Calibrating \([\text{O II}]\) star formation rates at \(z > 1\) from dual H\(\alpha\)-[O II] imaging from HiZELs

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ABSTRACT
We investigate the relationship between H\(\alpha\) and [O II](\(\lambda 3727\)) emission in faint star-forming galaxies at \(z = 1.47\) with dust uncorrected star formation rates (SFRs) down to \(1.4 \text{ M}_\odot \text{ yr}^{-1}\), using data in two narrow bands from wide-field camera/United Kingdom Infrared Telescope and Subaru prime focus camera/Subaru. A stacking analysis allows us to investigate H\(\alpha\) emission flux from bright [O II] emitters as well as faint ones for which H\(\alpha\) is not individually detected, and to compare them with a large sample of local galaxies. We find that there is a clear, positive correlation between the average H\(\alpha\) and [O II] luminosities for [O II] emitters at \(z = 1.47\), with its slope being consistent with the local relation. [O II] emitters at \(z = 1.47\) have lower mean observed ratios of H\(\alpha$/[O II] suggesting a small but systematic offset (at 2.8\(\sigma\) significance) towards lower values of dust attenuation, \(A_{\text{H} \alpha} \sim 0.35\), than local galaxies. This confirms that [O II] selection tends to pick up galaxies which are significantly less dusty on average than H\(\alpha\)-selected ones, with the difference being higher at \(z = 1.47\) than at \(z = 0\). The discrepancy of the observed line ratios between [O II] emitters at \(z = 1.47\) and the local galaxies may in part be due to the samples having different metallicities. However, we demonstrate that metallicity is unlikely to be the main cause. Therefore, it is important to take into account that the relations for the dust correction which are derived using H\(\alpha\) emitter samples, and frequently used in many studies of high-\(z\) galaxies, may overestimate the intrinsic SFRs of [O II]-selected galaxies, and that surveys of [O II] emission galaxies are likely to miss dusty populations.

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

1 INTRODUCTION
Star formation rate (SFR) is one of the most important properties to characterize the growth of a galaxy, and the star formation history of the Universe provides us with a fundamental insight into galaxy evolution. Several surveys have been conducted to reveal the star formation activity in the distant Universe by making use of various indicators such as ultraviolet (UV) luminosity, nebular emissions such as H\(\alpha\) and [O II](\(\lambda 3727\)) and infrared (IR) radiation. These have been used to estimate SFR of galaxies over a wide range of redshifts; e.g. UV (Ouchi et al. 2009; Bouwens et al. 2011), nebular lines (Geach et al. 2008; Ly et al. 2007, 2011; Shioya et al. 2008; Sobral et al. 2009, 2012, 2013), IR (Pérez-González et al. 2005; Magnelli et al. 2009, 2012; Goto et al. 2010; Wardlow et al. 2011). Such surveys have revealed that the redshift range \(z = 1–3\) is an essential and intriguing era for the study of galaxy formation and evolution, since SFR density (SFRD) in the Universe gradually increases towards \(z \sim 3\) from \(z \gtrsim 6\), has a peak at \(z \sim 1–2\) and decreases sharply from \(z \sim 1\) towards \(z \sim 0\) (e.g. Madau et al. 1996; Hopkins & Beacom 2006; Sobral et al. 2013). The H\(\alpha\) luminosity is widely used to derive the star formation activity of galaxies at \(z \lesssim 2\), but other emission lines at the bluer end of the galaxy spectral energy distribution (SED), such as the [O II] line, are also sufficiently bright to be widely used and can be employed up to \(z \sim 4\), after being calibrated relative to H\(\alpha\). The H\(\alpha\) emission line is a robust star formation indicator which has been well calibrated with data in the local Universe (e.g. Kennicutt 1998), and is significantly less affected by dust.

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extinction than bluer emission lines, such as [O II]. However, the Hα line is redshifted into near-IR (NIR) wavelengths for galaxies at $z > 0.4$, while the [O II] line can be observed with an optical instrument until $z \sim 1.7$, and thus many studies/surveys of star-forming galaxies at $z > 0.4$ rely on [O II] luminosity. Unfortunately, while [O II] luminosity is in general correlated with the star formation activity, it is also dependent on the metal abundance and the ionization state of nebular gas. The indirect relation with the star formation activity complicates the estimation of SFR from [O II] luminosity. Nevertheless, it is empirically calibrated and extensively utilized as an important SFR indicator for galaxies at $z \gtrsim 1$ (e.g. Kennicutt 1998; Moustakas, Kennicutt & Tremonti 2006; Gilbank et al. 2010).

In order to better relate the [O II] luminosity of a galaxy to its SFR, one can study the ratio of [O II] to Hα luminosities in local star-forming galaxies. However, it is not obvious that these calibrations can be blindly applied for galaxies at higher redshifts. It is therefore important to investigate their validity at earlier epochs in the Universe by studying higher redshift galaxies directly. According to recent studies, the [O II]/Hα ratio of galaxies up to $z \sim 1.0$ is on average consistent with that of local galaxies (Moustakas et al. 2006; Weiner et al. 2007). Sobral et al. (2012) investigated the [O II]/Hα ratio for star-forming galaxies at $z = 1.47$ by using wide-field, deep imaging with two narrow-band filters which can catch Hα and [O II] emission from $z = 1.47$ galaxies simultaneously. This study finds relatively little evolution in the line ratio when compared to lower redshift. However, the detection of both emission lines for galaxies at $z \sim 1.5$ is limited to relatively luminous galaxies with Hα luminosity larger than $\sim 10^{12}$ erg s$^{-1}$ (i.e. SFR $\gtrsim 10 M_\odot$ yr$^{-1}$), and little is known about the line ratio and nature of the more numerous fainter star-forming galaxies. Fortunately, the [O II] data obtained with the Subaru telescope can reach significantly lower luminosities in [O II] and, using a stacking analysis, the [O II]/Hα line ratio can now be studied down to galaxies with significantly lower SFRs.

The structure of this paper is as follows. The data used in this paper are described in Section 2. The stacking analysis procedure and the results from the stacked images are shown in Section 3. In Section 4, we show the ratios of Hα to [O II] luminosities for galaxies at $z = 1.47$, and compare them with those of local galaxies. We then discuss their implications with respect to the evolution in dust extinction and metallicity of [O II]-selected galaxies at $z = 1.47$. Our conclusions are presented in Section 5. Throughout this paper, magnitudes are presented in the AB system, and we adopt cosmological parameters of $h = 0.7$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

## 2 Observations and Selection

The bulk of the data used in this paper have been obtained as part of the High Redshift Emission Line Survey (HiZELS) targeting Hα (Geach et al. 2008; Sobral et al. 2009; Best et al. 2010), and as part of a matched [O II] follow-up survey (Sobral et al. 2012, 2013). The details of the data are described in two papers by Sobral et al. (2012, 2013), and therefore we only summarize them briefly here.

### 2.1 Hα and [O II] Emitters at $z = 1.47$

We use two narrow-band imaging data sets to obtain our samples of galaxies at $z = 1.47$ in two distinct square degree areas: the UKIDSS Ultra Deep Survey (UDS; Lawrence et al. 2007) and the Cosmological Evolution Survey (COSMOS; Koekemoer et al. 2007; Scoville et al. 2007) fields. NB921 narrow-band data ($\lambda_e = 1.617 \mu$m and $\Delta \lambda = 0.021 \mu$m) were taken with the wide-field camera (WFCAM; Casali et al. 2007) on United Kingdom Infrared Telescope (UKIRT), while NB921 narrow-band data ($\lambda_c = 9196$ Å and $\Delta \lambda = 132$ Å) were taken with Subaru prime focus camera (Suprime-Cam; Miyazaki et al. 2002) on the Subaru telescope (Fig. 1). Combining with broad-band imaging data in H and $\zeta$, which cover the same wavelength range as the individual narrow bands, to estimate the continuum level of the spectrum underlying the emission line, the narrow-band imaging can measure Hα and [O II] emission, simultaneously, for galaxies at $z = 1.47$ (Sobral et al. 2012, 2013).

The Hα and H images in the UDS field cover an effective area of 0.78 deg$^2$ where the regions with bad quality caused by cross-talk and bright stars are masked, while the images in the COSMOS field have an effective area of 1.6 deg$^2$. The 5σ limiting magnitudes in NB921 are $\sim 22.1$ and $\sim 21.9$ in the UDS and COSMOS fields, respectively, although the depth is slightly dependent on the position [see fig. 2 and table 2 in Sobral et al. (2013) for the details].

The NB921 data in UDS field are drawn from the archive of Suprime-Cam (Ouchi et al. 2010) and reduced as described in Sobral et al. (2012), while public data are available for $z'$ (Furusawa et al. 2008). In the COSMOS field, the NB921 data were taken in service mode with the Subaru telescope in 2010 December (Sobral et al. 2013), and they cover 69 per cent of the region where the NB921 and $H$ data are available (i.e. 1.1 deg$^2$). The 5σ limiting magnitudes in NB921 are 25.8 and 24.0 in the UDS and COSMOS fields, respectively.

Catalogues of Hα emitters at $z = 1.47$ in both the UDS and COSMOS fields are presented in Sobral et al. (2013). They include 188 Hα emitters in the UDS down to an Hα flux of

![Figure 1](https://example.com/figure1.png)
4.5 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \) (which corresponds to an H\text{\alpha} luminosity \log (L_{\text{H\alpha}}/\text{erg s}^{-1}) = 41.78 if the galaxies are at \( z = 1.47 \)) and 325 H\text{\alpha} emitters down to \( 2.7 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \) \( \log (L_{\text{H\alpha}}/\text{erg s}^{-1}) = 41.56 \) in the COSMOS field, respectively. The number densities of the H\text{\alpha} emitters are 0.97 and 0.18 arcmin \(^{-2}\) above the flux limits in UDS and COSMOS fields, respectively.

The catalogues of [O\text{\i}] emitters at \( z = 1.47 \) are updated from those of Sobral et al. (2012). Emission line galaxies are selected as galaxies with colour excess larger than 5\( \sigma \) (i.e. \( \Sigma > 5 \)) and equivalent width (EW) larger than 25 \( \AA \), which corresponds to EW\,\alpha > 10 \( \AA \) in rest frame at \( z = 1.47 \), where photometry is conducted with 2 arcsec diameter aperture. Then, [O\text{\i}] emitters at \( z = 1.47 \) are identified based on the colours, photometric redshift, and spectroscopic redshift (cf. Sobral et al. 2013). We note that the spectroscopic redshift information indicates that a significant number of galaxies at \( z \sim 1.3 \), selected as narrow-band emitters due to strong Balmer/4000 \( \AA \) break, are incorrectly included as [O\text{\i}] emitters. However, most of these contaminants are removed from the sample by filtering out galaxies with EW\,\alpha < 20 \( \AA \) \& \( i - z > 0.55 \). Thus, the numbers of [O\text{\i}] emitters selected are 2735 down to \( 4.2 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \) \( \log (L_{\text{O[i]}}/\text{erg s}^{-1}) = 40.76 \) in the UDS field, and 718 down to \( 1.3 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \) \( \log (L_{\text{O[i]}}/\text{erg s}^{-1}) = 41.24 \) in the COSMOS field, respectively. The number densities of the [O\text{\i}] emitters are 0.97 and 0.18 arcmin \(^{-2}\) above the flux limits in the UDS and COSMOS fields, respectively.

By matching the [O\text{\i}] emitters with the H\text{\alpha} emitters, Fig. 2 shows the relation between [O\text{\i}] and H\text{\alpha} luminosities for the [O\text{\i}] emitters in both the UDS and COSMOS fields, and the fraction of [O\text{\i}] emitters with a significant H\text{\alpha} emission detection as a function of [O\text{\i}] luminosity. As described in Section 1, the dual emitters with detections in both [O\text{\i}] and H\text{\alpha} are mainly limited to galaxies with [O\text{\i}] luminosities higher than \( \sim 10^{42} \text{ erg s}^{-1} \). For [O\text{\i}] emitters with [O\text{\i}] luminosities lower than \( \sim 10^{42} \text{ erg s}^{-1} \), the fraction is less than \( \sim 10 \% \), clearly showing that we can only investigate the relation between [O\text{\i}] and H\text{\alpha} luminosities individually for a small fraction of faint [O\text{\i}] emitters.

### 2.2 Differences between the profile of the two narrow-band filters

Although the NB\text{\i} and NB921 filters are well matched and enable us to detect both H\text{\alpha} and [O\text{\i}] emission lines from individual star-forming galaxies at \( z = 1.47 \), there is a slight difference in the redshift coverage (Fig. 1). The redshift coverage for [O\text{\i}] lines detected by NB921 filter is slightly wider than that by NB\text{\i} filter. It is possible that this difference causes us to underestimate the H\text{\alpha} luminosity for [O\text{\i}] emitters at redshifts corresponding to the edge of NB\text{\i} filter where the transmission is lower than that of NB921. To quantitatively evaluate how accurately the H\text{\alpha}/[O\text{\i}] line ratio can be measured by the two narrow-band images and how this effect may influence the results of the stacking analysis, a simulation was conducted following Sobral et al. (2012) (see section 4.5 of their paper for more details). In summary, we make a sample of galaxies at \( z = 1.40 - 1.52 \) with intrinsic line ratios between 0 and 2.0, where the distribution of [O\text{\i}] luminosity that galaxies have is based on the [O\text{\i}] luminosity function, and then investigate the measured H\text{\alpha}/[O\text{\i}] line ratios with the two NB filters. Fig. 1 also shows the result of the simulation: the bias (i.e. the difference between a measured H\text{\alpha}/[O\text{\i}] and an input H\text{\alpha}/[O\text{\i}] ratio) is distributed around unity in most of the range of the filter profile, although in the edge of the profile the observed line ratio is biased towards lower values. However, we make sure that the average value of bias is fairly close to unity. Because we focus on the average ratio of H\text{\alpha}/[O\text{\i}] by a stacking analysis in this paper, the slight difference of filter profile has only a small effect on the results over the whole investigated range of [O\text{\i}] luminosity. To further quantify this, we investigate the bias values for galaxies with a given range of observed [O\text{\i}] luminosity similar to luminosity bins shown in Table 1; we find that the [O\text{\i}]-selected galaxies have a redshift distribution peaking at \( z \sim 1.46 \) and with most sources having redshifts where the filter response is high, leading to an average value of the bias of \( \sim 0.97 \) in all bins, namely close to unity again. Thus, although the H\text{\alpha}/[O\text{\i}] ratio can be underestimated by 3 per cent (which we correct for), we conclude that the difference of the profiles in the two NB filters gives no significant influence on the results we find in this paper.

### 2.3 Stellar mass for emitters at \( z = 1.47 \)

Stellar masses are estimated by an SED-fitting method for H\text{\alpha} and [O\text{\i}] emitters at \( z = 1.47 \) in both fields consistently (Sobral et al., in preparation). The details of the procedure in the SED fitting are described in Sobral et al. (2011). The SED templates are created with...
Table 1. The average \([\text{O} \, \text{iii}]\) and \(\text{H}\alpha\) luminosities for \([\text{O} \, \text{iii}]\) emitters in the combined sample in the UDS and COSMOS fields. The first and second columns show the median \([\text{O} \, \text{iii}]\) luminosity and the number of \([\text{O} \, \text{iii}]\) emitters to be stacked in each sample. The third and fourth columns show the mean \(\text{H}\alpha\) luminosities measured on the stacked (NB\text{H}-\text{H}) images and the flux ratios of \(\text{H}\alpha\) to \([\text{O} \, \text{iii}]\). The contribution of [N ii] to the flux measured on the stacked image is removed under the assumption that the typical [N ii]/H\alpha\ ratio is 0.22 (Sobral et al. 2012). The flux ratios are corrected for any effects discussed in Sections 2.2 and 3.1. The [O iii] luminosities which are originally measured with a 2 arcsec aperture are corrected by a factor of 1.6 to convert to the total luminosities (Section 3.2).

| \([\text{O} \, \text{iii}]\) luminosity (erg s\(^{-1}\)) | Number | \(\text{H}\alpha\) luminosity (erg s\(^{-1}\)) | Flux ratio (H\alpha/[O iii]) |
|-----------------|--------|-----------------|-----------------|
| 42.43\(^{+0.38}_{-0.09}\) | 61 | 42.40\(^{+0.01}_{-0.01}\) | 1.15 \pm 0.35 |
| 42.22\(^{+0.13}_{-0.11}\) | 127 | 42.13\(^{+0.01}_{-0.01}\) | 0.99 \pm 0.16 |
| 42.03\(^{+0.08}_{-0.07}\) | 125 | 42.02\(^{+0.02}_{-0.02}\) | 1.19 \pm 0.13 |
| 41.90\(^{+0.06}_{-0.06}\) | 126 | 41.90\(^{+0.02}_{-0.02}\) | 1.41 \pm 0.13 |
| 41.77\(^{+0.07}_{-0.07}\) | 124 | 41.65\(^{+0.04}_{-0.05}\) | 0.92 \pm 0.13 |
| 41.50\(^{+0.19}_{-0.28}\) | 246 | 41.53\(^{+0.04}_{-0.04}\) | 1.28 \pm 0.37 |

the stellar population synthesis model by Bruzual & Charlot (2003) and Bruzual (2007) under the assumption of a Chabrier (2003) initial mass function and a range of exponentially declining star formation histories. In addition, the dust extinction law of Calzetti et al. (2000) is used in the SED fitting. Note that we have confirmed that the mass estimates are robust against the contribution of emission lines to the broad-band photometry, as they are based to fits to \(\sim 30\) photometric bands and hence line contamination in one or two bands does not have a strong influence. Among [O iii] emitters, stellar masses are derived for 2708 (99.0 per cent of the sample) and 706 (98.3 per cent) [O iii] emitters in the UDS and COSMOS field, respectively. The others, i.e. \(\sim 1\) per cent of the samples, do not have reliable stellar mass due to large errors in photometry and/or non-detection in most bands, suggesting that such [O iii] emitters are likely to be less massive galaxies. Galaxies for which the SED fitting fails are found to be very faint in the rest-frame optical (i.e. K band), which supports the indication that they are likely to be low-mass galaxies. In this paper, we restrict analysis to [O iii] emitters with stellar masses larger than \(\log (M_*/M_\odot) = 9.5\). This mass cut is made in order to maximize the number of [O iii] emitters included in the sample, but without picking up many lower mass galaxies for which the survey becomes incomplete. In addition, the Sloan Digital Sky Survey (SDSS) sample described below, which is used for the comparison of galaxies at \(z = 1.47\) with local galaxies, is also highly complete above this mass limit. After applying the mass cut, the numbers of [O iii] emitters are 643 and 212 in the UDS and COSMOS fields, respectively.

2.4 A comparison sample of galaxies at \(z \sim 0.1\)

We also use SDSS DR7 data to compare the results obtained for [O iii] emitters at \(z = 1.47\) with local galaxies (Abazajian et al. 2009). Galaxies in the redshift range \(z = 0.07-0.1\) are extracted from the SDSS spectroscopic catalogue. This redshift range is chosen so that the galaxies have small enough apparent angular sizes that most of their light is included in the fibre whilst guaranteeing that the sensitivity is still very high. An aperture correction on the emission line luminosities is still required, since the spectroscopic measurements are done with 3 arcsec diameter fibres. The fractional flux loss from the fibre is estimated from the ratio of total mass to fibre mass according to the same procedure adopted in Sobral et al. (2012). Moreover, note that the SDSS spectrophotometric calibration takes account of any wavelength dependence of the seeing, so the emission line flux ratios are also unaffected by this (Adelman-McCarthy et al. 2008).

By applying our selection criteria, we have selected 8285 SDSS galaxies with \(\log (L_{\text{OIII}}/\text{erg s}^{-1}) > 41\) and \(EW_{\text{H}} > 10\,\text{Å}\). Among these, only galaxies with detected [O iii] emission are used. However, we note that all but 38 (0.46 per cent) galaxies have H\alpha\ line detected, implying that the removal of galaxies without H\alpha\ detection gives no significant bias in the study of [H\alpha]/[O iii] line ratios. We are aware that the SDSS spectroscopic sample is magnitude limited, i.e. roughly mass limited. However, as described in Section 2.3, the criterion of \(\log (M_*/M_\odot) > 9.5\) is applied to both the SDSS sample and the [O iii] emitter samples at \(z = 1.47\) so that high completeness is kept above the mass limit for both samples; this was another factor driving our choice of redshift range for the SDSS sample. After applying our mass limit, we obtain our SDSS sample, which contains 7271 galaxies.

The SDSS sample is used to compare the [H\alpha]/[O iii] ratios of [O iii] emitters at \(z = 1.47\) with those of local galaxies at \(z = 0.07-0.1\) in Sections 3 and 4. We therefore must assure that both samples are fully comparable and that differences between them are not arising from a different distribution in e.g. stellar mass. Since correlations between SFR and stellar mass have been claimed at \(z \sim 2\) (e.g. Daddi et al. 2007), it is possible that [O iii] luminosity as well as H\alpha\ luminosity and metallicity are also correlated with stellar mass for the \(z = 1.47\) [O iii] emitter samples. We thus use the SDSS sample to construct a sample of local galaxies with a similar distribution of mass to that of [O iii] emitters at \(z = 1.47\) in order to reduce any mass-dependent bias on this study and so allow a robust comparison. Galaxies in the SDSS sample are selected at random so that the mass distribution is the same as that of [O iii] emitters at \(z = 1.47\) in each bin of [O iii] luminosity as shown by Fig. 3. The SDSS sample tends to include galaxies with fainter [O iii] luminosity, while [O iii] emitters at \(z = 1.47\) have brighter luminosity. Since the mass distribution is dependent on the [O iii] luminosity, the histograms of stellar mass for all galaxies in each sample are not in perfect agreement. However, the median masses in each luminosity bin are in good agreement (Fig. 3). In the following sections, we use the matched SDSS sample containing 1656 galaxies at \(z = 0.07-0.1\) to compare with the results for [O iii] emitters at \(z = 1.47\).

3 ANALYSIS AND RESULTS

In order to investigate the relation between H\alpha\ and [O iii] luminosities for galaxies at \(z = 1.47\), we stack and average the NB\text{H} images from which the corresponding H\alpha\ image is subtracted (clipping the pixels which deviate more than 3\(\sigma\)), and then estimated the average H\alpha\ flux for [O iii] emitters at \(z = 1.47\) in the UDS and COSMOS fields. Note that the results do not change if a median stacking is carried out instead.

3.1 Stacking method

For all the samples of galaxies to be stacked, a 80 arcsec \(\times 80\) arcsec region around individual galaxies is extracted from both NB\text{H} and H images. Some galaxies are rejected from each sample, because they are found in masked regions in the NB\text{H} image, where some artefacts and regions with low quality caused by bright/saturated
luminosities would be increased by \( \sim 10 \) Å at 
\[ \text{[N II]} \times z_{\text{II}} \sim 1.47 \] in the combined 

emitters which are individually detected as galaxies 
with (H–NB921) colour excess. We plot both the individual fields and our 
combined sample. The median and standard deviation of \( \Delta \log L_{\text{H}\alpha} \), the 
difference between both H\( \alpha \) luminosities, are 0.018 and 0.045, implying good 
agreement between the two H\( \alpha \) luminosities, which confirms the validity of 
our stacking analysis procedure.

The [N II]/H\( \alpha \) ratio is known as an indicator of metallicity, and 
thus it is probably dependent on the stellar mass. Indeed, we find 
for the SDSS galaxies that the [N II]/H\( \alpha \) line ratio correlates with 
stellar mass more strongly than with H\( \alpha \) or [O II] luminosities. Our samples include the emitters with a wide range of stellar mass, but 
the median stellar mass in each sample only varies by a factor of 4, 
from \( 5 \times 10^{9} \) to \( 2 \times 10^{10} M_{\odot} \). According to the mass–metallicity relation that Yabe et al. (2012) have found for star-forming galaxies 
at \( z \sim 1.4 \), these median stellar masses correspond to the [N II]/H\( \alpha \) ratios of 0.14–0.25, which are comparable to or slightly lower than 
the value we assumed. Even if the lowest ratio of [N II]/H\( \alpha \) = 0.14 is used instead, the H\( \alpha \) luminosities would be increased by 
only a factor of 1.07. It should be noted that the assumption of 
constant typical value of [N II]/H\( \alpha \) is reasonable, since average H\( \alpha \) 
luminosities are derived in this study (see also Fig. 4).

Contamination in the [O II] emitter samples would lead to the 
H\( \alpha \) fluxes measured on the stacked images being underestimated, 
since the images without H\( \alpha \) flux for the contaminants are also 
stacked. Although the bulk of the contaminants are removed using 
spectroscopic and photometric redshifts and colour cuts (Section 
2.1), some contamination will remain. Using the spectroscopically 
confirmed NB921 emitters, and accounting as best as possible for 
bias in the selection of spectroscopic targets, the residual rate of 
the contamination is estimated to be around 15 \( \pm 7 \) per cent. More 
specifically, it is found that the \( z = 1.47 \) [O II] emitter sample could 
include \( \sim 5 \) per cent contaminations at \( z < 1.0 \) and \( \sim 10 \) per cent ones 
at \( z > 1.0 \) (most of which are galaxies with a strong Balmer/4000 Å 
brack at \( z \approx 1.3 \)). We have also found that there is no clear trend of

![Figure 3](image_url)  
**Figure 3.** The left-hand panel shows stellar mass as a function of [O II] luminosity. The red dots show [O II] emitters at \( z = 1.47 \) in the combined sample and the blue dots show galaxies in the SDSS sample with similar median mass distribution to that of [O II] emitters at \( z = 1.47 \). The magenta circles and cyan diamonds show the median stellar mass of galaxies in each [O II] luminosity bin for the samples of [O II] emitters and SDSS galaxies, respectively. The right-hand panel shows the mass distribution of each samples: the black thin histogram shows the whole sample of SDSS galaxies with \( \log (L_{\text{O}2}/\text{erg s}^{-1}) > 41 \) and \( \Delta \log L_{\text{H}\alpha} > 0 \), the blue thick histogram shows those of local galaxies extracted from the SDSS sample and the red thick histogram shows the mass distribution of [O II] emitters at \( z = 1.47 \) in the combined sample including the UDS and COSMOS fields.

![Figure 4](image_url)  
**Figure 4.** Comparison between H\( \alpha \) luminosities measured on the stacked (NB\( \text{H} \)–H) image and median values of H\( \alpha \) luminosities extracted from the catalogues, for H\( \alpha \) emitters which are individually detected as galaxies with (H–NB921) colour excess. We plot both the individual fields and our combined sample. The median and standard deviation of \( \Delta \log L_{\text{H}\alpha} \), the difference between both H\( \alpha \) luminosities, are 0.018 and 0.045, implying good agreement between the two H\( \alpha \) luminosities, which confirms the validity of our stacking analysis procedure.
The nature of faint [O\textsc{ii}] emitters at $z = 1.47$

The comparison between $\text{H}z$ and [O\textsc{ii}] luminosities are corrected for luminosities of galaxies at luminosities measured on the [O\textsc{ii}] luminosity to [O\alpha]/[O\textsc{ii}] ratio above unity (e.g. Cid Fernandes et al. 2010), and so any AGN contamination in the $z = 1.47$ [O\textsc{ii}] samples would, if anything, bias the stacked H\alpha flux upwards, making the underlying trend found in Section 3.2 even stronger.

To estimate the error in the flux measured on the stacked image, 10 000 identical apertures are distributed at random across blank sky region around the galaxy, and then the 1\sigma error is derived by fitting a Gaussian profile to the histogram of the sky counts.

3.2 Stacking analysis for the emitter samples

Samples of galaxies to be stacked are created from the H\alpha or [O\textsc{ii}] emitters in the UDS and COSMOS fields by dividing them on the basis of their emission line luminosities, so that they contain nearly equal numbers of galaxies. However, the number of galaxies for the sample in the brightest (faintest) luminosity bin is smaller (larger) than the other samples. The stacking analysis was conducted first for H\alpha emitter samples. The analysis for galaxies with H\alpha emission detected individually enables us to check our stacking analysis by comparing our results with individually measured H\alpha luminosities. Fig. 4 shows the comparison between median H\alpha luminosity drawn from the catalogues for each H\alpha emitter sample and that measured on the stacked image. The median and standard deviation of $\Delta \log (L_{\text{H\alpha}}/\text{erg s}^{-1})$, the difference between both H\alpha luminosities, are 0.018 and 0.045, respectively. The good agreement shows that our procedure in the stacking analysis recovers well the average of actual individual measurements. We then moved on the stacking analysis for samples of [O\textsc{ii}] emitters which are classified on the basis of their [O\textsc{ii}] luminosities.

Fig. 5 shows the average H\alpha luminosities of galaxies at $z = 1.47$ in the individual fields of UDS, COSMOS and the combination of the two, as a function of their [O\textsc{ii}] luminosity (see also Table 1). The H\alpha luminosity is estimated from the stacked NB$_{H}-H$ image with a 4.8 arcsec aperture (Section 3.1), and the [O\textsc{ii}] luminosity is a median value of individual [O\textsc{ii}] luminosities of emitters in the sample which are derived from NB921 imaging. It should be noted that we apply an aperture correction to the [O\textsc{ii}] luminosities in order to ensure a matched comparison with the H\alpha luminosities. We obtain this correction by comparing the 2 arcsec photometry (Sobral et al. 2012, 2013) and that obtained with 4.8 arcsec apertures on the stacked NB921–$\gamma$ images. We find that a correction of 1.6 is required to recover total stacked luminosities. Also, the [O\textsc{ii}] luminosities are corrected by 3 per cent for the bias caused by the difference of profile of the two narrow-band filters (Section 2.2) and by 15 per cent for the possible contamination of emitters at different redshifts that might be included in the sample (Section 3.1).

There is a clear positive correlation between the mean [O\textsc{ii}] and H\alpha luminosities, with almost constant luminosity ratio for [O\textsc{ii}] emitters at $z = 1.47$. This fact suggests that the [O\textsc{ii}] luminosity can be easily calibrated as an SFR indicator for galaxies with SFRs down to 1.4 $M_\odot$ yr$^{-1}$, even at $z \sim 1.5$. The distribution of local galaxies extracted from the SDSS sample is also shown in the figures, and the median H\alpha luminosities are plotted in each [O\textsc{ii}] luminosity bin. For $z = 1.47$ [O\textsc{ii}] emitters with a given [O\textsc{ii}] luminosity, H\alpha luminosities are on average lower than those of local galaxies, implying that the ratio of H\alpha to [O\textsc{ii}] is different between local galaxies and [O\textsc{ii}] emitters at $z = 1.47$. To evaluate the statistical significance of the difference in H\alpha/[O\textsc{ii}] ratio, we compare the H\alpha/[O\textsc{ii}] ratios of [O\textsc{ii}] emitters at $z = 1.47$ with those of local galaxies, calculate how significantly the [O\textsc{ii}] emitters at $z = 1.47$ deviate towards a lower value from the local galaxies in each [O\textsc{ii}] luminosity bin and then combine these in quadrature (using equal weighting) to give a total offset significance. We find that there is an overall difference in the line ratio which is significant at the 2.8\sigma level.

The systematic offset is intriguing. It is unlikely that the offset is caused by a difference in stellar mass, since the mass distributions of the two sample are matched to each other (Section 2.4). Possible systematic effects that might drive the offset are discussed in the next subsection, but are unlikely to be able to account for all of the difference, suggesting a small but genuine cosmic evolution of the mean H\alpha to [O\textsc{ii}] ratio.

3.3 Possibility of underestimation of H\alpha luminosity

One possible cause of bias towards low H\alpha luminosities for [O\textsc{ii}] emitters at $z = 1.47$ with a given [O\textsc{ii}] luminosity is contamination in the [O\textsc{ii}] emitter samples from emitters at different redshifts which are not removed by our spectroscopic redshift, photometric redshift and colour–colour selection cuts. As discussed in Section 3.1, a correction for the contamination, 15 per cent, has already been applied to the stacked fluxes. If the upper limit to the contamination of 22 per cent is the true contamination, then the calculated H\alpha
luminosities for the [O II] emitters can be also underestimated by \( \sim 7 \) per cent.

Another possibility is that the contribution of [N II] emission is lower than what we assume in this paper as discussed in Section 3.1. This effect can result in the underestimation of H\( \alpha \) luminosity by \( \sim 7 \) per cent at most. Finally, there is a bias caused by the difference of profile of the two narrow-band filters (Section 2.2) which can lead to the H\( \alpha \) luminosities being underestimated in the wings of the filter profile. Our simulations have led us to apply an \( \sim 3 \) per cent correction factor for this, but these simulations assume a uniform redshift distribution for the [O II] emitters across the redshifts probed. If large-scale structure causes the [O II] emitters to be clustered at the low- or high-redshift end of the filter coverage, the true correction factor could potentially be a few per cent higher.

In order for the H\( \alpha \) luminosities at \( z = 1.47 \) to be comparable to those of galaxies at \( z \sim 0.1 \) for a given [O II] luminosity, all of the effects that might potentially cause an underestimation of H\( \alpha \) luminosities would have to be at or above their maximal combined values of \( \sim 15 \) per cent. Thus, it is likely that the offset of H\( \alpha \) luminosities for galaxies with a given [O II] luminosity is real, and the H\( \alpha \)/[O II] ratios of [O II] emitters at \( z = 1.47 \) seem to be shifted towards lower values than those of the local galaxies to some extent. In the next section, we discuss the implication of the different H\( \alpha \)/[O II] ratio in the properties of galaxies.

4 DISCUSSION

4.1 Line ratios for the local galaxies

As discussed by Sobral et al. (2012), H\( \alpha \)/[O II] ratios can be dependent on both dust extinction and metallicity, because the two factors influence the [O II] luminosity more than the H\( \alpha \) luminosity. Therefore, before discussing the line ratios found in the previous section (Fig. 5), the SDSS sample with matched mass distribution is used to evaluate how the two factors of dust extinction and metallicity relate to the ratio of H\( \alpha \)/[O II] and to understand which factors are the main driver of the difference in the line ratio between [O II] emitters at \( z = 1.47 \) and galaxies at \( z \sim 0.1 \). The Balmer decrement of H\( \alpha \)/H\( \beta \) is an indicator of dust extinction, while the ratio of [N II]/H\( \alpha \), the so-called N2 index, offers a rough estimator of metallicity. The H\( \alpha \)/[O II] ratios for the SDSS sample described in Section 2.4 are plotted as a function of H\( \alpha \)/H\( \beta \) and [N II]/H\( \alpha \) in Fig. 6, where a polynomial function of the fourth degree is fitted to the data. The figure implies that the ratio of H\( \alpha \) to [O II] is dependent on both factors in the sense that it increases with higher dust extinction and higher metal abundance.

It is natural to expect that the H\( \alpha \)/[O II] ratios are sensitive to dust, since a large amount of dust prevents more [O II] emissions at rest-frame 3727 Å from escaping from the star-forming regions in a galaxy than H\( \alpha \) emissions at rest-frame 6563 Å. On the other hand, the H\( \alpha \)/[O II] line ratio is also dependent on the metallicity as shown in Fig. 6. According to the metallicities estimated from the mass–metallicity relations that recent studies have suggested, the figure suggests that the difference in metallicity between star-forming galaxies at \( z \sim 1.4 \) and \( z \sim 0.1 \) could account for an offset of \( \Delta \log (\text{H}\alpha/\text{O} \ II) \sim 0.3 \) dex.

In reality, dust attenuation and metallicity are likely to be correlated. To investigate the independent effect of metallicity on the line ratio, Fig. 6 also shows the offsets of H\( \alpha \)/[O II] ratio from the best-fitting polynomial function shown in Fig. 6, as a function of [N II]/H\( \alpha \), i.e. metallicity. A weak correlation is seen in the sense that the offset of \( \Delta \log (\text{H}\alpha/\text{O} \ II) \) gets larger with increasing [N II]/H\( \alpha \), although the dispersion is large. At fixed dust attenuation, the difference in metallicity between star-forming galaxies at \( z \sim 1.4 \) and \( z \sim 0.1 \) suggests an offset of at most \( \sim 0.1 \) dex in the mean value of \( \Delta \log (\text{H}\alpha/\text{O} \ II) \). This seems to suggest that the metallicity is not the major factor on the offset of the H\( \alpha \)/[O II] ratio. The same suggestion is also obtained with larger sample of SDSS data by Sobral et al. (2012). In contrast, Fig. 6 shows the offsets of H\( \alpha \)/[O II] ratio from the best-fitting polynomial function shown in Fig. 6, as a function of H\( \alpha \)/H\( \beta \). This figure suggests that the offset is larger with higher dust extinction and the dependence of the offset on the dust extinction seems to be stronger than the dependence seen in Fig. 6 for metallicity, although dispersion is still large. This may suggest that dust extinction is the more important factor in changing the H\( \alpha \)/[O II] ratio.

4.2 Implications for dust extinction and metallicity

The average H\( \alpha \)/[O II] ratios are plotted in Fig. 7 as a function of [O II] luminosity. We find that they shift slightly towards a lower value at \( 2.8 \sigma \) significance than those of galaxies at \( z \sim 0.1 \). According to the results of Fig. 6, the ratio of H\( \alpha \)/[O II] \( \sim 1 \) implies that the typical [O II] emitters at \( z = 1.47 \) are not dusty, metal-rich galaxies. Moreover, it is unlikely that the metallicities of the [O II] emitters at \( z = 1.47 \) deviate significantly from the mass–metallicity relation that Yabe et al. (2012) have found for galaxies at \( z \sim 1.4 \). That is, it seems that metallicity is not a main cause of the difference
The nature of faint [O II] emitters at \( z = 1.47 \)

5 CONCLUSIONS

We investigate the mean relation between \( H\alpha \) and [O II] luminosities for [O II] emitters at \( z = 1.47 \) in the UDS and COSMOS fields using a stacking analysis which enables us to examine the \( H\alpha \) luminosity of galaxies at \( z = 1.47 \) even if the individual galaxies are too faint to detect both \( H\alpha \) and [O II] emission lines simultaneously. The [O II] emitters at \( z = 1.47 \) are selected with the NB921 narrow-band data taken with Suprime-Cam on Subaru Telescope, while the \( H\alpha \) luminosities are measured on the stacked NB921 narrow-band data taken with WFCAM on UKIRT.

We find that on average there is a positive correlation between \( H\alpha \) and [O II] luminosities for not only bright galaxies but also faint ones with [O II] luminosity down to \( 10^{41} \) erg \( s^{-1} \), i.e. SFR = \( 1.4 M_\odot \) yr\(^{-1} \). The trend that galaxies with higher [O II] luminosities have higher \( H\alpha \) luminosities is consistent with that of the local galaxies, suggesting that [O II] luminosities can be used as an indicator of SFR even at the high redshift of \( z = 1.47 \).

However, we have to use the [O II] luminosities with caution to estimate SFRs at \( z = 1.47 \) based on the relation calibrated with local galaxies. This is because [O II] emitters at \( z = 1.47 \) show observed \( H\alpha/[O\text{ II}] \) line ratios corresponding to \( A_{H\alpha}/A_{[O\text{ II}]} \sim 0.35 \) and are less subject to dust attenuation than the local galaxies selected based on [O II] luminosity. Therefore, [O II]-selected emitters at \( z = 1.47 \) are biased towards less dusty populations. The use of dust-correction relations derived with \( H\alpha \) emitter samples may cause us to overestimate the amount of dust extinction and hence the dust-corrected SFR. At the same time, surveys of star formation activity based on [O II] emissions may miss populations of dusty starburst galaxies.

On the other hand, we note a caveat to our interpretation of the results in terms of dust extinction only, because the \( H\alpha/[O\text{ II}] \) line ratio is also dependent on the metallicity. Hence the discrepancy of the line ratio between [O II] emitters at \( z = 1.47 \) and local galaxies \( z \sim 0.1 \) may be explained in terms of metallicity difference. Therefore, the possibility that the low \( H\alpha/[O\text{ II}] \) ratio is not only due to the lower dust extinction, but also due to the lower metallicities of [O II] emitters at \( z = 1.47 \), cannot be completely ruled out. To distinguish the two factors of dust extinction and metallicity completely, we require deep spectroscopy to obtain the nebular emissions from the individual or stacked spectra.

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