

ENVIRONMENTAL EFFECTS ON THE STAR FORMATION ACTIVITY IN GALAXIES AT $z \simeq 1.2$ IN THE COSMOS FIELD*

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ABSTRACT

We investigate the relation between the star formation activity in galaxies and environment at $z \simeq 1.2$ in the Cosmic Evolution Survey field, using the fraction of [O II] emitters and the local galaxy density. The fraction of [O II] emitters appears to be almost constant over the surface density of galaxies between 0.2 and 10 Mpc^{-2} . This trend is different from that seen in the local universe where the star formation activity is weaker in higher density regions. To understand this difference between $z \sim 1$ and $z \sim 0$, we study the fraction of non-isolated galaxies as a function of local galaxy density. We find that the fraction of non-isolated galaxies increases with increasing density. Our results suggest that the star formation in galaxies at $z \sim 1$ is triggered by galaxy interaction and/or mergers.

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

1. INTRODUCTION

To understand the formation and evolution of galaxies strongly relies on investigations of when and where stars formed in the history of the universe from high redshift to the present day. Since the pioneering study by Madau et al. (1996), a number of observational studies have investigated how the star formation rate density (SFRD) varies as a function of redshift. Such studies brought us a global evolutionary picture of the SFRD; the SFRD steeply increases in the first 900 Myr, peaks at $z \sim 3-1$, and then decreases rapidly toward the present day (e.g., Madau et al. 1996; Lilly et al. 1996; Fujita et al. 2003; Bouwens & Illingworth 2006). However, we are still far from a complete understanding of the galaxy evolution since the redshift evolution of the SFRD gives us only the “averaged” picture of the star formation history in the universe. There exists a wide variety of environments in the universe, such as field, groups, and clusters of galaxies. Moreover, even within the field, there are structures like high- and low-density regions. It is thus essential to study the star formation in galaxies as a function of both the

redshift and the environment. One possible approach is to study the relation between the galaxy properties and the environments at various epochs.

The environmental effects on galaxy properties in the local universe have been extensively studied in the past. Star formation activity in galaxies is known to decline with increasing density (e.g., Lewis et al. 2002; Gomez et al. 2003), and the fraction of star formation galaxies decreases with increasing density (e.g., Carter et al. 2001; Balogh et al. 2004; Mateus & Sodré 2004). These findings agree quite well with the so-called morphology–density relation, i.e., the fraction of early type galaxies increases with increasing density, while the fraction of late-type galaxies decreases with increasing density (e.g., Dressler 1980; Dressler et al. 1997; Goto et al. 2003; Capak et al. 2007). All these results suggests that the star formation in the high-density region are more active than in the low-density regions. In contrast, recent observational studies in the Great Observatories Origins Deep Survey (GOODS; Dickinson & Giavalisco 2002) and the DEEP2 Galaxy Redshift Survey (DEEP2; Davis et al. 2003) shows that this relation becomes completely opposite at $z \sim 1$; the star formation activity depends positively on the density of galaxies (Elbaz et al. 2007; Cooper et al. 2008). The origin of this drastic change between $z \sim 1$ and $z \sim 0$ is still not clear.

In this paper, we present the relationship between the star formation activity and the environment at $z \simeq 1.2$, in the Cosmic Evolution Survey (COSMOS; Scoville et al. 2007a) field. We estimate star formation activity by focusing on the “emitter fraction.” Specifically we investigate the fraction of galaxies emitting [O II] $\lambda 3727$ emission (hereafter “[O II] emitters”), as a function of the galaxy local density. The [O II] $\lambda 3727$ (hereafter [O II]) emission line is a good estimator of the star formation activity in galaxies at intermediate redshift (e.g., Jansen et al. 2001). Although it is known that the [O II] emission line is

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affected by dust extinction and metallicity, such effects on the emitter fraction are thought to be small, since our [O II] emitters are selected based on the equivalent widths (EWs). Specifically, the [O II] EW is significantly smaller in very metal-poor and metal-rich galaxies, with respect to galaxies with the solar metallicity. However, it is observed that the variation is relatively small, only a factor of 2–3, in the metallicity range of $7.7 < 12 + \log(\text{O}/\text{H}) < 9.2$ (e.g., Nagao et al. 2006). Since galaxies with metallicity out of this range are expected to be rare, we consider that the metallicity effect on the emitter fraction is not significant.

We have already carried out the Subaru imaging observations of the COSMOS field (Taniguchi et al. 2007). The sample of [O II] emitters in the COSMOS field was obtained by Takahashi et al. (2007) using a narrowband filter NB816 [$\lambda_c = 8150 \text{ \AA}$ and $\Delta\lambda(\text{FWHM}) = 120 \text{ \AA}$] (see also Murayama et al. 2007; Shioya et al. 2008). Thanks to the very large survey area (2 deg^2) of the COSMOS field, we are able to obtain a typical picture of the star formation activity in galaxies, avoiding the cosmic variance. The COSMOS field includes various regions within a wide range of galaxy density (e.g., Scoville et al. 2007a, 2007b; Takahashi et al. 2007), so that we are able to investigate systematically the environmental effects on the star formation activity in galaxies.

In Section 2, we describe the sample selection and discuss the possible contamination in the photometric-redshift sample. The results of the star formation activity–environment relation at $z \simeq 1.2$ and the dependence of the morphology on the density are presented in Section 3. The interpretation of our results is discussed in Section 4. And finally we give a brief summary in Section 5. Throughout this paper, magnitudes are given in the AB system. We adopt a flat universe with the following cosmological parameters: $\Omega_{\text{matter}} = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. THE SAMPLE

2.1. Sample Selection

In order to derive the emitter fraction and investigate its environmental dependence, we require two samples of galaxies: the [O II] emitter sample and the total galaxy sample (i.e., both galaxies with and without [O II] emission). The former one is used to identify actively star-forming galaxies. The latter one is necessary to estimate the galaxy local density for each position in the COSMOS field.

We carried out the imaging survey for [O II] emitters at $z \simeq 1.2$ with a narrowband filter NB816 (see Ajiki et al. 2003 for details) in the COSMOS 2 deg^2 field, using the Suprime-Cam (Miyazaki et al. 2002) on the Subaru Telescope (Kaifu et al. 2000; Iye et al. 2004). This survey covers a sky area of 6700 arcmin^2 in the COSMOS field and a redshift range between 1.17 and 1.20 for [O II] ($\Delta z = 0.03$, corresponds to 70 Mpc in the comoving distance), corresponding to a survey volume of $5.5 \times 10^5 \text{ Mpc}^3$. We have obtained a sample of 3176 [O II] emitters from these data, down to $i' \simeq 26.1$. The selection threshold of the [O II] EW is $> 12 \text{ \AA}$ in the observed frame or $> 12 \text{ \AA}$ in the rest frame (see Takahashi et al. 2007 for more details). We use a subsample of this parent sample of [O II] emitters for our analysis and discussion.

To identify both galaxies with and without [O II] emission in the range of $1.17 < z < 1.20$ (i.e., the coverage of the NB816 filter for [O II] emitters), we select galaxies with a photometric redshift (photo- z , z_{ph}) in the range of $1.17 < z_{\text{ph}} < 1.20$ from

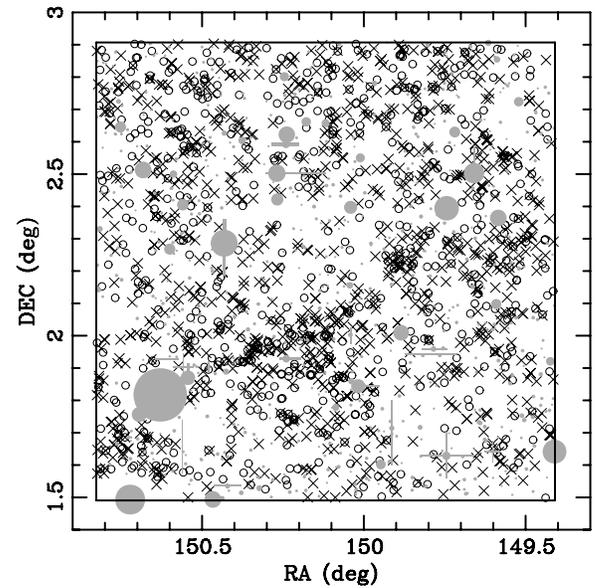


Figure 1. Spatial distributions of our sample at $1.17 < z < 1.20$ in the COSMOS field. Open circles denote non-emitters in our sample. Cross symbols denote [O II] emitters selected by Takahashi et al. (2007) in our sample. The circle areas are masked out for the detection. We select galaxies in the region of the large solid square: $149:40917 < \text{R.A. (J2000)} < 150:82680$ and $1:49056 < \text{decl. (J2000)} < 2:90705$ (Takahashi et al. 2007).

the COSMOS photo- z catalog (Ilbert et al. 2009). Since fainter galaxies have larger photo- z errors, we select only bright galaxies to avoid possible contaminations. Specifically we limit our sample only in galaxies with $i' < 24$, because the estimated photo- z error is $\sigma_z = 0.02$ for galaxies with $i' < 24$ and $z_{\text{ph}} < 1.25$. Note that photo- z errors for galaxies with $i' < 25$ and $i' < 25.5$ are $\sigma_z = 0.04$ and 0.07 , respectively. Consequently, we obtain 1553 galaxies with $1.17 < z < 1.20$ and $i' < 24$.

We find by cross-checking these two samples that 965 among 1553 photo- z selected galaxies are [O II] emitters selected by Takahashi et al. (2007). The other 588 objects are galaxies without [O II] emission (more strictly, without [O II] emission with $\text{EW} < 12 \text{ \AA}$ rest frame). The star formation rate (SFR) of [O II] emitters is estimated through the relation of $\text{SFR} = 1.41 \times 10^{-41} L([\text{OII}]) M_{\odot} \text{ yr}^{-1}$ (Kennicutt 1998). The minimum and maximum SFR values in our sample of the [O II] emitters (with $i' < 24$) are $12 M_{\odot} \text{ yr}^{-1}$ and $275 M_{\odot} \text{ yr}^{-1}$, respectively.

The spatial distribution of all galaxies in our sample at $1.17 < z < 1.20$ is presented in Figure 1. This figure shows that our sample includes galaxies in various density regions, and therefore the sample is suitable to investigate the environmental effects on the star formation activity in galaxies at $z \simeq 1.2$.

2.2. Contamination in the Photometric-redshift Sample

We estimate how our photo- z sample is contaminated by foreground or background objects. We use 22 objects with the spectroscopic redshifts (spec- z : class “3” and class “4” in Lilly et al. 2007) to examine the accuracy of our photo- z estimation. Among these objects, 18 objects have spec- z similar to our target range, $1.17 < z < 1.20$, within the photo- z error, $\sigma_z = 0.02$, while the remaining objects have spec- z out of this redshift range. The expected contamination rates for the photo- z sample are thus estimated to be 18%. We also estimate the incompleteness of our photo- z sample, using 22 objects with the spec- z within our target range. Among these objects, 17 objects have photo- z in our target range within the photo- z error.

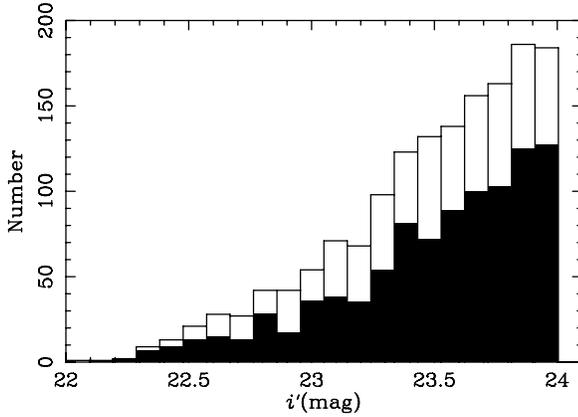


Figure 2. Number count of our sample as a function of the i' magnitude. Open boxes denote our total sample, including both [O II] emitters and non-emitters. Filled boxes denote [O II] emitters.

The expected incompleteness rate for the photo- z sample is thus estimated to be 22%. From these results, we consider that at least about 80% of photo- z in our sample is reliable. We will show that this contamination and incompleteness do not affect our results.

3. RESULTS

3.1. Magnitude Dependence of the Emitter Fraction

As described in Section 2.1, we selected 965 [O II] emitters and 588 non-emitters. Accordingly, $\approx 62\%$ of galaxies at $z \simeq 1.2$ are [O II] emitters. We show the i' -band number count of our sample in Figure 2. This figure shows that the emitter fraction does not depend significantly on the i' magnitude. This indicates that more than half of galaxies at $z \simeq 1.2$ are active star-forming galaxies, regardless of galaxy magnitude. This is completely different from the properties of [O II] emitters in the local universe. Gomez et al. (2003) reported that the median [O II] EW of galaxies in the local universe in the Sloan Digital Sky Survey (SDSS; York et al. 2000) Early Data Release (EDR; Stoughton et al. 2002) sample is $\sim 5 \text{ \AA}$ and the [O II] emitter fraction (i.e., the rest-frame [O II] EW larger than 12 \AA) is $\approx 15\%$, much lower than our result at $z \simeq 1.2$ ($\approx 62\%$). This is consistent with the redshift evolution of the SFRD between $z \simeq 1.2$ and $z \simeq 0$ (e.g., Lilly et al. 1996; Fujita et al. 2003).

3.2. Environmental Effects on the Star Formation Activity

Here we examine the relation between the star formation activity and the galaxy environment. We adopt the projected 10th nearest-neighbor surface density as an indicator of the galaxy environment, following the manner in Dressler (1980). This density is estimated by using the distance to the 10th nearest neighbor from each object. This distance is used to estimate the surface density as

$$\Sigma_{10\text{th}} = \frac{11}{\pi r^2}. \quad (1)$$

Galaxies near the edge of our field of view, i.e., $r_{10\text{th}}$ is greater than the distance from the edge, are not used in the analysis since the local galaxy density of such galaxies is not correctly estimated. As discussed in Section 2.1, we limit our sample only in galaxies with $i' < 24$. This limiting magnitude corresponds to $M(V) = -20.5$, adopting the typical spectral energy distribution (SED) in our sample. This limit is close to those used by Gomez et al. (2003) [$M(r^*) =$

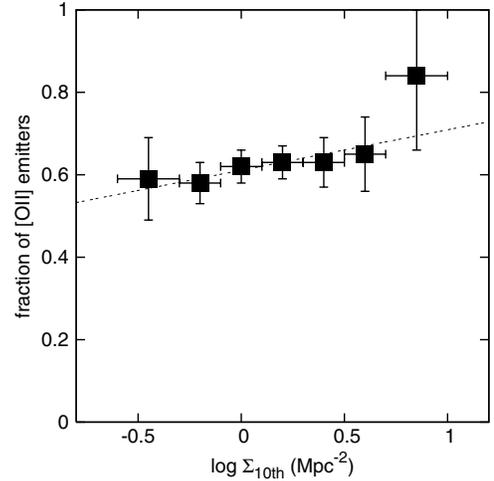


Figure 3. Fraction of [O II] emitters is plotted as a function of the galaxy local density. The dotted line shows the linear fit to the data. The star formation activity is more active in higher density regions. Here, the adopted size of the $\log \Sigma_{10\text{th}}$ bin is 0.2 dex, except for the lowest- and highest- $\log \Sigma_{10\text{th}}$ bins where there are only a few objects (0.3 dex for these bins).

-20.6) and Dressler (1980) [$M(V) = -19.7$]; note that these magnitudes are re-calculated by using the cosmology adopted in our paper. Our local galaxy density of 1 Mpc^{-2} corresponds to $\approx 1.15 \text{ Mpc}^{-2}$ if adopting the Cosmology used by Gomez et al. (2003). Note that Dressler (1980) calculated the local galaxy density differently from our method, i.e., we eliminate foreground and background galaxies using the photometric redshift. Thus, our 10th nearest neighbor is much farther away than that obtained through Dressler's definition. Therefore, we do not compare our results with those of Dressler (1980).

To quantify the typical star formation activity of galaxies as a function of the local galaxy density, we use the fraction of [O II] emitters. We expect a positive or negative dependence of the [O II] emitter fraction on the number density of galaxies, if the star formation activity at $z \sim 1$ has any preferences on galaxy environments. We show the relation between the [O II] emitter fraction and the local galaxy density in Figure 3. We then apply a linear fit to obtain the relation, $\text{fraction} = (0.098 \pm 0.081) \log \Sigma_{10\text{th}} + (0.611 \pm 0.023)$. We find no significant correlation between the [O II] emitter fraction and the local galaxy density. The star formation activity is almost constant at any local densities, although we see a marginal signature of positive correlation between the star formation activity and the local galaxy density. This trend appears to be different from the relation in the local universe. It should be noted that the redshift bin size in our sample ($\Delta z = 0.03$) is comparable to the photo- z error ($\sigma_z = 0.02$). In order to examine how the photo- z uncertainty affects our results, we have made a similar analysis adopting a larger redshift bin size of $\Delta z = 0.07$, considering the photo- z error. In this case, we still obtained the result that the star formation activity tends to be higher in higher density regions. To be consistent with previous studies (Dressler 1980), we used a criterion of the 10th nearest neighbor. We have tried to adopt a lower value (third and fifth) and found the same trend of the results shown in Figure 3.

3.3. Effects of the Contamination and Incompleteness in the Sample

Here we consider the possible influence of the contamination and incompleteness on the photo- z catalog. As

Table 1
The Fraction of Isolated Galaxies and Non-Isolated Galaxies

| | [O II] Emitters | Non-Emitters |
|-----------------------|-----------------|--------------|
| Isolated fraction | 57% | 72% |
| Non-isolated fraction | 43% | 28% |
| Total | 100% | 100% |

Table 2
The Fraction of [O II] Emitters and Non-Emitters

| | Isolated Galaxies | Non-Isolated Galaxies |
|----------------------|-------------------|-----------------------|
| [O II] fraction | 56% | 71% |
| Non-emitter fraction | 44% | 29% |
| Total | 100% | 100% |

mentioned in Section 2.2, the estimated photo- z contamination and incompleteness is $\sim 20\%$. It is thought that our main result is not affected by the contamination and incompleteness, except for the case that the fraction of contamination or incompleteness depends strongly on the number density of galaxies. This is unlikely, because the photo- z errors mainly depend on the photometric accuracy, which is independent of the environment except for highly confused regions (not majority in our sample). Even if we overestimate or underestimate $\Sigma_{10\text{th}}$, the data points in Figure 3 would shift just slightly along the $\Sigma_{10\text{th}}$ -axis. We thus conclude that the contamination and incompleteness of the photo- z sample do not affect significantly our results and discussion.

3.4. Environmental Effects on the Galaxy Morphology

Our results imply that star formation activity is also high in high-density regions at $z \simeq 1.2$, showing a different trend from that seen in the local universe (Figure 3). Here we consider what is the origin of this difference between $z \sim 1$ and $z \sim 0$. As a possible origin, we expect the influence of the galaxy interaction or merger because it is known that companion galaxies (galaxy interactions and mergers) can trigger star formation (e.g., Taniguchi & Wada 1996). We investigate environmental effects on the fraction of non-isolated galaxies (non-isolated fraction) to study if galaxy interaction and mergers relate to star formation in high-density regions at $z \sim 1$. To define the subsamples of isolated galaxies and non-isolated galaxies, we searched for the nearest neighbor for each galaxy in the sample satisfying the following two conditions:

$$1.17 < z_{\text{ph}} < 1.20 \quad (2)$$

and

$$|i'_t - i'_n| < 2.5, \quad (3)$$

where i'_t and i'_n are the i' magnitudes of a target object and its nearest neighbor, respectively. We define non-isolated galaxies as objects that have the nearest neighbors within the apparent separation of less than 10 arcsec. This corresponds to ≈ 80 kpc in proper distance, being similar to the distance between our Galaxy and its satellite galaxies. The remaining objects are defined as isolated galaxies. We note that our non-isolated galaxies do not include galaxies having a very small effect of the gravitational interaction between galaxies since we adopt the following condition: $|i'_t - i'_n| < 2.5$.

We find that the fraction of the non-isolated galaxies is 37% over the whole sample, including both the 43% [O II]

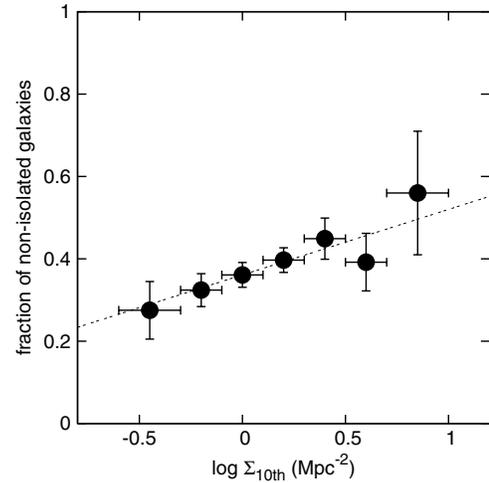


Figure 4. Fraction of non-isolated galaxies is plotted as a function of the galaxy local density. The dotted line shows the linear fit to the data. Here the adopted size of the $\log \Sigma_{10\text{th}}$ bin is 0.2 dex, except for the lowest- and highest- $\log \Sigma_{10\text{th}}$ bins where there are only a few objects (0.3 dex for these bins).

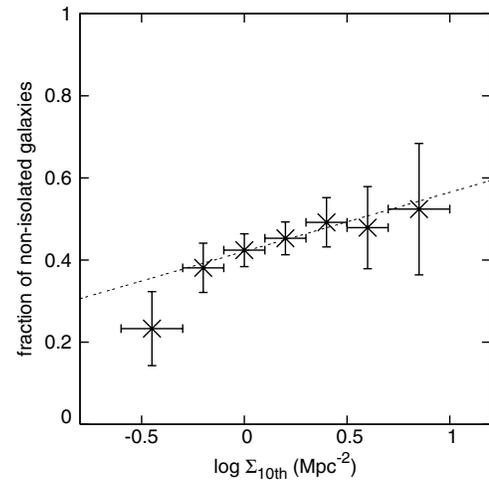


Figure 5. Fraction of non-isolated galaxies among [O II] emitters is plotted as a function of the galaxy local density. The dotted line shows the linear fit to the data. Here the adopted size of the $\log \Sigma_{10\text{th}}$ bin is 0.2 dex, except for the lowest- and highest- $\log \Sigma_{10\text{th}}$ bins where there are only a few objects (0.3 dex for these bins).

emitters and 28% non-emitters (Table 1). And, 71% of all non-isolated galaxies in the sample are [O II] emitters (Table 2), suggesting that interacting and/or merging galaxies tend to be star-forming galaxies. Based on the results of our classification, we study the relation between the non-isolated fraction among the [O II] emitters and the local galaxy density. Here, we again adopt $\Sigma_{10\text{th}}$ as a measure of the local density. Figure 4 shows the results of this relation. The linear fit gives the relation, $\text{fraction} = (0.159 \pm 0.073) \log \Sigma_{10\text{th}} + (0.361 \pm 0.019)$. This result shows that the non-isolated fraction is higher in denser regions and suggest that galaxies in high-density regions have a greater tendency to interact or merge than low-density regions. In order to confirm whether interacting and merging galaxies are related to star formation in high-density regions, we plot the non-isolated fraction among the [O II] emitters as a function of the local galaxy density (Figure 5). Figure 5 shows that the non-isolated fraction among the [O II] emitters increases with increasing local density. These results indicate that galaxy interactions and/or mergers tend to occur in higher density

regions. We make the same analysis with $|i'_t - i'_n| < 1.5$ as a test and find the same trend as seen in Figures 4 and 5.

4. THE ORIGIN OF THE ENVIRONMENTAL EFFECTS

In the local universe, it is well known that the star formation in galaxies is inactive in high-density regions (e.g., Gomez et al. 2003; Mateus & Sodré 2004). For instance, Gomez et al. (2003) found an overall shift of [O II] EW distributions to lower values in high-density regions based on their analysis on the SDSS data. However, our results show that the relation between the fraction of [O II] emitters and the local galaxy density at $z \simeq 1.2$ appears to be flat or to show a slight positive correlation (Figure 3). This implies that star formation in high-density regions is also active, showing a different trend from that seen in the local universe.

Recently, Elbaz et al. (2007) and Cooper et al. (2008) reported that the mean SFR of galaxies is higher in higher density regions at $z \sim 1$, which is completely different from the tendency seen at $z \sim 0$. Specifically, Elbaz et al. (2007) studied the mean SFR of galaxies in the GOODS fields at $z \sim 1$ by using both UV and IR luminosity, and found that it depends positively on the local galaxy density. On the other hand, using the SFR measured with [O II] luminosities, Cooper et al. (2008) also studied the mean SFR–local galaxy density relation in the DEEP2 and the SDSS and found a similar trend. Both analyses indicate that the star formation activity in high-density regions is higher than that in low-density regions at $z \sim 1$, unlike the case of the local universe. This gives close agreement with our results on the relationship between the [O II] fraction and density that the environmental dependence of the star formation activity in galaxies is completely different between $z \sim 1$ and $z \sim 0$.

Here we discuss the following question: what is the origin of this difference between $z \sim 1$ and $z \sim 0$? Such a different trend was predicted by semi-analytic models for the hierarchical galaxy formation, in the sense that galaxies in the denser regions evolve more earlier in the history of universe (Elbaz et al. 2007). Moreover, it is also claimed observationally that the evolution of galaxies occurred earlier in higher density regions, which is suggested by the discovery that the build-up of the color–magnitude relation appears to be delayed in lower-density environments (Tanaka et al. 2005). As a possible origin of the difference between $z \sim 1$ and $z \sim 0$, we expect the influence of the galaxy interaction or merger because it is known that galaxy interaction and merger trigger intense star formation (e.g., Taniguchi & Wada 1996; Mihos & Hernquist 1996; Taniguchi et al. 1999). That is, many galaxies in higher density regions could have experienced interaction and/or merging with star formation in the past, and then the star formation in them becomes inactive because they gradually consume their gas. As a consequence, the number density of active star-forming galaxies could shift from high-density regions to low-density regions with time.

If our interpretation is correct, it is expected that there are many interacting and/or merging galaxies in higher density regions at high redshift. In order to examine this expectation, we studied the morphology of the galaxies, as already described in Section 3.4. We found that the fraction of non-isolated galaxies in the [O II] emitter sample is higher than in the non-[O II] emitter sample (see Tables 1 and 2). In addition, the non-isolated fraction among the whole sample (including both [O II] and non-[O II] emitters) increases with increasing local galaxy density (Figure 4) and the non-isolated fraction among the [O II] emitters is higher in a denser region (Figure 5). These results

show that galaxy interactions and/or mergers tend to occur in higher density regions, inducing their active star formation. Note that the non-isolated fraction among the [O II] emitters does not reach unity in high-density regions, although it is significantly higher than this in lower density regions. We speculate that some advanced-merger and/or minor-merger systems are included in the [O II] emitter at high-density regions, which seems to be hard to be recognized as non-isolated galaxies morphologically. Our results are consistent with our expectation that interaction and/or merger-induced star formation is a possible origin of star formation in high-density regions at $z \simeq 1.2$.

Here we mention that the ram pressure affects the star formation activity in high-density regions in addition to the galaxy interaction and/or mergers. This is because the gas stripping due to the ram pressure generally quenches the star formation in clusters of galaxies (e.g., Gunn & Gott 1972; Hester 2006). However, the ram pressure does not significantly influence our results, since our sample does not include very high-density regions such as central regions of clusters of galaxies. Therefore, we consider that the star formation activity of galaxies in high-density regions is induced by the galaxy interaction, at $z \sim 1$. Here we point out that the gas fraction in galaxies is higher at $z \sim 1$ than that at $z \sim 0$ even in high-density regions. This difference results in that the galaxy mergers at $z \sim 1$ tend to be “wet,” while the galaxy mergers at $z \sim 0$ tend to be “dry” (e.g., Lin et al. 2008). Since the wet mergers naturally result in active star formation (e.g., Woods et al. 2006; Bridge et al. 2007), the star formation is induced by interacting and/or merging galaxies even in high-density regions, at $z \sim 1$. In contrast, galaxy interactions and mergers in high-density regions do not cause active star formation at $z \sim 0$. This picture is completely consistent with the results of Elbaz et al. (2007) and of Cooper et al. (2008).

5. SUMMARY

In this paper, we present the relation between the star formation activity and the galaxy density at $z = 1.17\text{--}1.20$, using 1553 objects with $i' < 24$ in the COSMOS field. We estimate star formation activity by focusing on the “emitter fraction.” Our main results are as follows.

1. The relation between the fraction of [O II] emitters and the local galaxy density at $z \simeq 1.2$ is flat, or positively correlated possibly, suggesting a different trend from the tendency observed in the local universe.
2. The fraction of non-isolated galaxies (interactions, mergers, and multiples) increases with increasing density, and this fraction is systematically higher in [O II] emitters than in non-[O II] emitters.

Through the observational studies in the local universe, it is known that star formation is inactive at high-density regions. However, our results indicate that the star formation is active also in high-density regions at $z \simeq 1.2$. We conclude that the origin of this difference is the influence of “wet” galaxy interactions and/or mergers. That is, galaxies in high-density regions have experienced interacting and/or merging with star formation at $z \sim 1$, while the star formation in them occurs because their gas is gradually consumed. And so the number density of active star-forming galaxies shifted from high-density regions to low-density regions with time. This implies that the evolution of galaxies in high-density regions occurs earlier, relative to that in low-density regions.

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REFERENCES

- Ajiki, M., et al. 2003, *AJ*, 126, 2091
 Balogh, M., et al. 2004, *MNRAS*, 348, 1355
 Bouwens, R. J., & Illingworth, G. D. 2006, *Nature*, 443, 189
 Bridge, C. R., et al. 2007, *ApJ*, 659, 931
 Capak, P. L., Abraham, R. G., Ellis, R. S., Mobasher, B., Scoville, N. Z., Sheth, K., & Koekemoer, A. 2007, *ApJS*, 172, 284
 Carter, B. J., Fabricant, D. G., Geller, M. J., & Kurtz, M. J. 2001, *ApJ*, 559, 606
 Cooper, M. C., et al. 2008, *MNRAS*, 383, 1058
 Davis, M., et al. 2003, *Proc. SPIE*, 4834, 161
 Dickinson, M., & Giavalisco, M. 2003, in *ESO/USM Workshop, The Great Observatories Origins Deep Survey*, ed. R. Bender & A. Renzini (Berlin: Springer), 324
 Dressler, A. 1980, *ApJ*, 236, 351
 Dressler, A., et al. 1997, *ApJ*, 490, 577
 Elbaz, D., et al. 2007, *A&A*, 468, 33
 Fujita, S. S., et al. 2003, *ApJ*, 586, L115
 Gomez, P. L., et al. 2003, *ApJ*, 584, 210
 Goto, T., Yamauchi, C., Fujita, Y., Okamura, S., Sekiguchi, M., Smail, I., Bernardi, M., & Gomez, P. L. 2003, *MNRAS*, 346, 601
 Gunn, J. E., & Gott, J. R. 1972, *ApJ*, 176, 1
 Hester, J. A. 2006, *ApJ*, 647, 910
 Ilbert, O., et al. 2009, *ApJ*, 690, 1236
 Iye, M., et al. 2004, *PASJ*, 56, 381
 Jansen, R. A., Franx, M., & Fabricant, D. 2001, *ApJ*, 551, 825
 Kaifu, et al. 2000, *PASJ*, 52, 1
 Kennicutt, R. C. 1998, *ARA&A*, 36, 189
 Lewis, I., et al. 2002, *MNRAS*, 334, 673
 Lilly, S., et al. 2007, *ApJS*, 172, 70
 Lilly, S. J., Le Fevre, O., Hammer, F., & Crampton, D. 1996, *ApJ*, 460, L1
 Lin, L., et al. 2008, *ApJ*, 681, 232
 Madau, P., Ferguson, H. C., Dickinson, M. E., Giavalisco, M., Steidel, C. C., & Fruchter, A. 1996, *MNRAS*, 283, 1388
 Mateus, A., & Sodré, L. 2004, *MNRAS*, 349, 1251
 Mihos, J. C., & Hernquist, L. 1996, *ApJ*, 464, 641
 Miyazaki, S., et al. 2002, *PASJ*, 54, 833
 Murayama, T., et al. 2007, *ApJS*, 172, 523
 Nagao, T., et al. 2006, *A&A*, 459, 85
 Shioya, Y., et al. 2008, *ApJS*, 175, 128
 Scoville, N. Z., et al. 2007a, *ApJS*, 172, 1
 Scoville, N. Z., et al. 2007b, *ApJS*, 172, 150
 Stoughton, C., et al. 2002, *AJ*, 123, 485
 Takahashi, M. I., et al. 2007, *ApJS*, 172, 456
 Tanaka, M., et al. 2005, *MNRAS*, 362, 268
 Taniguchi, Y., & Wada, K. 1996, *ApJ*, 469, 58
 Taniguchi, Y., et al. 1999, *IAUS*, 186, 307
 Taniguchi, Y., et al. 2007, *ApJS*, 172, 9
 Woods, D. F., Geller, M. J., & Barton, E. J. 2006, *AJ*, 132, 197
 York, D. G., et al. 2000, *AJ*, 120, 1579