[O II] emitters at $z \sim 4.6$ in the GOODS field: a homogeneous measure of evolving star formation

K. D. Bayliss,$^{1,*}$ R. G. McMahon,$^1$ B. P. Venemans,$^2$ M. Banerji$^1$ and J. R. Lewis$^1$

$^1$Institute of Astronomy, Madingley Road, Cambridge CB3 0HA
$^2$European Southern Observatory, Karl-Schwarzschild Strasse, 85748 Garching bei München, Germany

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ABSTRACT

We present the results of a high-redshift, $z = 4.6$, survey of [O II] $\lambda$ 3727 emission line galaxies in the GOODS-S field. The survey uses deep near-infrared data in the NB2090 ($\lambda_c = 2.095$ $\mu$m, $\Delta \lambda = 0.02$ $\mu$m) and KS ($\lambda_c = 2.146$ $\mu$m, $\Delta \lambda = 0.324$ $\mu$m) filters taken with the European Southern Observatory instrument, HAWK-I. The images reach an emission line flux limit ($5\sigma$) of $3.16 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$. At $z = 4.6$, the survey probes a comoving volume of $\sim 6680$ Mpc$^3$.

Three [O II] emission line candidates at $z \sim 4.6$ are selected using the Lyman-break criteria. Photometric redshift analysis supports the conclusion that these are genuine [O II] emitters, ruling out a $z \leq 3$ solution entirely for one of the candidates. In the analysis presented in this paper, two scenarios are considered: first, all three candidates are genuine [O II] emitters and secondly, only the most likely candidate is a genuine [O II] emitter.

We use the line fluxes of these objects to place confidence limits on the star formation rate density (SFRD) in bright $(\log(L_{[O\ II]}) > 42.0)$ [O II] emission line galaxies. Assuming an observed [O II]/H$\alpha$ line ratio of 0.45 and $A(H\alpha) = 1.0$ mag, we report an SFRD of $\dot{\rho}_\star(\log(L_{[O\ II]}) > 42.0) = 0.058 M_\odot$ yr$^{-1}$ Mpc$^{-3}$ in our objects. Using small number statistics, we then place a 50 per cent confidence interval on the global star formation rate of $\dot{\rho}_\star(\log(L_{[O\ II]}) > 42.0) = 0.058 \pm 0.013 M_\odot$ yr$^{-1}$ Mpc$^{-3}$. By combining our results with those from low-$z$ surveys, we compile the first homogeneous set of measurements of the SFRD in bright [O II] emitters from $z = 0$ to 4.6. From this, we conclude that there was an increase in the SFRD in the brightest [O II] emitters of at least a factor of 2 between $z = 4.6$ and 1.85.

Key words: galaxies: distances and redshifts – galaxies: high-redshift – galaxies: luminosity function, mass function – galaxies: star formation.

1 INTRODUCTION

Measuring the evolution of the star formation rate density (SFRD) with respect to redshift is one of the most fundamental and challenging goals of modern observational cosmology. A robust determination will provide a benchmark against which to test theoretical models and with sufficient redshift resolution, the relation will be a powerful discriminator between different theories of galaxy formation (see e.g. Somerville, Primack & Faber 2001). Whilst the relation is constrained to within 20–30 per cent at redshifts below 1, it is less well constrained at high redshift, being uncertain up to a factor of 3.

Much of this scatter is due to the wide range of star formation rate (SFR) indicators used ($L_{\text{UV}}$, $L_{\text{H}\alpha}$, $L_{\text{FIR}}$) and the different reddening corrections applied to them.

*E-mail: kdb25@ast.cam.ac.uk

Secondly, the range of sample selection methods employed (e.g. Lyman-break, narrow-band imaging, blind spectroscopy, submm) also adds scatter to the relation as each has its own selection biases and resulting completeness issues; it is particularly difficult to produce volume-limited samples at high redshift. Finally, each survey has a different luminosity limit and when integrating over the full luminosity range to calculate the global SFRD, assumptions have to be made about the faint-end slope of the luminosity function. Removing these influences to create a uniform set of measurements to compare with simulations requires surveys that use single SFR indicators and unified sampling methods. Importantly, the SFR indicator also needs to be visible over wide redshift ranges in order for homogeneous measurements to be made.

One promising SFR indicator that can address these issues is the [O II] $\lambda$ 3727 doublet. Whilst the [O II] doublet has largely been overlooked in favour of H$\alpha$, recent advancements in the calibration of [O II] have increased its reliability such that the accuracy of the...
[O II] doublet as an SFR indicator now approaches that of Hβ (see Kewley, Geller & Jansen 2004; Moustakas, Kennicutt & Tremonti 2006; Kennicutt et al. 2009).

Addressing concerns over the dependence of [O II] on metallicity and excitation, Moustakas et al. (2006) found that variations in metallicity and excitation are second-order effects in most galaxies and that the majority of uncertainty in the [O II]–SFR conversion is in fact due to dust extinction, similar to Hβ. Gilbank et al. (2010) looked at the dependence of the [O II]–SFR relation on stellar mass and concluded that the [O II]–SFR relation only breaks down for the highest mass galaxies (log(M/M⊙) > 10), where a larger correction is needed to compensate for the effects of metallicity and dust extinction.

At low z, a range of empirical calibrations have been developed between [O II] luminosity and SFR including those of Kennicutt et al. (2009) which incorporate weighted combinations of either total infrared (TIR) or Spitzer measurements of 24 or 8 µm flux to correct for dust extinction. Kennicutt et al. (2009) report that for z = 0 galaxies, the dispersion of [O II] flux, corrected using their empirical relations, is equivalent to that of their corrected Hβ samples, suggesting that [O II] can be well calibrated, at least at low redshift.

The rewards of calibrating the [O II] doublet are high as [O II] is visible in the near infrared out to a redshift of 5 (compared to the near-infrared limit of z ∼ 3 for Hβ) and can act as a homogeneous SFR indicator covering the full redshift range from 0 to 5. In picking apart the factors that influence the [O II]–SFR calibration, we also address the interesting underlying physics including variations of metallicity, mass and the ionization state of the gas.

[O II] has been used to measure the SFRD in a number of narrow-band studies at low redshift including Ly et al. (2007), Takahashi et al. (2007), Zhu, Moustakas & Blanton (2009) and most recently Bayliss et al. (2011) at z = 1.85. With the interest in detecting z > 7 Lyα emitters, large volumes of narrow-band data will become available over the next few years which will facilitate particularly deep studies of this kind over large survey volumes. As a result, narrow-band surveys targeting the [O II] doublet are a promising way of employing both a single indicator and a single selection method to make homogeneous measurements of the SFRD from z = 0 to 5.

This paper will detect the [O II] into z ∼ 4.6 using deep NB2090 images from the European Southern Observatory (ESO) instrument, HAWK-I. This is the highest redshift survey of [O II] to date and acts as a proof of concept that [O II] can be used to measure the SFRD at high redshift. Throughout this paper, magnitude measurements are on the AB scale (mAB = 48.60 − 2.5logλ0 flux, where the units of the flux density are erg s−1 cm−2 Hz−1). A standard cosmology is assumed with ΩM = 0.3, ΩΛ = 0.7 and h = 0.70.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Observations

This paper uses data from the ESO instrument, HAWK-I (Kissler-Patig et al. 2008), an NIR (0.85–2.5 µm) wide field, cryogenic imager on UT4 at the VLT facility in Paranal, Chile. A single dithered pointing (α = 03h32m32.9s; δ = −27° 47′ 16.5′′; PA = −44°) was taken in the GOODS field south between 2008 August 21 and September 8 in the programme 081.A-0932(A): Testing the physics of Lyman alpha emission in cosmological populations. We have a total of 17h 1 in the NB2090 filter (λc = 2.095 µm; Δλ = 0.020) and 2.38 h in the HAWK-I Ks band (λc = 2.146 µm; Δλ = 0.324). The filter profiles can be seen in Fig. 1. The data were reduced using a pipeline specially developed for HAWK-I at the Cambridge Astronomy Survey Unit that incorporates components of the VISTA Data Flow System (Irwin et al. 2004). The reduction pipeline is presented in detail in Bayliss et al. (2011).

The zero-points of the Ks and NB2090 images were determined by calibrating the measured fluxes of stars directly on to the public ISAAC Ks GOODS mosaic (Retzlaff et al. 2010). Stars were identified using full width at half-maximum (FWHM) versus magnitude diagrams. Each star was also visually inspected to ensure that we had a clean sample. The images were then scaled to a common zero-point of 30.0 (AB), accurate to 0.05 mag. The NB2090 and Ks images were astrometrically registered using point sources for reference. The images were also point spread function matched by smoothing the Ks image with a Gaussian kernel until the stellar FWHM values were equal to those measured in the NB2090 image. These stages ensure that equal-sized apertures, placed at the same xy coordinates in each image, measure flux from the same patch of sky and that the measurements are directly comparable. Details of the exposure times, seeing and image depths are given in Table 1.

We find the 5σ NB2090 limiting magnitude in a circular aperture, 10 pixels (1.06 arcsec) in diameter is mNB2090 = 24.68. Converting this limiting magnitude into a line flux, assuming the emission is at the peak of the NB2090 filter transmission profile and that there is no detectable continuum flux, produces a limiting line flux of fλ = 3.16 × 10−18 erg s−1 cm−2. For an [O II] emitter at z = 4.6, this flux corresponds to a line luminosity of log(Lλ) = 42.0. Assuming no dust extinction, [O II]/Hα = 0.45 and SFR = 7.9 × 10−42 L⊙/M⊙ yr−1 (Kennicutt 1998), this [O II] limiting line luminosity implies a limiting SFR of 19.0 M⊙ yr−1.

The point source completion of the NB2090 image was estimated by introducing artificial point sources into the images using the IRAF program MKOBJECT and recovering them using Source Extractor (Bertin & Arnouts 1996). The FWHM values of the simulated stars were matched to the image seeing (5.15 pixels; 0.55 arcsec). In this way, we found the 90 per cent recovery rate for point sources to be mNB2090 = 24.65.

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Figure 1. Transmission profiles of the NB2090 and Ks filters.

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3 SEARCH FOR [O III] EMISSORS AT $z = 4.6$

Source Extractor is run on the NB2090 image to produce an NB2090 selected source catalogue. Objects are extracted if at least eight contiguous pixels are detected with fluxes 1.5$\sigma$ above the background. The full list of Source Extractor parameters is given in Table 2. For each object in the catalogue, two flux measurements are made: Ks−NB2090 colour and total NB2090 flux. Both colour and total measurements are made using circular apertures. The size of each aperture is tuned to the size of the object as described in Labbé et al. (2003) and summarized in Bayliss et al. (2011), ensuring high signal-to-noise measurements are made irrespective of the object size. Colour measurements are made using Source Extractor in dual-image mode to ensure that measurements made in each band have the same spatial origin.

Emission line candidates are chosen based on clear excess NB2090 flux according to two criteria. First, the parameter $\Sigma$ (Bunker et al. 1995) is used to characterize the significance of the NB2090 excess compared to a flat spectrum, taking into account the noise properties of the images. A colour significance of $\Sigma = 3$ is used to select the emission-line galaxy (ELG) candidates. The selection curve is then given by

$$m_Y - m_{NB} = -2.5 \log_{10} \left[ 1 + \Sigma 10^{-0.4(30.0-m_{NB})} \sqrt{\sigma_{NB}^2 + \sigma_Y^2} \right],$$

where $\sigma_{NB}$ and $\sigma_Y$ are the noise in the NB2090 and $Y$ images, respectively, and 30.0 is the scaled zero-point as described in Section 2.

Secondly, we impose a minimum observed equivalent width criterion of 50 Å, equivalent to a colour cut of

$$Y - NB2090 > 0.40.$$  

The colour magnitude selection diagram is shown in Fig. 2. Normal galaxies and stars are coloured in black, the $\Sigma = 3$ selection curve is shown with the curved dashed red line and the equivalent width criterion is indicated with the horizontal dashed red line. Objects selected as ELGs lie above these lines and are shown in blue. After visibly inspecting the candidates and removing artefacts, we have a sample of 95 ELG candidates.

![Figure 2. NB2090–Ks candidate selection diagram. Ordinary, non-ELG objects are shown in black. The curved and horizontal dashed red lines show the $\Sigma$ selection criteria and the equivalent width criteria, respectively. The 95 objects selected as ELG candidates lie above the red selection lines and are highlighted in blue.](https://example.com/figure2.png)

## Table 1. Exposure times, seeing and image depth.

| Filter  | Filter centre ($\mu$m) | Filter width ($\mu$m) | $N$ exposures | Exposure time (s) | Total exposure time (h) | Depth$^a$ (mag) (AB) | Seeing (arcsec) |
|---------|-----------------------|----------------------|--------------|------------------|------------------------|---------------------|----------------|
| NB2090  | 2.095                 | 0.020                | 411          | 150              | 17.125                 | 24.68               | 0.55           |
| Ks      | 2.146                 | 0.324                | 72           | 118.8            | 2.376                  | 24.80               | 0.53           |

$^a$5$\sigma$ limiting magnitude in a 1 arcsec aperture.

## Table 2. Source Extractor parameters – NB2090 source catalogue.

| Parameter             | Unit | Value |
|-----------------------|------|-------|
| DETECT_MINAREA        | pix  | 8     |
| DETECT_THRESH         | $\sigma$ | 1.5  |
| ANALYSIS_THRESH       | $\sigma$ | 1.5  |
| BACK_SIZE             | pix  | 64    |
| BACK_FILTERSIZE       | pix  | 5     |
| DEBLEND_NTHRESH       | ADU  | 32    |
| CLEAN                 | $Y$  |       |
| CLEAN_PARAM           |       | 2.0   |
| PIXEL_SCALE           | arcsec/pix | 0.1064 |

## Table 3. Emission lines that could be detected in the NB2090 filter.

| Emission line | $\lambda_{\text{rest}}$ ($\mu$m) | $z$ | $V_c^a$ ($Mpc^3$) | $\log(L_{\text{Ha}})^b$ (erg s$^{-1}$) | SFR$_{\text{Lin}}^c$ ($M_\odot$ yr$^{-1}$) |
|---------------|---------------------------------|----|-----------------|---------------------------------|---------------------------------|
| Pa$\alpha$    | 1.870                           | 0.120 | 0.011 | 39 | 38.3 |
| Fe $\Pi$      | 1.6367                          | 0.280 | 0.012 | 215 | 39.1 |
| Pa$\beta$     | 1.280                           | 0.637 | 0.016 | 976 | 39.9 |
| H$\alpha$     | 0.6563                          | 2.19  | 0.029 | 4445 | 41.3 | 1.43 |
| [O $\Pi$]     | 0.5007                          | 3.18  | 0.038 | 5696 | 41.7 |
| [O $\Pi$]     | 0.4959                          | 3.22  | 0.038 | 5735 | 41.7 |
| H$\beta$      | 0.4861                          | 3.31  | 0.039 | 5813 | 41.7 |
| [O $\Pi$]     | 0.3727                          | 4.62  | 0.051 | 6672 | 42.0 | 19.0 |
| Ly$\alpha$    | 0.1216                          | 16.2  | 0.156 | 7248 | 43.3 |

$^a$Co-moving volume defined by the NB2090 filter width.

$^b$Luminosity corresponding to an NB2090 line flux of $f_{\lambda} = 3.16 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$, the 5$\sigma$ NB2090 limit of the data (1 arcsec aperture).

$^c$Limiting SFR corresponding to the limiting luminosity in column 6, assuming SFR = $7.9 \times 10^{-42} L_{\text{Ha}}$ (Kennicutt 1998) and [O $\Pi$]/H$\alpha = 0.45$.

The ELGs in the sample will be a mixture of H$\alpha$ emitters at $z \sim 2.2$, [O $\Pi$] $\lambda\lambda 4959, 5007$ and $z \sim 3.2$ as well as [O $\Pi$] $\lambda 3727$ emitters at $z \sim 4.6$. Table 3 summarizes the brightest detectable lines and the corresponding redshift ranges, volumes and luminosity limits over which each line can be detected in this survey. The sample may also include a small number of faint lines at low redshift, such as Pa$\alpha$, Pa$\beta$ or Fe $\Pi$.

At $z \sim 4.6$, [O $\Pi$] emitters are B-band dropouts which enable us to extract them from the lower redshift emitters based on their broadband optical colours. In particular, objects can be ruled out as [O $\Pi$] emitters if they show significant flux blueward of the dropout filter, in this case flux in the $U$ band.
We match the candidates to the MUSIC (v2) catalogue (Santini et al. 2009) using a search radius of 0.36 arcsec, corresponding to 3σMAD of the distribution of offsets between the MUSIC and HAWK-I catalogue matches (σMAD is the standard deviation associated with the median absolute deviation of the offset in arcseconds between the RA and Dec. measured in the HAWK-I images and the MUSIC catalogue). MUSIC contains a compilation of broad-band photometry in 13 filters from the UV to the far infrared, a compilation of spectroscopic redshifts and photometric redshift estimates.

72 of the 95 candidates match to the MUSIC catalogue. 43 of the 72 matches can be ruled out as high redshift [O ii] emitters based on a detection in either the VIMOS U-band filter or one of the WFI U35 and U38 filters. These objects have signal-to-noise ratios that satisfy

\[ S/N(U_{\text{VIMOS}}, U_{\text{35}}, U_{\text{38}}) > 2 \]

and are therefore removed from the sample. 24 objects are undetected at the 2σ level in all of the U bands. No U-band data are available for the remaining five MUSIC matches or for the 23 objects that do not match to MUSIC.

Whilst equation (3) can be used to pick out low-z galaxies, it is not sufficient to select high-z [O ii] emitters as the objects failing this criteria (U dropouts) could be either [O ii] at z = 4.6 or [O iii] emitters at z ~ 3.2. To distinguish [O ii] emitters from [O iii] emitters, we use the Lyman-break criterion for B-band dropouts.

We match the full HAWK-I catalogue to the latest version of the ACS multi-band source catalogue (release r2.0z based on v2.0 data released in 2008 May; see Giavalisco et al. 2004; Giavalisco & the GOODS Team, in preparation), using a 0.36 arcsec search radius, corresponding to 3σMAD of the distribution of radial offsets in RA–Dec. between the ACS and HAWK-I catalogues. The ACS catalogue contains a full suite of aperture measurements in the B125, V606, i775 and z850 bands including a range of circular apertures as well as Source Extractor’s AUTO and ISO apertures. 88 of the 95 objects in our catalogue match to the ACS catalogues and we find that all 72 objects that previously matched to MUSIC also match to ACS.

We use the B-drop criterion of Stark et al. (2009) as a starting point for our selection, namely

\[ B_{125} - V_{606} > (1.1 + V_{606} - z_{850}) \]

\[ B_{125} - V_{606} > 1.1 \]

\[ V_{606} - z_{850} < 1.6 \]

\[ S/N(V_{606}) > 5 \]

and

\[ S/N(i_{775}) > 3. \]

Fig. 3 shows the \( B_{125} - V_{606}, V_{606} - z_{850} \) colour–diagram using ACS apertures 0.5 arcsec in diameter. The dotted lines correspond to equations (4)–(6).

Low redshift emitters with U-band detections above the 2σ level (equation 3) are shown with black squares, whilst open circles denote U-band dropouts. Objects with no available U-band data are shown with small filled circles. Coloured triangles denote objects for which there is a reliable spectroscopic redshift in the VIMOS catalogue with Hα shown in red, [O iii] in green and objects with z < 2.0 (low-z Pachen lines) shown in purple.

The B-drop criterion was developed to select high-redshift galaxies from samples with continuous distributions of redshifts. In this survey, the problem is somewhat simplified given that we know that the redshifts of our galaxy sample are restricted to the discrete ranges given in Table 3. We are therefore looking for isolated populations in \( B_{125} - V_{606}, V_{606} - z_{850} \) colour space.

With this in mind, we indicate the objects that satisfy

\[ S/N(B_{125}) < 2 \]

as lower limits. Based on these criteria, we consider four objects as potential [O ii] emitters at \( z = 4.6 \); these are labelled (with their catalogue identities) as objects 65, 1028 and 1120, 1157. These objects are chosen as they all have S/N < 2 in both the B and U bands.

Five additional objects satisfy the Lyman-break criterion of Stark et al. (2009), yet have S/N > 2 in the B band. Two of the five have secure spectroscopic redshifts of 3.1823 and 3.193 [both grade A quality, from VIMOS (Balestra et al. 2010) and CXO-CDFS (Szokoly et al. 2004), respectively] which would lead us to classify them as [O iii] emitters (see Table 3). Using the average observed Scd spectrum of Coleman, Wu & Weedman (1980), we redshift the spectra in steps of 0.1 and compute the colours of each iteration. We find that for the Scd spectrum, a galaxy at redshift 3.6 has a \( B-V = 2.0 \). Given that all five of these emitters have B-band detections above 2σ and \( B-V < 2.0 \), it is more likely that they are all [O iii] emitters at \( z \approx 3.3 \) than [O ii] at \( z \approx 4.6 \). These will be discussed further in Section 4.
Finally, seven of our emitters have no counterparts in either MUSIC or the ACS catalogues, yet upon visual inspection of the NB2090 images appear to be genuine objects. To investigate these further, we run Source Extractor directly on the ACS images, to see if these objects can be detected if the Source Extractor thresholds (namely DETECT_THRES and DETECT_MINAREA) are relaxed. None of these objects appear in the lower threshold catalogues, even if the detection threshold, DETECT_THRES, is reduced to 1.5σ of the background and the minimum number of contiguous pixels required for extraction, DETECT_MINAREA, is reduced to six contiguous pixels. In the absence of additional data, it is not possible to determine whether these are [O II] emitters, ELGs at some other redshift with particularly faint continua or noise artefacts. Until such data become available, we will take this group of objects into consideration statistically (see Section 6).

4 CANDIDATE [O II] EMMITERS AT z = 4.6

The four objects identified in the previous section as [O II] candidates are catalogued in MUSIC. MUSIC includes both broad-band photometry and a photometric redshift estimate. For the objects selected, the MUSIC photometric redshift estimates are $z_{\text{phot}} = 4.17, 0.35, 2.84$ and 2.75 for objects 65, 1028, 1120 and 1157, respectively.

There are 1697 spectroscopic redshift measurements in the full MUSIC catalogue. At high ($z_{\text{phot}} > 1.5$) redshift, we find the median offset between the spectroscopic measurements and the photometric estimates to be $(z_{\text{phot}} - z_{\text{spec}}) = +0.05$ with a dispersion of $\sigma_{\text{MAD}} = 0.18$. At $z_{\text{phot}} = 4.17$, the photometric redshift estimate of object 65 is therefore well within 3σ of the [O II] redshift of $z = 4.6$.

To investigate why our other $z = 4.6$ candidates have low photometric redshift estimates, we run the photometric code, EAZY (Brammer, van Dokkum & Coppi 2008), on the photometry in our catalogues to output the full chi-square distribution for each object. For each object, we run two separate simulations, first on the AUTO measurements provided in the ACS catalogue ($B_{606}, V_{606}, I_{775}$ and $z_{850}$) and secondly on the set of broad-band colours provided in MUSIC (full set of 13 bands: $U, B_{435}, V_{606}, I_{775}, z_{850}, J, H, K_s, IRAC \, 3.6, 4.5, 5.5$ and 8µm and MIPS 24µm).

When the four ACS bands are considered in the photo-z, minima are found at $z \sim 4$ as expected from the colour–colour diagram for three of the four [O II] galaxies. These are at $z = 4.29, 4.37$ and 3.97 for objects 65, 1028 and 1120, respectively. The chi-square plot rules out a solution at $z > 4$ for object 1157.

The results of the photometric redshift simulations based on the full suite of measurements in the MUSIC catalogue are shown in Fig. 4. Each sub-figure provides a summary for an individual candidate. The upper panel of each sub-figure shows chi-square with respect to redshift in black with the corresponding relative probability distribution overlain in grey. The code is also rerun with a fixed input redshift of $z = 4.6$, the output of which provides the best-fitting SED model for the galaxy, if the galaxy were an [O II] emitter at this redshift. The results of these simulations are shown in the lower panels of each sub-figure, along with the objects’ actual broad-band flux measurements for comparison.

Table 8 gives a full set of multi-wavelength observations are taken into consideration, we find $z_{\text{phot}} = 3.91$ for object 65 (compared with $z_{\text{phot}} = 4.17$ in MUSIC) and reproduce a low redshift result similar to MUSIC of $z_{\text{phot}} = 0.38$ for object 1028. The solution for object 1120 shows two peaks in the probability distribution, a primary peak at $z = 4.13$, consistent (within 3σ) with the object being an [O II] emitter at $z = 4.6$ and a secondary peak at $z = 2.67$ consistent (again within 3σ) of the object being an Hα emitter.

Interestingly, although we reproduce the low-z solution for object 1028, we also find a secondary minima in the chi-square distribution at $z_{\text{phot}} = 4.55$. There are no lines with redshift ranges that cover $z = 0.38$, the nearest lines being Fe II with a redshift range of $z = 0.27$–0.29 and Paβ at $z = 0.63$–0.64. At these redshifts, the survey also probes particularly small volumes: 215 and 976 Mpc$^3$ for Fe II and Paβ, respectively. In this case, it is therefore probable that object 1028 is an [O II] emitter at $z \sim 4.6$.

The photometric redshifts unambiguously indicate that object 1157 is a low redshift object, most probably a faint Hα emitter. Object 1157 is particularly faint in the optical, with MUSIC magnitudes of $m_B = -28.593, m_V = 27.236, m_J = 28.889$ and $m_K = 26.430$, as such it is likely that object 1157 has an S/N < 2 in the $B$ band due to the object being near to the flux limit of the $B$ image, rather than there being a break in the SED.

For completeness, the code is then run on the full sample of 72 MUSIC-matched candidates. When converting from a chi-square distribution to a probability distribution, a prior is usually introduced such that the probabilities are weighted by the likelihood of detecting an object at the specific redshift. The prior most commonly used in photometric redshift analysis is an apparent magnitude prior derived from the observed luminosity functions of galaxies. In this analysis, as highlighted in Section 3, we expect the ELG population to lie in the discreet redshift ranges given in Table 3. In addition to the standard prior, we therefore consider a second prior whereby only the redshift ranges given in Table 3 are allowed. We find that we select the same sample of [O II] candidates, irrespective of the prior used to calculate the probabilities, suggesting that the selection method is robust.

Finally, we investigate the five objects in Section 3 that satisfied the Lyman-break criteria but did not satisfy $S/N(B) < 2.0$. Two of these candidates had spectroscopic redshifts that categorized them as [O II] at $z = 3.1823$ and 3.193. The photometric redshift code outputs values of $z = 3.39$ and 3.26 for these objects, respectively, within 1σ of the spectroscopic values. The remaining three objects also have photometric redshifts within 1σ of the central redshift for [O II] in the filter, suggesting that the conclusion drawn in Section 3, that these are all [O II] emitters, was correct.

In summary, based on the analysis above, of the four $z \sim 4.6$ candidates in Section 3, object 1157 is almost certainly a faint Hα emitter at $z \sim 2.2$. Although the full photometric redshift solutions of objects 65, 1120 and 1028 allow them to be [O II] emitters at $z = 4.6$, none can unambiguously be classified as such. The most likely candidate is object 65, for which the photometric redshift solution clearly rules out $z < 3$ in favour of $z \sim 4$.

5 RESULTS AND DISCUSSION

Although the colour–colour analysis and photometric redshift simulations provide evidence in support of objects 65, 1028 and 1120 being [O II] emitters at $z \sim 4.6$, spectroscopic follow-up (not currently planned) would be needed to confirm this. In the following analysis, we therefore consider two scenarios, first that all three of the candidates are [O II] emitters and secondly that only the most likely high redshift candidate (object 65) is in fact an [O II] emitter. We then use the narrow and broad-band fluxes to place limits on the SFR in these scenarios. In Section 6, we also consider the possibility that none of the candidates are genuine and also address the seven ELG candidates highlighted in Section 3 for which there is no available auxiliary data.
Figure 4. Summary of the photometric redshift simulations for the four [O II] candidates found in this survey. The upper plots in each pair show the chi-square distribution in black, alongside the relative probability of the object being at each redshift in grey. The flux measurements are shown in the lower plot, overlain with the best-fitting model SED at $z = 4.6$, to illustrate how well the flux measurements agree with a $z = 4.6$ solution.

Given the small number of objects under consideration (either one or three), it is not possible to directly fit a luminosity function to the data. We therefore turn to deriving confidence limits on the SFR from the observations. Madore (2010) sets out a method of determining confidence intervals on the mean of an underlying distribution, given only a single observation drawn from it. The logic is summarized as follows. We assume that the observation $y_i$ is drawn from an underlying distribution with some dispersion and...
that all values considered in the calculation are non-negative. Given that only a single observation is available, this observation is the best estimate of the true mean of the population, \( \langle Y \rangle \). Madore then defines the ‘g factor’ which is the multiplicative factor which would convert the observation into its own error on the true mean, such that one of the limits of

\[
y_i \pm y_i \ g_i
\]

is equal to the true population mean. If \( \epsilon_i \) is the absolute value of the difference between the observation and the true population mean,

\[
\epsilon_i = |\langle Y \rangle - y_i|,
\]

then

\[
g_i = |\langle Y \rangle/y_i - 1.0|.
\]

Calculating \( g_i \) for a large number of values of \( y_i \), drawn from a distribution, builds up the corresponding \( g \) distribution. Confidence limits can be defined (by integrating the \( g \) distribution) such that, for example, \( g(50) \) is the \( g \) value for which for any single observation randomly drawn from the distribution, \( y_i \pm y_i \ g(50) \) incorporates the true mean 50 per cent of the time, and similarly, the confidence interval \( y_i \pm y_i \ g(90) \) incorporates the true mean 90 per cent of time.

In the context of this paper, we assume three priors, first that the \([\text{O} \text{II}] \) luminosities are drawn from a Schechter function (Schechter 1976) of the form

\[
\Phi(L) \ dL = \phi^* \left( \frac{L}{L^*} \right)^{-\alpha} \exp\left(-\frac{L}{L^*}\right) \ d\left(\frac{L}{L^*}\right),
\]

where \( L^* \) and \( \alpha \) are unknown and \( \phi^* \) is a normalization constant.

Secondly, we assume that \( L^* \) satisfies \( \log(L^*) = 42.5 \pm 0.5 \) and thirdly, \( \alpha = -1.3 \pm 0.2 \). This range of \( \alpha \) values are either measured or assumed by other authors in low redshift \([\text{O} \text{II}] \) surveys (e.g. Takahashi et al. 2007; Zhu et al. 2009; Bayliss et al. 2011). The range of \( L^* \) was chosen based on two premises: first that it is unlikely that \( L^* < L_{\text{Lim}} \) as in such a case, the luminosity function would rapidly fall away above \( L_{\text{Lim}} \) and we would not expect to measure any \([\text{O} \text{II}] \) emitters at all. Secondly, if the \([\text{O} \text{II}] \) luminosity function follows the same trends as the global luminosity function, it is unlikely that \( L^* \) would significantly increase between redshifts 2 and 4. We therefore assume a range of \( L^* \) that encompasses the range of \( L^* \) values measured at low redshift above \( L_{\text{Lim}} \).

Letting \( L^* \) and \( \alpha \) vary within these ranges (\( \log(L^*) = 42.5 \pm 0.5 \) and \( \alpha = -1.3 \pm 0.2 \), respectively), we calculate the \( g \) distributions for 231 combinations of \( L^* \) and \( \alpha \), varying each in turn in steps of \( \delta \alpha = 0.02 \) and \( \delta \log(L^*) = 0.2 \).

For each combination, only the portion of the Schechter function above the luminosity limit of the survey (\( \log(L_{\text{Lim}}) = 42.0 \)) is considered, as an observation made in our survey could not have a value below this limit. 100 000 observations were then randomly drawn from the distribution and the corresponding \( g \) factors calculated. To illustrate this process, the underlying probability distribution and corresponding \( g \) distribution for a Schechter function with \( \log(L^*) = 42.5 \) and \( \alpha = -1.3 \) is shown in Fig. 5 where the values of \( g(50), g(68), g(90) \) and \( g(98) \) are marked in the figure in blue lines.

Each combination of \( L^* \) and \( \alpha \) produces different \( g \) confidence intervals \( (g(\text{CI})) \) values. A histogram of the values of \( g(50), g(68) \) and \( g(90) \) gained from a full set of simulations is shown in Fig. 6. It can be seen that the \( g \) confidence values are clustered. By taking the maximum value of \( a \) (CI) distribution, e.g. the maximum of the \( g(50) \) distribution, \( g(50)_{\text{max}} \), we produce a conservative confidence limit, such that \( y_i \pm y_i \ g(50)_{\text{max}} \) encompasses the mean for at least 50 per cent of observations randomly drawn from an underlying distribution with any combination of \( L^* \) and \( \alpha \) within the ranges \( \log(L^*) = 42.5 \pm 0.5 \) and \( \alpha = -1.3 \pm 0.2 \). In this way, conservative confidence limits can be put on the mean luminosity of objects above the luminosity limit of the survey, irrespective of the precise form of the underlying distribution.
We note that Schechter functions with \( \log(L^*) < 42.0 \) are also covered by these \( g \) confidence values, as Schechter functions with \( L^* < L_{lim} \) rapidly fall away above \( L^* \) and so any object is very close to the mean value of possible observations above \( L_{lim} \), by virtue of the fact that so few observations are permitted at these luminosities, over a very limited range. In these cases, \( y_i \sim \langle Y \rangle \) and \( g_i \) therefore tends to zero.

The preceding logic applies to an observation of a single object. In the case that three objects are available, we modify the underlying assumptions, such that the best estimate of the mean is the mean of the three observations, \( \langle y \rangle \), and re-calculate the \( g \) distribution in the same way as before, in each case substituting \( \langle y \rangle \) for the single observation \( y_i \). We subsequently refer to the resulting \( g \) distribution as the ‘modified’ \( g \) distribution, \( g' \).

Randomly drawing three objects from a distribution and re-calculating the modified \( g' \) values produce a tighter \( g' \) distribution, reflecting the fact that more observations place a tighter constraint on the mean \([O\,\text{II}]\) luminosity.

The results of both sets of simulations are summarized in Table 4. The table provides the maximum \( g \) values to convert one or three observations into confidence intervals on the mean value of an underlying Schechter function for confidence intervals of 50, 68.5, 90, 95, 98 and 99.7. The underlying Schechter function may take any combination of \( L^* \) and \( \alpha \) within the ranges \( \log(L^*) < 43.0 \) and \( \alpha = -1.3 \pm 0.2 \). We note that this method is broadly a reworking (and possibly more intuitive form) of the Bayes theorem, where the ranges of \( \alpha \) and \( L^* \) assumed are analogous to the priors in the Bayes theorem.

5.1 Limits on the SFRD (single object)

We recall that the goal of this section is to calculate confidence intervals on the SFRD in galaxies with \( \log(L[O\,\text{II}]) > 42.0 \). We now consider the two scenarios proposed at the beginning of this section. First, we consider the case that only one of our three \([O\,\text{II}]\) candidates (either object 65, 1028 or 1120) is a genuine \([O\,\text{II}]\) emitter. In this case, the confidence limits on the mean luminosity can be calculated from the individual luminosities of these objects using the relation \( CI = \langle y \rangle \pm y g(\text{CI}) \) where \( g(\text{CI}) \) are the \( g \) values for each confidence interval given in the first row of Table 4.

The \([O\,\text{II}]\) luminosities are calculated from the NB2090 and Ks magnitudes in two stages. First, we calculate the line flux from the NB2090 and Ks fluxes according to

\[
f_i = f_{\text{NB2090}} - \epsilon f_{Ks},
\]

where \( f_{\text{NB2090}} \) and \( f_{Ks} \) are the flux densities in the NB2090 and Ks filters, respectively. Line fluxes are converted into \([O\,\text{II}]\) luminosities, assuming that the ELG lies at the centre of the filter, i.e. that the object lies at \( z = 4.6 \). Under this approximation, the luminosity distance is \( d_L = 42.523 \text{ Mpc} \) and the \([O\,\text{II}]\) luminosity is

\[
L[O\,\text{II}]_{\text{obs}} = 4\pi d_L^2 f_i.
\]

For each candidate, the luminosity is then converted into confidence limits on the mean \([O\,\text{II}]\) luminosity in the survey volume, using the \( g(\text{CI}) \) values in Table 4. The mean luminosities are converted into the total luminosity density by multiplying by the number density of observations. In the case that only one object is selected, the number density, \( n/\text{vol} \), is \( 1/6672 \text{ Mpc}^{-3} \). Table 5 lists the RA and Dec. of each candidate, along with its Ks and NB2090 magnitudes, line flux and \([O\,\text{II}]\) luminosity. The 50 per cent confidence limits on the total luminosity density derived from the object if it were the only emitter are given in column 10 of Table 5.

The limits on the total luminosity density are now converted into limits on the SFRD. First, we convert the total \([O\,\text{II}]\) luminosity densities into total H\(\alpha\) luminosity densities assuming an observed \([O\,\text{II}]\)/H\(\alpha\) ratio of \( L_{[O\,\text{II}]} / L_{\text{H\alpha,obs}} = 0.45 \) (Kennicutt 1998; Hopkins & Beacom 2006). We correct for dust by assuming a uniform extinction of \( A(\text{H}\alpha) = 1.0 \text{ mag} \) (Hopkins & Beacom 2006). The corrected H\(\alpha\) luminosity is converted into an SFRD, \( \rho_\alpha \), using the relation given in Kennicutt (1998):

\[
\rho_\alpha = 7.9 \times 10^{-42} L_{\text{H\alpha,corr}} M_\odot \text{ yr}^{-1}.
\]

The ‘standard’ 1.0 mag H\(\alpha\) extinction correction, as used in the compilation of star formation rate measurements made by Hopkins & Beacom (2006), is adopted here to provide a homogeneous set of measurements. The validity of such an assumption is discussed in Sections 5.2 and 6.

The 50 per cent confidence intervals on the SFRD that would be derived from each single object if it were confirmed as the only genuine \([O\,\text{II}]\) emitter are given in the final column of Table 5.

5.2 Limits on the SFRD (full sample)

In the case when all three candidates are genuine \([O\,\text{II}]\) emitters at \( z \sim 4.6 \), we calculate the limits on the SFRD using the modified

Figure 6. Distributions of the \( g(50) \), \( g(68.2) \) and \( g(90) \) values for one observation drawn from a Schechter function. A range of input Schechter function parameters were considered, with \( \alpha \) ranging from \(-1.1 \) to \(-1.5 \) in steps of \( 0.02 \) and \( \log(L^*) = 42.0 \) to 43.0 in steps of 0.2.

Table 4. \( g \) values to derive confidence intervals on the mean of an underlying Schechter function based on one or three observations drawn randomly from the distribution. From a single observation, \( y_i \), confidence intervals of CI per cent are computed as \( y_i \pm g(\text{CI})y_i \), where the \( g(\text{CI}) \) values are taken from the first row of the table. In the case of three objects, the confidence intervals are calculated according to \( y_i \pm g'(\text{CI})y_i \), where \( g'(\text{CI}) \) are the values in the second row of the table.

| Objects | \( g(50) \) | \( g(68.2) \) | \( g(90) \) | \( g(95) \) | \( g(98) \) | \( g(99.7) \) |
|---------|--------------|---------------|-------------|-------------|-------------|--------------|
| 1       | 0.6250       | 1.075         | 2.025       | 2.275       | 2.425       | 2.475        |
| 3       | 0.2250       | 0.325         | 0.625       | 0.775       | 1.025       | 1.225        |

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Table 5. Astrometry photometry and star formation rates of the three \( z \sim 4.6 \) candidates found in this study.

| ID  | RA (J2000)  | Dec. (J2000) | \( m_{\text{NB2090}} \) | \( \sigma_{\text{NB2090}} \) | \( m_{Ks} \) | \( \sigma_{Ks} \) | \( \rho_L(\text{O} \alpha) \) | \( \rho_L(\text{O} \alpha)(50) \) | SFR(50) \( \times 10^{-25} \text{ erg s}^{-1} \text{ M}_\odot \text{ yr}^{-1} \) |
|-----|-------------|-------------|----------------|----------------|----------|----------|----------------|----------------|-----------------------------|
| 65  | 53.140755   | −27.873248  | 23.02           | 0.11           | 23.67    | 0.14     | −16.81         | 42.52          | 38.70 ± 0.21               |
| 1028| 53.106266   | −27.825932  | 23.81           | 0.13           | 24.63    | 0.19     | −17.06         | 42.27          | 38.45 ± 0.21               |
| 1120| 53.173699   | −27.759455  | 23.11           | 0.09           | 23.98    | 0.14     | −16.76         | 42.57          | 38.74 ± 0.21               |

\( a \) Measurements in degrees.

\( b \) NB2090 and KS magnitudes are on the AB scale.

\( c \) Observed line flux (erg cm\(^{-2}\) s\(^{-1}\)).

\( d \) Observed line luminosity (erg s\(^{-1}\)).

\( e \) Implied 50 per cent confidence limits on the [O\( \alpha \)] luminosity density if the object proved to be the only genuine [O\( \alpha \)] emitter in the survey volume at \( z \sim 4.6 \) (erg s\(^{-1}\) Mpc\(^{-3}\)). Other confidence intervals can be calculated in the same way, using the appropriate \( g(CI) \) values given in Table 4.

\( f \) Corresponding 50 per cent confidence interval on the SFRD in galaxies with [O\( \alpha \)] luminosities \( \log(L_{\text{[O} \alpha \text{]}}) > 42.0 \), if the object proved to be the only genuine [O\( \alpha \)] emitter. (See the text for further details.)

\( g \) values, \( g(CI) \). The mean luminosity of the three candidates is \( \log(L_{\text{[O} \alpha \text{]TOT}}) = 42.93 \text{ erg s}^{-1} \). Confidence intervals on the mean [O\( \alpha \)] luminosity in the survey volume are calculated using the \( g \) values in the second row of Table 4. The 50 per cent confidence interval is \( \log(L_{\text{[O} \alpha \text{]TOT}}) = 42.93 \pm 0.11 \text{ erg s}^{-1} \). This luminosity is converted into a luminosity density, by multiplying by the number density which, in the case of there being three objects detected, is \( 3/6672 \text{ Mpc}^{-3} \).

The limits are then converted into SFRD measurements using the conversions outlined in Section 5.1 to produce a 50 per cent confidence interval on the SFRD of \( \rho^\ast \log(L > 42.0)) = 0.058 \pm 0.013 \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3} \). Other confidence intervals can be calculated in the same way, using the appropriate \( g(CI) \) values given in Table 4.

The results are plotted in Fig. 7, where the grey error bars indicate the range implied if just object 65 is a genuine [O\( \alpha \)] emitter and the coloured points indicate the 50 and 90 per cent confidence intervals if all three candidate [O\( \alpha \)] emitters are genuine. Note that the grey range has been offset slightly in redshift for clarity. Alongside the results from this work are those of lower redshift surveys, including the analogous HAWK-I survey at \( z \sim 1.85 \) (Bayliss et al. 2011) in red, the results from the survey of Ly et al. (2007) in black diamonds, the results of Takahashi et al. (2007) in red crosses and those of Zhu et al. (2009) in blue squares. Results from the other surveys were calculated by integrating the reported observed luminosity functions above \( \log(L_{\text{[O} \alpha \text{]}}) > 42.0 \), to make them directly comparable to our survey. The luminosity densities were converted into SFRD values using the same underlying assumptions of 1 mag H\( \alpha \) extinction and [O\( \alpha \)]/H\( \alpha \) = 0.45. It should be noted that the points from Zhu et al. (2008) lie slightly above the main trend as Zhu et al. fit a power law to the luminosity function which is top-heavy in comparison to the Schechter function fit used in the other surveys. The blue lines show the evolution of the SFRD and the \( \pm \sigma \) errors reported by Bouwens et al. (2007) for bright \( (L > 0.3 L_{\text{TOT}}) \) (see Bouwens et al. fig. 7) galaxies in the UV. The curve is scaled to overlap with the result of Bayliss et al. (2011) at \( z = 1.85 \). The increase in the SFRD measured between \( z = 4.6 \) and 1.85 in the surveys presented in this study is in good agreement with the increase in SFRD reported by Bouwens in the UV over the same redshift range.

A study of the H\( \alpha \) emitters at \( z = 2.2 \) in the data set used in this paper was presented in Hayes, Schaerer & Östlin (2010). As a consistency check, we take the luminosity function reported there \( (log(L_{\text{H} \alpha}) = 43.07 \pm 0.02 \text{ erg s}^{-1}, log(\rho^\ast_L(\text{H} \alpha)) = −3.45 \pm 0.52 \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}) \), \( \alpha = −1.60 \pm 0.15 \), and integrate it over the equivalent luminosity range of \( \log(L_{\text{H} \alpha}) > 42.35 \) (assuming [O\( \alpha \)]/H\( \alpha \) = 0.45). This gives an SFR of \( \rho^\ast_L(\log(L_{\text{H} \alpha}) > 42.35)) = 0.083 \pm 0.05 \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3} \) which is in good agreement with our measurements. This result is shown by the green triangle in Fig. 7.

In Section 3, seven objects were observed that appeared to be real in the NB2090 image, yet had no counterparts in the MUSIC or ACS catalogues. Out of the 88 remaining candidates, three (~4 per cent) were flagged as [O\( \alpha \)] emitters. If the same proportion of the unclassified candidates are actually [O\( \alpha \)] emitters, this would imply that less than one of the seven objects is missed from our sample. The mean line flux of these objects is \( \log(f_\alpha^\ast) = −16.95 \).
candidates to be \([\text{O} \text{ ii}]\) shown in Fig. 7 by \(\sim 7\) per cent from 0.059 to 0.063 M_⊙ yr\(^{-1}\).

The results as they stand suggest an increase in the SFRD in bright \([\text{O} \text{ ii}]\) emitting galaxies of between a factor of 2 and 5 between redshifts 1.85 and 4.6. Hopkins & Beacom (2006) parametrize the SFRD evolution by fitting two curves to their compilation of SFRD measurements. The best-fitting curves using the Cole et al. (2001) parametrization and a linear piecewise fit suggest an increase in the global SFRD (integrated over the full galaxy luminosity range) of a factor of \(\sim 2.7\) and \(\sim 1.4\) between redshifts 4.6 and 1.85, respectively. The result found in this paper suggests that the SFRD in the brightest galaxies may be increasing faster than the global SFRD between redshifts 1.85 and 4.6. This would support the idea that a higher proportion of star formation occurs in smaller, less luminous galaxies at \(z = 4.6\) than at 1.85.

Whilst the ‘standard’ assumptions used to convert the \([\text{O} \text{ ii}]\) luminosity density into SFRD (Hopkins & Beacom 2006) are a useful basis for comparing measurements at different epochs, it is possible that evolution in the \([\text{O} \text{ ii}]/\text{H}\alpha\) ratio or dust content account for some of the observed trend.

Bayliss et al. (2011) measured the dust content of 26 \([\text{O} \text{ ii}]\) emitters at \(z = 1.85\) using rest-frame 8 \(\mu\)m fluxes and found a lower average dust extinction of \(A(\text{H}\alpha) = 0.52 \pm 0.11\) mag compared to the present. To remove the observed increase in the SFRD of a factor of 2–5, extinctions of \(A_{\text{H}\alpha} = 1.75–2.75\) at \(z = 4.6\) compared to \(A_{\text{H}\alpha} = 1.0\) at \(z = 1.85\) (or 1.27–2.27 mag at \(z = 4.6\) compared to 0.52 mag at \(z = 1.85\)) would be needed. It is therefore unlikely that systematic evolution in the dust content between galaxies at \(z = 4.6\) and the present day could account for the change in SFRD reported here, as that would require a decrease in extinction between \(z = 1.85\) and 4.6.5, contrary to the increase in dust extinction observed between \(z = 1.85\) and the present day.

With respect to the observed \([\text{O} \text{ ii}]/\text{H}\alpha\) ratio, the observations could be accounted for by a factor of 2–5 decrease in the \([\text{O} \text{ ii}]/\text{H}\alpha\) ratio between \(z = 4.6\) and 1.85, rather than a factor of 2–5 increase in SFRD. Detailed spectroscopic surveys of galaxy samples at high redshift are needed to study this possibility further.

The proceeding paragraphs concerned the evolution of the extinction of populations of \([\text{O} \text{ ii}]\) objects; however, this paper has presented a study of just three objects. Could the variation in dust content between individual galaxies account for the result? Bayliss et al. (2011) found a dispersion in the measured dust content at \(z = 1.85\) of 0.6 mag. If the dust contents of \([\text{O} \text{ ii}]\) emitters at \(z = 4.6\) have a similar dispersion to their counterparts at \(z = 1.85\), then this could account for some of the result. If the objects detected in our study are particularly dusty examples of \([\text{O} \text{ ii}]\) emitters at \(z = 4.6\), then this might imply that a correction as high as \(A_{\text{H}\alpha} = 1.6\) would be more appropriate, leading to an increase in reported SFRD from 0.058 to 0.10 M_⊙ yr\(^{-1}\) Mpc\(^{-3}\). As discussed earlier, extinctions of \(A_{\text{H}\alpha} = 1.75\) to 2.75 at \(z = 4.6\) compared to \(A_{\text{H}\alpha} = 1.0\) at \(z = 1.85\) are needed to remove the observed increase in SFRD by a factor of 2–5, so a dust content of this magnitude could account for a large proportion of the observed increase in SFRD between \(z = 4.6\) and 1.85. It is important to note though that in the absence of any other information, by the same logic, we could also suggest that we might have detected examples of \([\text{O} \text{ ii}]\) emitters that are relatively dust free compared to the average and a correction of \(A_{\text{H}\alpha} = 0.4\) and SFRD of 0.03 M_⊙ yr\(^{-1}\) Mpc\(^{-3}\) would be more appropriate.

Whilst there is clear uncertainty in the appropriate dust correction to use at high redshift, the strength of the collection of SFRD measurements presented here lies in their homogeneity. The surveys included in Fig. 7 all draw their samples from narrow-band surveys using the same selection techniques and have been integrated over a luminosity range appropriate for the sample as a whole. As a result, when more information on the dust content of similar high redshift galaxies becomes available, the measurements can be updated by simply multiplying each value by an appropriate scaling factor \(10^{0.4(\lambda_0/10\mu\text{m})}\). As such, these measurements provide a solid baseline for future studies in this area and are a homogeneous measure against which simulations can be tested.

6 SUMMARY

This paper has used deep near-infrared data from the ESO HAWK-I instrument in the NB2090 and Ks filters to select \([\text{O} \text{ ii}]\) \(\lambda 3727\) ELGs at \(z \sim 4.6\).

(i) Out of 95 ELG candidates, four were highlighted as possible \([\text{O} \text{ ii}]\) emitters based on their broad-band optical colours. Photometric redshift estimates, based on the 13 broad-band measurements in the MUSIC catalogue, led to one of the candidates to be re-classified as an H\alpha emitter at \(z \sim 2.2\). The photometric redshifts allowed high redshift \(z > 4\) solutions for the three remaining candidates; however, none could unambiguously be classified as \([\text{O} \text{ ii}]\) emitters at \(z \sim 4.6\).

(ii) Given the uncertainty in classification of the emitters, we then considered two scenarios; first that all three of the emitters were genuine \([\text{O} \text{ ii}]\) emitters and secondly that only the most likely candidate was actually a genuine \([\text{O} \text{ ii}]\) emitter. For both of these scenarios, small number statistics were used to put confidence limits on the SFRD taking place in luminous \([\text{O} \text{ ii}]\) emitters \((\log(L(\text{[O} \text{ ii}])) > 42.0)\) using the prescription outlined in Madore (2010).

(iii) Using the results from a range of comparable low-\(z\) \([\text{O} \text{ ii}]\) surveys, we compiled a homogeneous set of \([\text{O} \text{ ii}]\)-derived SFRD measurements from \(z = 0–4.6\). From these measurements, we inferred a drop in the SFRD in bright \([\text{O} \text{ ii}]\) emitters of at least a factor of 2 between \(z = 1.85\) and 4.6.

This paper has provided a proof of concept that the \([\text{O} \text{ ii}]\) \(\lambda 3727\) doublet can be used to make homogeneous measurements of the SFRD from \(z = 0\) to 4.6. In the coming years, wider and deeper narrow-band surveys will allow this work to be expanded to allow particularly robust measurements of the SFRD to be made. The last scientific value of these results as they stand lies in their homogeneity over such a wide redshift range. The surveys included in Fig. 7 all draw their samples from narrow-band surveys; no faint-end slope has been assumed and so the measurements do not depend on an integral that is uncertain at the faint end; although a common dust correction has been assumed here, any dust–redshift relationship could be grafted on to the results by multiplying each value by an appropriate scaling factor \(10^{0.4(\lambda_0/10\mu\text{m})}\). As such, these measurements provide a simple, homogeneous measure against which simulations can be tested.

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