between $z \sim 1.2$ and $z \sim 0.9$ does not depend on the galaxy environment, but might simply be related to physical properties of each galaxy such as gas mass fraction.

4.2. Evolution of the Fraction of [O ii] Emitters between $z \sim 1.2$ and $z \sim 0.9$

In this section, we discuss the strength of the evolution in the fraction of [O ii] emitters from $\sim 60\%$ at $z \sim 1.2$ to $\sim 30\%$
Figure 10. Evolution of the local galaxy density between $z \sim 1.2$ and $z \sim 0.9$ for mock galaxies in the semi-analytic model by Font et al. (2008). The top panels show comparisons of the three-dimensional local densities at different redshifts for the same model galaxies, while the bottom panels show those of the two-dimensional projected densities with the photometric redshift error. The local density at $z \sim 1.2$ is estimated from galaxies with $M_U < -19.71$. The left panels show the case in which the local density at $z \sim 0.9$ is estimated from galaxies with $M_U < -19.71$, while the right panels show the results for the density at $z \sim 0.9$ measured from those with $M_U < -19.31$. The solid line shows the median value of the density at $z \sim 0.9$ as a function of the density at $z \sim 1.2$, while the dashed lines represent the 16th and 84th percentiles.

(A color version of this figure is available in the online journal.)

at $z \sim 0.9$. First, we examined how the local density for each galaxy evolves between $z \sim 1.2$ and $z \sim 0.9$ by using the same semi-analytic model as in Section 3.3, since the strong evolution of the density could make the comparison between the different redshifts more complicated (e.g., Poggianti et al. 2010). Figure 10 shows the comparisons of the local density between the redshifts for the same model galaxies for Samples A and B. For model galaxies at $z \sim 1.2$, we similarly calculated the three-dimensional density and the two-dimensional projected density including the random offsets due to the photometric redshift error at $z \sim 1.2$. Note that the average number densities of galaxies at $z \sim 0.9$ are different between both samples by a factor of $\sim 2$. It is seen from the upper panels of the figure that the evolution of the true three-dimensional density is relatively small (a factor of $\lesssim 2$) for most model galaxies except for the high-density region. The projected density also mildly evolves at $0.3 \text{ Mpc}^{-2} \lesssim \Sigma_{10h} \lesssim 10 \text{ Mpc}^{-2}$ especially for Sample B. By combining this with the lack of the environmental dependence at the both redshifts, we infer that the change in the local density probably does not strongly affect the evolution of the fraction of [OII] emitters in the range of the density we investigated. Therefore, we can fairly compare the fractions of [OII] emitters at the same range of the local density between $z \sim 1.2$ and $z \sim 0.9$. 


In Figure 11, we plot the evolution of the fraction of [O II] emitters between \( z \sim 0.9 \) and \( z \sim 1.2 \) predicted by the semi-analytic model. The strength of the evolution in the model does not seem to be affected by the criterion of \( \text{EW}_{0}([\text{O II}]) \), and it could be slightly large at \( \Sigma_{100h} \sim 3-10 \) Mpc\(^{-2} \). The observed strength of the evolution seen in Figure 3 is larger than that in the model.

We next consider the evolution of the \( \text{EW}_{0}([\text{O II}]) \) distribution. Figure 12 shows a comparison of the observed \( \text{EW}_{0}([\text{O II}]) \) distribution between the \( z \sim 0.9 \) and \( z \sim 1.2 \) samples. The \( \text{EW}_{0}([\text{O II}]) \) for each [O II] emitter is calculated from the narrowband excess (NB711 \(- r'\)). In Figure 12, the fraction of galaxies with \( \text{EW}_{0}([\text{O II}]) > 12 \) Å at \( z \sim 0.9 \) is lower than that at \( z \sim 1.2 \) as expected from Figure 3. If we simply assume that the \( \text{EW}_{0}([\text{O II}]) \) of all star-forming galaxies decreases by the same factor from \( z \sim 1.2 \) to \( z \sim 0.9 \), the observed \( \text{EW}_{0}([\text{O II}]) \) distributions suggest that the \( \text{EW}_{0}([\text{O II}]) \) needs to decrease by a factor of \( 1.75^{+0.55}_{-0.35} \) in this redshift interval in order to reproduce the fraction of [O II] emitters with \( \text{EW}_{0}([\text{O II}]) > 12 \) Å at \( z \sim 0.9 \) (\( \sim 0.3 \pm 0.1 \)).

We here try to interpret the \( \text{EW}_{0}([\text{O II}]) \) evolution as the evolution of star formation activity in galaxies. Figure 13 compares [O II] LFs between \( z \sim 0.9 \) and \( z \sim 1.2 \) in the COSMOS field and the Subaru Deep Field (SDF). The [O II] LFs in the COSMOS field are derived from our samples at \( z \sim 0.9 \) and \( z \sim 1.2 \) (see the Appendix), and those in the SDF are the results by Ly et al. (2007). It is seen that the characteristic luminosity decreases by a factor of \( \approx 2 \) from \( \log L_{\ast} \sim 42.5 \) at \( z \sim 1.2 \) to \( \log L_{\ast} \sim 42.2 \) at \( z \sim 0.9 \) in the both fields, while the normalization shows no significant evolution. If we assume that there is no strong evolution in the average metallicity of galaxies between \( z \sim 1.2 \) and \( z \sim 0.9 \), this luminosity evolution reflects the decrease of star formation activity in galaxies. Many previous studies of the evolution of the cosmic SFR density also suggest that star formation activity in the universe decreases by a factor of \( \approx 2 \) from \( z \sim 1.2 \) to \( z \sim 0.9 \) on average (e.g., Hopkins & Beacom 2006; Sobral et al. 2012). Then we calculate the evolution in the \( \text{EW}_{0}([\text{O II}]) \) for the case that the SFR decreases by a factor of two in the redshift interval. The [O II] line luminosity is simply expected to decrease by the same factor as the SFR if we ignore the metallicity/dust extinction evolution. If we assume exponentially decaying star formation histories (i.e., SFR \( \propto \exp(-\text{age}/\tau) \)) between \( z \sim 1.2 \) and \( z \sim 0.9 \) for simplicity, the evolution of a factor of \( \approx 2 \) in the SFR which is expected from the [O II] LF at \( z \sim 1.2 \) and \( z \sim 0.9 \) corresponds to the star formation timescale of \( \tau = 1.2-1.8 \) Gyr. In this case, the continuum luminosity at the rest-frame 3727 Å is expected to decrease by a factor of \( \approx 1.5 \). This is also consistent with the evolution of the characteristic magnitude of the rest-frame 3500 Å LF (0.4 mag) mentioned in Section 2.1. Therefore, we can expect that the \( \text{EW}_{0}([\text{O II}]) \) decreases by a factor of \( 1.3-1.6 \) between \( z \sim 1.2 \) and \( z \sim 0.9 \), taking into account the possible effect of the Balmer break on the measurement of the narrowband excess (NB711 \(- r'\)). This is roughly consistent with the evolution of the \( \text{EW}_{0}([\text{O II}]) \) expected from the evolution in the fraction of [O II] emitters (\( 1.75^{+0.55}_{-0.35} \)). In the right panel of Figure 12, we compare the observed \( \text{EW}_{0}([\text{O II}]) \) distribution at \( z \sim 0.9 \) with the simulated distributions that are calculated by dividing the \( \text{EW}_{0}([\text{O II}]) \) at \( z \sim 1.2 \) by factors of 1.3 and 1.6. The agreement of the \( \text{EW}_{0}([\text{O II}]) \) distribution is relatively good, especially in the case where the \( \text{EW}_{0}([\text{O II}]) \) decreases by a factor of 1.6, although the observed \( \text{EW}_{0}([\text{O II}]) \) at \( z \sim 0.9 \) could be slightly lower than those predicted from the evolution of the star formation activity. Thus, the decrease of the fraction of [O II] emitters from \( z \sim 1.2 \) to \( z \sim 0.9 \) seems to be explained mainly by the decrease of the overall star formation activity in the universe, while the additional offset seen in the right panel of Figure 12 might be explained by the evolution of the gas metallicity and/or dust extinction in star-forming galaxies.
Figure 12. Left: comparison of the normalized differential distributions of $EW_0([\text{O} \text{II}])$ between $z \sim 0.9$ and $z \sim 1.2$. The black and gray histograms show that for galaxies at $z \sim 0.9$ and $z \sim 1.2$, respectively. The vertical dashed line shows the equivalent width limit of $EW_0([\text{O} \text{II}]) = 12 \, \text{Å}$ for our $[\text{O} \text{II}]$ emitter selection. Note that only galaxies classified as $[\text{O} \text{II}]$ emitters are plotted, while the calculation of the normalization constant takes into account of all galaxies including objects that do not satisfy the selection criteria for the $[\text{O} \text{II}]$ emitter. Right: the same as the left panel, but for the observed $EW_0([\text{O} \text{II}])$ for $[\text{O} \text{II}]$ emitters at $z \sim 1.2$ is divided by a factor of 1.3 and 1.6 (short- and long-dashed histograms). A decrease by a factor of 1.3–1.6 in $EW_0([\text{O} \text{II}])$ from $z \sim 1.2$ to $z \sim 0.9$ is expected from the simple model where SFRs of star-forming galaxies decrease by a factor of two in the redshift interval (see the text).

Figure 13. $[\text{O} \text{II}]$ luminosity function for $[\text{O} \text{II}]$ emitters at $z \sim 0.9$ and $z \sim 1.2$. The solid circles show the result for our $[\text{O} \text{II}]$ emitter sample at $z \sim 0.9$ in the COSMOS field. The thick dotted, solid, and dashed lines represent the best-fit Schechter functions for $\alpha = -1.0$, $\alpha = -1.2$, and $\alpha = -1.4$, respectively. The thin dash-dotted line shows $[\text{O} \text{II}]$ LF for $[\text{O} \text{II}]$ emitters at $z \sim 0.9$ in the Subaru Deep Field from Ly et al. (2007). The thin solid line represents the result at $z \sim 1.2$ in the COSMOS field updated from Takahashi et al. (2007) with the newest version of the COSMOS photometric redshift catalog. The thin dotted lines show $[\text{O} \text{II}]$ LF at $z \sim 1.2$ in the Subaru Deep Field from Takahashi et al. (2007).

5. SUMMARY

We investigated the fraction of $[\text{O} \text{II}]$ emitters in the photo-$z$-selected galaxies at $z \sim 0.9$ as a function of the local galaxy density in the COSMOS field. $[\text{O} \text{II}]$ emitters are selected by the narrowband excess technique with the NB711-band data taken with Subaru/Suprime-Cam. We used the magnitude limits and selection criteria for $[\text{O} \text{II}]$ emitters which are consistent with our previous study at $z \sim 1.2$ in order to make a direct comparison between $z \sim 0.9$ and $z \sim 1.2$. Our final sample consists of 614 (291) photo-$z$-selected galaxies with $M_{U3500} < -19.31$ ($M_{U3500} < -19.71$) at $z = 0.901$–0.920, which includes 195 (95) $[\text{O} \text{II}]$ emitters. Our main results are as follows.

1. The fraction of $[\text{O} \text{II}]$ emitters at $z \sim 0.9$ is nearly constant ($\sim 0.3$) at $0.3 \, \text{Mpc}^{-2} < \Sigma_{[\text{O} \text{II}]} < 10 \, \text{Mpc}^{-2}$. The flat distribution holds, even if we use the magnitude limit for which the luminosity evolution of galaxies is taken into account. No significant environmental dependence is similar to the result in our previous study at $z \sim 1.2$.

2. The fraction of $[\text{O} \text{II}]$ emitters decreases from $\sim 0.6$ at $z \sim 1.2$ to $\sim 0.3$ at $z \sim 0.9$ in all environments we investigated.

3. Instead of $[\text{O} \text{II}]$ emitters, we used galaxies with blue rest-frame colors of $NUV - R < 2$ at $0.91 - 0.023 \leq \zeta_{\text{phot}} \leq 0.91 + 0.023$ as the star-forming population in order to measure both the fraction of star-forming galaxies and the local galaxy density from the same sample. The fraction of blue galaxies with $NUV - R < 2$ also does not significantly depend on the local density.

4. We checked the effects of the projection over the redshift slice and the photometric redshift error on our density measurement using the semi-analytic model by Font et al. (2008). Although these effects seem to smear out very high and low density regions to some degree, we confirmed that the fraction of $[\text{O} \text{II}]$ emitters clearly depends on the projected density in the simulation, which is different from the observed results.

5. Most $[\text{O} \text{II}]$ emitters have relatively small stellar masses of $M_{\text{star}} < 10^{10} \, M_\odot$, and the overlap between $[\text{O} \text{II}]$...
emitters and bright 24 μm sources with $f_{24\mu m} \gtrsim 150–200$ μJy is relatively small. The [O ii] emitter selection seems to miss massive dusty star-forming galaxies. Such a selection bias might cause different behaviors in the SFR-density relation among studies with the different SFR indicators.

6. If we simply assume that SFRs of star-forming galaxies decrease by a factor of two from $z \sim 1.2$ to $z \sim 0.9$, which is expected from the evolution of the [O ii] LF and cosmic SFR density in the redshift interval, the expected evolution of the EW$_{0}([O \text{ ii}])$ is roughly consistent with the observed EW$_{0}([O \text{ ii}])$ distributions at $z \sim 1.2$ and $z \sim 0.9$. Therefore, the decrease of the fraction of [O ii] emitters from $z \sim 1.2$ to $z \sim 0.9$ seems to be explained mainly by the decrease of the overall star formation activity in the universe.

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APPENDIX

LUMINOSITY FUNCTION OF [O ii] EMITTERS AT $z \sim 1.2$ IN THE COSMOS FIELD

In this appendix, we describe the derivation of the [O ii] LF at $z \sim 0.9$ in the COSMOS field. To derive the total [O ii] flux, we have used the total flux density of $r'$, $i'$ (or $i''$), and NB711. The flux of [O ii] emission line is given by

$$f_{[O \text{ ii}]} = \Delta NB - \frac{f_{NB} - f_{ri}}{1-0.68(\Delta NB/\Delta i')} ,$$

(A1)

where $f_{NB}$ is the total flux density of NB711, $f_{ri}$ is the $ri$ continuum flux density, $\Delta NB$ and $\Delta i'$ are the effective bandwidth of the NB711 and $i'$ filters, respectively: \(\Delta NB = 72.5 \pm 5.6 \text{ Å} \) and \(\Delta i' = 1489.4 \pm 14\). Since the flux of the [O ii] emission line is affected by the dust obscuration, it is necessary to correct the extinction effect. Here, we apply a constant extinction of $A_{[O \text{ ii}]} = 1.87$ mag, which corresponds to $A_{r'} = 1$ mag, following previous studies (Hopkins 2004; Takahashi et al. 2007; Sobral et al. 2012). We also apply the filter transmission effect since the actual NB711 filter transmission is not rectangular. We adopt a factor of 1.24 following Shioya et al. (2009).

Then, the [O ii] flux is given by

$$f_{\text{cor}}([O \text{ ii}]) = f_{[O \text{ ii}]} \times 10^{0.4A_{[O \text{ ii}]}} \times 1.24,$$

(A2)

and the [O ii] luminosity is estimated by

$$L([O \text{ ii}]) = 4\pi d_l^2 \cdot f_{\text{cor}}([O \text{ ii}]),$$

(A3)

where $d_l$ is the luminosity distance: $d_l = 5883 \text{ Mpc}$.

The [O ii] LF is constructed by the following formula:

$$\Phi(\log L) = \frac{1}{A\log L} \sum_j \frac{1}{V_j},$$

(A4)

with $|\log L_i - \log L_j| < (1/2)\Delta \log L$, where $\Delta \log L$ is the logarithmic bin size and $V_j$ is the volume covered by the filter. Here we use $\Delta \log L = 0.2$ and $V_j = 2.28 \times 10^5 \text{ Mpc}^3$. We show the [O ii] LF in Figure 13.

We fit the [O ii] LF with the Schechter function (Schechter 1976)

$$\Phi(L) dL = \frac{\phi_{\star}}{L_{\star}} \left( \frac{L}{L_{\star}} \right)^{\alpha} \exp \left( -\frac{L}{L_{\star}} \right) dL \quad (A5)$$

by the STY method (Sandage et al. 1979). Before fitting the [O ii] LF, we estimate the lower and upper limiting luminosities ($L_{\text{low}}$ and $L_{\text{up}}$) that evaluate whether or not the sample is complete. Using the observed limiting magnitudes of $ri$ and NB711, we obtain $L_{\text{low}} = 41.83 \text{ erg s}^{-1}$. On the other hand, the saturation magnitude of $r'$ gives the upper limiting luminosity of $L_{\text{up}} = 43.65 \text{ erg s}^{-1}$. Since it is difficult to accurately estimate the power index $\alpha$ because of incompleteness at the faint end, we show our results for the following three cases: $\alpha = -1.0, -1.2, -1.4$ in Table 2.

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