[O II] emitters in the GOODS field at $z \sim 1.85$: a homogeneous measure of evolving star formation

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ABSTRACT

We present the results of a deep, near-infrared, narrow-band imaging survey at a central wavelength of 1.062 μm (FWHM = 0.01 μm) in the GOODS-South field using the ESO VLT instrument, HAWK-I. The data are used to carry out the highest redshift search for [O II] λ3727 Å emission line galaxies to date. The images reach an emission line flux limit (5σ) of $1.5 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$, additionally making the survey the deepest of its kind at high redshift. In this paper we identify a sample of [O II] λ3727 Å emission line objects at redshift $z \sim 1.85$ in a comoving volume of $\sim 4100$ Mpc$^3$. Objects are selected using an observed equivalent width (EW$_{\text{obs}}$) threshold of EW$_{\text{obs}} > 50$ Å. The sample is used to derive the space density and constrain the luminosity function of [O II] emitters at $z = 1.85$. We find that the space density ($\rho$) of objects with observed [O II] luminosities in the range log($L_{\text{[O II]}}$) > 41.74 erg s$^{-1}$ is log($\rho$) = $-2.45 \pm 0.14$ Mpc$^{-3}$, a factor of 2 greater than the observed space density of [O II] emitters reported at $z \sim 1.4$. After accounting for completeness and assuming an internal extinction correction of $A_H = 1$ mag (equivalent to $A_{\text{[O II]}} = 1.87$), we report a star formation rate density of $\dot{\rho}_* \sim 0.38 \pm 0.06$ M⊙ yr$^{-1}$ Mpc$^{-3}$. We independently derive the dust extinction of the sample using 24-μm fluxes and find a mean extinction of $A_{\text{[O II]}} = 0.98 \pm 0.11$ magnitudes ($A_H = 0.52$). This is significantly lower than the $A_H = 1$ ($A_{\text{[O II]}} = 1.86$) mag value widely used in the literature. Finally, we incorporate this improved extinction correction into the star formation rate density measurement and report $\dot{\rho}_* \sim 0.24 \pm 0.06$ M⊙ yr$^{-1}$ Mpc$^{-3}$.

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

1 INTRODUCTION

The volume-averaged star formation history is a fundamental property of the Universe: its reliable determination will provide a powerful probe with which to explore the physics of galaxy formation and evolution.

Much effort has been focused on this field and a variety of star formation rate (SFR) indicators at different redshifts have contributed to the current picture whereby star formation starts between $z \sim 20$ and 8, peaks at $z \sim 1$–3 and then declines towards $z = 0$. Although constrained within 30–50 per cent below $z \sim 1$, the SFR is less well determined at higher redshifts, being uncertain up to a factor of 3 between $1 < z < 6$ (Hopkins & Beacom 2006).

Variation among different measurements is primarily due to differences in sample selection, biases among different SFR indicators and underlying cosmic variance. Whilst using a combination of different indicators has provided a qualitative description of the evolution of the SFR, such biases make it difficult to properly quantify the evolution. Indeed, as pointed out by Geach et al. (2008), piecing together measurements from different indicators is no longer improving our understanding.

To make progress, homogeneous indicators are needed, visible over wide redshift ranges. Although H$\alpha$ remains the SFR indicator of choice, the [O II] λ3727 doublet has a particular advantage over H$\alpha$ in being visible to $z \sim 5$ in the near-infrared, compared to the $z \sim 2.5$ limit of H$\alpha$ surveys.

Up until recently, [O II] has for the most part remained on the periphery of efforts to measure the SFR history of the Universe. As a collisionally excited forbidden line, the [O II] doublet is not directly coupled to the UV ionizing radiation and as such, the [O II]–SFR calibration is subject to scatter due to excitation variations related to metal abundances and ionization state (see the review by Kennicutt 1998). Despite these limitations, the intrinsic

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[O II]/Hα variation is typically a factor of 2 or less over wide ranges of galaxy environments and abundances and [O II] has been employed in a range of previous studies (see Hippelein et al. 2003; Hopkins 2004; Kewley, Geller & Jansen 2004; Ly et al. 2007; Takahashi et al. 2007; Zhu, Moustakas & Blanton 2009) acting as a useful index, particularly for large statistical samples.

Recent advances in the calibration of the [O II] λ3727 doublet (see Kewley, Geller & Jansen 2004; Moustakas, Kennicutt & Tremonti 2006; Kennicutt et al. 2009) have made it possible to use [O II] with greatly improved precision, approaching that of more traditional SFR indicators. Addressing concerns over metallicity and excitation, Moustakas et al. (2006) found that the majority of variation between [O II] and SFR is due to dust-reddening (derived from the Hα/Hβ decrement) and that variations in metallicity and excitation are in fact second-order effects in most galaxies.

Taking this further, Kennicutt et al. (2009) developed empirical calibrations between [O II] luminosity and SFR using weighted combinations of either total infrared (TIR), 24 µm or 8 µm flux to correct for dust extinction. They report that for z = 0 galaxies, the dispersion of [O II] flux, corrected using their empirical relations, is equivalent to that of their corrected Hα samples, thus facilitating the first reliable [O II]-derived measurements of the SFR to be made.

In this paper, we apply these advancements in the calibration of [O II] to the highest redshift narrow-band survey for [O II] emitters to date, concentrating on objects in the GOODS field at z = 1.85. Using the new HAWK-I instrument on the ESO VLT facility, the survey covers a comoving volume of \(\sim 4100 \text{Mpc}^3\) to a depth of \(1.5 \times 10^{-17} \text{erg cm}^{-2} \text{s}^{-1}\).

In Section 2 we describe the data set, data reduction and cataloguing techniques used in the study. Section 3 describes the method for selecting emission line galaxies (ELGs) and how we remove emitters other than [O II] from the sample. After taking into account the completeness, we compute the luminosity function in Section 4. Section 5 looks at the number density evolution of [O II] emitters between z = 0.8 and z = 1.85. In Section 6, we convert the integrated [O II] luminosity into an SFR, first using a standard extinction correction and secondly using the improved locally derived calibrations of Kennicutt et al. (2009). Throughout this paper, magnitude measurements are on the AB scale \((m_{AB} = 48.60 - 2.5 \log_{10} \text{flux})\). A standard cosmology is assumed with \(\Omega_m = 0.3\), \(\Omega_{\Lambda} = 0.7\) and \(h = 0.70\).

# 2 Observations and Data Reduction

## 2.1 Observations

This study utilizes deep NIR data in two overlapping bands, a broad Y filter centred on 1.021 µm and a narrow-band filter at 1.060 µm. Filter centres and FWHM were calculated using the prescriptions in Pascual, Gallego & Zamorano (2007). Filter transmission profiles are plotted in Fig. 1. The data were obtained using HAWK-I (Kissler-Patig et al. 2008), an NIR (0.85–2.5 µm) wide field, cryogenic imager on UT4 at the ESO VLT facility in Paranal, Chile. The HAWK-I focal plane is made up of four square Hawaii detectors separated by a cross-shaped gap of 15 arcsec. Each filter has a 2048 pixel width and a pixel scale of 0.106 arcsec pix\(^{-1}\). The HAWK-I field of view is 7.5 \(\times\) 7.5 arcmin. The data were collected in the Science Verification phase as part of programme 60.A-9284(B) (Fontana et al.: A deep infrared view on galaxies in the early Universe). A single pointing was taken in a region of the GOODS field centred on the coordinates \(\alpha = 29^h 0^m, -27^\circ 44\arcmin 28\arcsec\).

![Figure 1. Transmission curves of the Y and NB1060 filters used in this study](https://example.com/figure1.png)

**Table 1.** Filter statistics and image seeing.

| Filter     | \(\lambda_c\) (µm) | \(\Delta\lambda\) (µm) | Seeing (arcsec) | Exposure time (h:min:s) |
|------------|---------------------|------------------------|-----------------|------------------------|
| NB1060     | 1.0619              | 0.0104                 | 0.74            | 8:20:00                |
| Y          | 1.0193              | 0.1018                 | 0.57            | 1:10:30                |

Table 1 gives basic filter information, the average seeing of the images and the total exposure time in each filter.

## 2.2 Reduction and calibration

The observations are made up of a series of spatially offset (dithered) exposures, comprising \(141 \times 30\) s exposures in Y and \(100 \times 300\) s exposures in NB1060. 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 pipeline can be summarized as follows.

First, each exposure has its dark current and flat-field instrumental signature removed. The dark current was subtracted using a master dark image created from dark frames with the same exposure time as the image (about 100 dark frames were available per exposure time).

The images were then flat fielded to remove the pixel-to-pixel quantum efficiency variation as well as the large-scale vignetting profile. A master flat-field for each filter was formed from exposures of the twilight sky, which were scaled to bring them to a common median background and then combined using a mean combination algorithm with sigma-clipping (5σ). The telescope was moved slightly between each twilight flat exposure so that when twilight flat-field images are combined, any remaining astronomical objects are removed by the rejection algorithm.

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Any pedestal scalefactors between the individual detectors (due to differences in gain or average QE) were removed by normalizing the images by the ensemble median of the background flux.

Once the jittered exposures are dark and flat corrected, they are median combined to form a sky background image. The background images are normalized to a zero median so that the median background level in the corrected images is preserved. The background-corrected images from each jitter sequence are registered internally using visible sources and then shifted and combined.

A world coordinate system is added by fitting sources detected on the image to the 2MASS point-source catalogue. Finally, all the stacks are combined together to form a single deep stack for each filter.

The zero-point of the $Y$ images was determined by calibrating stellar counts on to ISAAC $J$ and $H$ images Retzlaff et al. (2010), using synthetic $J - H$ and $Y - J$ colours generated by Hewett et al. (2006) as reference. $Y - NB1060$ colours generated by the same synthetic codes were used to calibrate the NB1060 images on to the $Y$ band.

The images were then scaled to a common zero-point of 30.0 (AB), accurate to 0.1 magnitudes.

### 2.3 Cataloguing and photometry

The NB1060 and $Y$ images are registered using stellar point sources as a reference. Similarly, the images are PSF matched by smoothing the $Y$ image with a Gaussian kernel until the stellar FWHM values are equal to those measured in the NB1060 image. SOURCE EXTRACTOR (Bertin & Arnouts 1996) is then run on the NB1060 image to produce an NB1060-selected source catalogue. Extraction parameters are given in Table 2. We find slight deviations in the background of the order of a few per cent in the NB1060 detector 2 image. This appears to be due to radio active decay tracks created near the detector. For this reason, only for this detector, the background is determined by filtering over smaller areas to produce a more accurate local background for each object. The altered parameters are given in the final column of Table 2. Values were chosen to minimize the fluctuations in the background measured by SOURCE EXTRACTOR (assessed by outputting a ‘check image’ of type ‘BACKGROUND’).

For each object in the catalogue, two flux measurements are made: $Y - NB1060$ colour and total NB1060 flux. Circular apertures are used throughout. The size of each aperture is tuned to the size of the object as described in Labbé et al. (2003). The Labbé et al. scheme recommends different sized apertures for making colour and total flux measurements, including modifications for blended, extended and particularly compact objects. Colour measurements are made in circular apertures of diameter $D_{\text{col}} = 2(A_{\text{ISO}}/\sigma)^{1/2}$, where $A_{\text{ISO}}$ is the measured isophotal area within the detection isophote. Similarly, total flux measurements are made in apertures of diameter $D_{\text{TOT}} = 2(A_{\text{KRON}}/\sigma)^{1/2}$ where $A_{\text{KRON}}$ is the Kron area; the area of the ellipse defined by the Kron radius (see Kron 1980) (in SOURCE EXTRACTOR this is the area of the ‘AUTO’ aperture).

For colour measurements, the object is detected in the narrow-band and then equal-sized circular apertures are placed in the same position on both the NB1060 and $Y$ images, in an analogous way to using SOURCE EXTRACTOR in dual image mode. Colour measurements therefore have the same spatial origin.

Objects within $\sim 10$ arcsec of the edges of the stacks are removed due to the lower exposure time in these regions, leaving a survey area of 46.24 arcmin$^2$. Detections with an $S/N < 3.0$ in the narrow-band are additionally removed from the catalogue.

There are 2150 objects in the full catalogue. We find the $5\sigma$ NB1060 flux limit in a circular aperture, 10 pixels (1.06 arcsec) in diameter is $1.5 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ ($m_{\text{NB1060}} = 24.55$). To estimate the point source completion of the catalogue, we insert artificial point sources into the images using the IRAF program MKSOBJECT and extract them using SOURCE EXTRACTOR as described above. We find that the 90 per cent completeness limit of point sources in the NB1060 catalogue is $m_{\text{NB1060}} = 24.40 \pm 0.4$ (1.73 $\times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$).

### 3 EMISSION LINE GALAXY SELECTION

We expect ELGs to have excess NB1060 flux compared to the $Y$-band continuum. ELGs are therefore selected based on a clear flux excess in the narrow-band, i.e., $Y - NB1060 > 0$. An object is selected based on two criteria as follows.

The parameter $\Sigma$ (Bunker et al. 1995) is used to characterize the significance of the NB1060 excess compared to a flat spectrum, taking into account the noise properties of the images. For this work, the appropriate selection curve is given by

$$m_Y - m_{\text{NB}} = -2.5 \log_{10} \left[ 1 - \Sigma \times 10^{-0.4(30.0-m_{\text{NB}})/\sigma^2_{\text{NB}} + \sigma_Y^2} \right].$$

where $\sigma_{\text{NB}}$ and $\sigma_Y$ are the noise in the NB1060 and $Y$ images, respectively, and 30.0 is the scaled zero-point as described in Section 2.3.

We use a colour significance of $\Sigma = 3$ to select the ELG candidates (Bunker et al. 1995). This assures that the fraction of ordinary non-ELGs scattered into the sample due to noise is very low, $\sim 1$ in 1000 objects.

Secondly an observed equivalent width (EW$_{\text{obs}}$) criterion of EW > 50 Å is imposed, equivalent to a colour cut of

$$Y - NB1060 > 0.37.$$  

This corresponds to a rest-frame equivalent width of 17.5 Å for [O II] at $z = 1.85$.

Fig. 2 shows the colour magnitude selection diagram along with the $\Sigma = 3.0$ selection line (curved) and the equivalent-width criterion (solid horizontal line). Candidate ELGs are highlighted in

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**Table 2.** SOURCE EXTRACTOR parameters – NB1060 source catalogue.

| Parameter          | Unit | Value$^a$ | Value$^b$ |
|--------------------|------|-----------|-----------|
| DETECT_MINAREA     | pix  | 8         |           |
| DETECT_THRESH      | $\sigma$ | 1.5     |           |
| ANALYSIS_THRESH    | $\sigma$ | 1.5     |           |
| BACK_SIZE          | pix  | 64        | 15        |
| BACK_FILTERSIZE    | pix  | 5         | 3         |
| DEBLEND_NTHRESH    | ADU  | 32        |           |
| CLEAN              | $Y$   |           |           |
| CLEAN_PARAM        | $\text{arcsec pix}^{-1}$ | 2.0   | 0.1064    |

$^a$Parameters used for detectors 1, 3 and 4.

$^b$Changes made to standard parameter input for detector 2 to compensate for low-level background variations.
Table 3. Emission lines possibly detected in the NB1060 filter.

| Emission line | \( \lambda_{\text{rest}} \) (\( \mu \text{m} \)) | \( z \) | \( d_c \) (Mpc) | \( V_c \) (\( \text{er} \) \( \text{s}^{-1} \)) | \( \log(L_{\lambda_{\text{lim}}}^b) \) (\( \text{erg} \) s\(^{-1} \)) | SFR_{\lambda_{\text{lim}}}^b (\text{M}_\odot \text{yr}^{-1}) |
|---------------|-------------|---------|---------|----------------|----------------|----------------|
| H\( \alpha \) | 0.6563 | 0.62 | 0.016 | 950 | 40.38 | 0.19 |
| [O\( \text{II} \)] | 0.5007 | 1.12 | 0.021 | 2353 | 41.02 | |
| [O\( \text{III} \)] | 0.4959 | 1.14 | 0.021 | 2410 | 41.04 | |
| H\( \beta \) | 0.4861 | 1.18 | 0.021 | 2528 | 41.08 | |
| [O\( \text{I} \)] | 0.3727 | 1.85 | 0.028 | 4138 | 41.56 | |
| Ly\( \alpha \) | 0.1216 | 7.73 | 0.085 | 7977 | 43.04 | |

Note: \( \lambda_{\text{rest}} \) is the rest-frame wavelength, \( d_c \) is the comoving distance, \( V_c \) is the velocity, \( L_{\lambda_{\text{lim}}}^b \) is the luminosity, and SFR is the star formation rate.

3.1 Selection of [O\( \text{II} \)] emitters at \( z = 1.85 \)

The 58 NB selected ELGs are expected to be comprised of [O\( \text{II} \)] \( \lambda \lambda 3727, 3729 \), H\( \alpha \), [O\( \text{I} \)] \( \lambda \lambda 4959,5007 \) and H\( \beta \) emitters, along with a small fraction of redshift interlopers. The possible emission lines and their corresponding redshifts and volumes are given in Table 3.

We split the sample into composite line samples in two ways: (1) we use the spectroscopic and photometric redshifts reported in the GOODS MUSIC catalogue, version 2 (Santini et al. 2009); (2) we use galaxy evolution tracks in the colour–colour diagram \(-J, V-i\) to split the ELG sample into low- and high-redshift populations according to colour.

Photometric redshifts in the MUSIC catalogue are based on photometry in 15 bands spanning the optical to the far-infrared. We find good agreement between the 1697 spectroscopic redshift measurements in the catalogue and their equivalent photometric redshift estimates. Splitting the MUSIC measurements into low-redshift (\( z_{\text{phot}} < 1.5 \)) and high-redshift (\( z_{\text{phot}} > 1.5 \)) groups, we find that the median of the low-redshift group is \( z_{\text{phot}} = \langle z_{\text{phot}} - z_{\text{spec}} \rangle = -0.004 \) with a dispersion of \( \sigma_{\text{MAD}} = 0.072 \) (where \( \sigma_{\text{MAD}} \) is the standard deviation associated with the median absolute deviation of \( z_{\text{phot}} - z_{\text{spec}} \)) and equivalently for the high-redshift group, \( z_{\text{phot}} = \langle z_{\text{phot}} - z_{\text{spec}} \rangle = +0.05 \) with a dispersion of \( \sigma_{\text{MAD}} = 0.18 \).

Our catalogue is matched to GOODS MUSIC using a search radius of 0.5 arcsec. All but two candidates have MUSIC matches. Fig. 3 shows a histogram of the photometric redshift measurements (ZPHOT parameter in MUSIC) of candidate ELG galaxies. The histogram clearly shows three peaks corresponding to [O\( \text{II} \)] \( \lambda \lambda 3727 \) at \( z_{\text{phot}} \approx 2 \), H\( \alpha \) at \( z_{\text{phot}} \approx 0.6 \) and a merged peak at \( z_{\text{phot}} \approx 1 \) comprised of [O\( \text{III} \)] \( \lambda \lambda 4959,5007 \) and H\( \beta \) emitters. We discard five galaxies with \( z_{\text{phot}} < 0.3 \) or \( z_{\text{phot}} > 2.7 \) as redshift interlopers (~8 per cent of the sample), noting that one with a photometric redshift of 6.88 is likely to be a T-dwarf (Eyles et al. 2007). Gaussian curves are fitted individually to each population. Fit parameters are \( z_{\text{phot}},[O\text{II}] = 2.05 \pm 0.27 \) for the [O\( \text{II} \)] candidate population and \( z_{\text{phot}},H\alpha = 0.62 \pm 0.032 \) for the H\( \alpha \) population. The broader spread of the [O\( \text{II} \)] peak compared to the H\( \alpha \) reflects the reduced accuracy of the photometric redshifts at a high redshift.

For the second diagnostic, we calculate galaxy evolution tracks in \( z - J, V-i \) colour space using the photometric redshift code detailed in Banerji et al. (2010). Galaxy types E, Sbc and Scd are modelled using the average observed spectra of Coleman, Wu & Weedman (1980). In addition we use the observed starburst model (SB2) from Kinney et al. (1996) and a synthetic spectrum of a galaxy with an instantaneous 50-Myr starburst, generated using the PEGASE code (Fioc & Rocca-Volmerange 1997).
emitter.

ζ = 0.6, showing 1.85, indicating where [OII] emitters are expected to lie in the diagram. Similarly, the red line joins points at z = 0.6, showing where Hα emitters are expected to lie and the green lines join points at z = 1.12, 1.14 and 1.18 corresponding to [OII] λλ4959,5007 and Hβ. Candidate emitters are colour coded according to their photometric redshifts as in Fig. 3 with [OII] candidates in blue, [OIII] and Hβ in green and Hα in red. Asterisks indicate spectroscopically confirmed candidates (Santini et al. 2009).

Each model is redshifted in steps of 0.01 producing tracks from z = 0.6 (the lowest redshift, Hα emitters) to z = 1.85 (the highest redshift, [OII] 3727 emitters).

In Fig. 4, the evolutionary tracks are indicated by black lines, where (from top to bottom) the elliptical track is shown in the dotted line, type Sbc in dashed, Scd in dash–dotted, the 50-Myr starburst model in long-dash and the starburst (SB2) model in the solid line. Joining up the points on the tracks at the redshift of each line emitter in the filter delineates where each population of line emitters is expected to lie in the colour–colour space. The blue line joins points at z = 1.85, indicating where [OII] 3727 emitters are expected to lie. Similarly, the red line joins points at z = 0.63 corresponding to Hα and lines joining points at z = 1.12, 1.14 and 1.18 are shown in green corresponding to [OII] λλ4959,5007 and Hβ (top to bottom, respectively).

We use z − J, V − i photometry from the MUSIC catalogue to overplot the ELGs. The ELGs in the sample, indicated by circles, are blue in z − J, V − i; consistent with them being star-forming galaxies. The candidates clearly split into two regions in colour space, the lower layer attributed to [OII] objects and the upper to a combination of Hα, Hβ and [OIII] emitters.

Final classifications, taking both colour and photometric redshift into account, are colour coded on the figure with objects classified as [OII] shown in blue (26 objects), Hα in red (14 objects) and Hβ or [OIII] objects in green (13 objects). One object has a photometric redshift, placing it as an [OII] or Hβ emitter, yet appears in the [OII] stream in Fig. 4. Upon visual inspection, this object appears to be blended with a neighbouring object in the image which may be affecting the measurements and we therefore discard it from the sample. 10 objects have good-quality spectroscopic redshifts and these are indicated in the figure with asterisks.

Overall, there is a good agreement between the track, photometric redshift and spectroscopic classifications. When the zphot classification is taken into consideration, objects in Fig. 4 clearly split into three classes, with [OII] and Hβ emitters bluer than Hα in V − i.

Four objects are left unclassified: two with no MUSIC match and a further two with partial entries in MUSIC, not including JHK or photometric redshift measurements. These are classified using B − i, V − z colours in the same manner as in Fig. 4. For the two objects with no MUSIC data, colours are determined from ACS cutouts generated by the MAST cutout tool and the documented zero-points for the ACS images. On the basis of the positions of these objects in B − i, V − z space, three were classified as [OII] emitters and the remaining object was classified as either an [OII] or an Hβ emitter.

We checked that the sample was uncontaminated by stars by visually inspecting each object and additionally ensuring that none of the objects was flagged as a star in the MUSIC catalogue. None of the objects were flagged as AGN in MUSIC and none of our objects matched the Chandra Deep Field-South: 2Ms Source Catalogue (Luo et al. 2008), suggesting that the sample is uncontaminated by AGN as well.

In summary, of 58 initial ELG candidates, 53 were identified as genuine ELGs. Our final [OII] emitter sample contains 26 objects.

4 THE OBSERVED LUMINOSITY FUNCTION

The observed luminosity function is calculated in four stages as follows. In Section 4.2, the luminosity function is computed under the simplifying assumption that the NB1060 filter is a perfect top hat function with a width equal to the FWHM of the real filter. In Section 4.3 we investigate the completeness limit of the survey. In Section 4.4 we fit a Schechter function to the complete region of the luminosity function and finally in Section 4.5, simulations are undertaken to scale the luminosity function to take into account the real filter shape and produce the corrected observed luminosity function.

4.1 Line fluxes and [OII] luminosities

The narrow-band contains both line and continuum emission. We correct for continuum emission using the Y flux density. Given that the NB1060 and Y bands overlap, the appropriate equation for the line flux is given by

$$f_l = \frac{f_{NB1060} - \epsilon f_Y}{1 - \epsilon}. \quad (3)$$

where $f_{NB1060}$ and $f_Y$ are the total fluxes in the narrow and broad-band filters and $\epsilon$ is the ratio of the widths of the narrow- and broad-band filters (in this survey $\epsilon = 0.102$).

Assuming that all objects in the [OII] sample lie at the centre of the filter at z = 1.85 and that the luminosity distance $d_L = 4.36 \times 10^{28}$ cm, the observed [OII] line luminosities are

$$L_{[O\text{II}]} = 4\pi d_L^2 f_l. \quad (4)$$

NB1060 and Y magnitudes, along with the line fluxes and line luminosities for the sample of 26 [OII] emitters, are given in Table 4.
4.2 Fixed-volume luminosity function

The luminosity function is initially calculated by assuming the NB1060 filter is a perfect top hat function. Under this approximation, all objects are visible through the FWHM of the filter, leading to a constant survey volume. Additionally, we assume that the filter is sufficiently narrow such that it has uniform sensitivity to line strengths throughout the full filter width (i.e. moving an object of fixed intrinsic line luminosity across the redshift range defined by the filter will not significantly alter its observed line flux.)

For clarity, the resulting binned luminosity function is referred to as the ‘fixed-volume’ luminosity function, given by the relation

$$\phi(\log L([\text{O} \, \text{II}])) = \frac{1}{\Delta[\log L([\text{O} \, \text{II}])]} \frac{N_i}{V_r},$$

where $V_r$ is the fixed comoving volume probed by the filter, $\Delta[\log L([\text{O} \, \text{II}])]$ is the binwidth and $N_i$ is the number of galaxies with $[\text{O} \, \text{II}]$ luminosity in the range $\log L([\text{O} \, \text{II}]) \pm 0.5 \sigma_L$. When assuming a top-hat filter function, $V_r$ is fixed to the volume defined by the FWHM of the NB1060 filter (0.0104 μm.) With a survey area of 46.24 arcmin$^2$, at $z = 1.85$ the survey covers a comoving volume of $V_r = 4138$ Mpc$^{-3}$. The fixed-volume luminosity function is tabulated in Table 5.

### Table 5. The fixed-volume luminosity function.

| $\log L([\text{O} \, \text{II}])$ (erg s$^{-1}$) | $\log \phi$ (log $L^{-1}$ Mpc$^{-3}$) | Galaxy counts |
|-----------------|-----------------|----------------|
| 41.34 | −2.22 | 5  |
| 41.54 | −2.22 | 5  |
| 41.74 | −2.14 | 6  |
| 41.94 | −2.14 | 6  |
| 42.14 | −2.44 | 3  |
| 42.34 | −2.92 | 1  |

4.3 Sample completeness

4.3.1 Detection limit

By using the NB1060 image as the detection image (SOURCE EXTRACTOR in Dual Image Mode), it is not necessary for an object to be detected in the $Y$ band for it to be included in the sample. In principle, therefore, the survey is sensitive to objects with infinitely high equivalent width lines.

Given that objects are detected solely in the narrow-band, the limiting line flux is closely linked to the NB1060 detection limit. The detection limit and detection efficiency are explored by introducing synthetic populations of objects into the images using the IRAF package MIRFAC. These are then recovered using the detection...
techniques described in Section 2.3. The detection completeness is the percentage of input objects that are successfully extracted from the images.

As expected for high-redshift populations, the real [\text{O ii}] emitters are not well resolved in the HAWK-I images. The average morphology of the [\text{O ii}] emitters (measured from the HAWK-I stacked image) is approximated by an exponential disc with scalelength $r_s = 2.5$ arcsec. Due to the high redshift of the objects and the low resolution, we find the average profile to be representative of the [\text{O ii}] population as a whole. For this reason, the simulations were limited to a single input profile.

Batches of 100 objects were introduced into the NB1060 image with continuum magnitudes 18–27 in steps of 0.2 mag. Source EXTRACTOR was run on the images using the detection parameters given in Table 2 and the detection rate was measured. The results of the simulations can be seen in Fig. 5, which shows how the detection efficiency of the [\text{O ii}] emitter profile varies with input narrow-band magnitude. The figure indicates that for the [\text{O ii}] emitter profile, the survey is 90 per cent complete to magnitude 24.2 [cf. 90 per cent completeness to magnitude 24.4 for point sources (Section 2.3)].

**4.3.2 Line flux completion**

Whilst sensitive to high equivalent widths, the equivalent-width threshold applied in the selection procedure in Section 3 results in objects with EW$_{\text{obs}} < 50$ Å (equivalent to EW$_{\text{rest}} = 17.5$ Å) being omitted from the survey.

Fig. 6 shows the selection diagram. Objects above the $\Sigma = 3$ selection line are highlighted in bold. ELGs that are potentially missed by the EW$_{\text{obs}} > 50$ Å threshold lie between the curved and solid red lines. Of the objects falling in this category, we find that most of them are either stars (highlighted in orange asterisks) or spectroscopically confirmed redshift interlopers (red crosses). Such a high proportion of confirmed redshift interlopers indicates that the equivalent-width threshold chosen in this study is largely robust.

Of the remaining objects, only five have MUSIC photometric redshifts that could lead to them being classified as [\text{O ii}] emitters; these are denoted by blue diamonds. We assess the significance of this group of omitted objects by overplotting lines of constant [\text{O ii}] line luminosity, representing the edges of the bins of the fixed-volume luminosity function in Table 5. For a bin to be complete, all objects between the lines of constant-line luminosity corresponding to the edges of the bin must be selected. For example, for the bin centre on log($L$) = 41.74 erg s$^{-1}$ to be complete, all objects between the lines log($L_{[\text{O ii}]}$) = 41.64 erg s$^{-1}$ and log($L_{[\text{O ii}]}$) = 41.84 erg s$^{-1}$ must be selected.

It can be seen that three of the five potential [\text{O ii}] candidates below the equivalent-width threshold have colours placing them in the two lowest luminosity bins in the fixed-volume luminosity function. These bins both lie fainter than the 90 per cent detection limit of $m_{\text{NB1060}} = 24.2$ defined in Section 4.3.1. The two lowest luminosity bins in the study are therefore incomplete due to a combination of detection and selection incompleteness.

The small number of possible [\text{O ii}] emitters falling in brighter bins leads us to conclude that we do not lose a significant fraction of emitters using this EW criterion.

Furthermore, completeness simulations (using the [\text{O ii}] profile described in Section 4.3.1) show a recovery rate greater than 90 per cent for [\text{O ii}] emitters with $Y$-band continuum magnitudes fainter than magnitude 23 and lines brighter than log($L_{[\text{O ii}]}$) = 41.74. This recovery rate rapidly drops off for fainter lines. These results, together with those presented in Fig. 6, lead us to conclude that an appropriate completeness limit for the study is the minimum luminosity, log($L_{\text{min}}$) = 41.74 erg s$^{-1}$.

![Figure 5. Detection completeness as a function of magnitude for synthetic galaxies modelled with the average [O ii] emitter profile, an exponential disc with $r_s = 2.5$ arcsec.](image)

![Figure 6. Same as Fig. 2, overlaid with lines of constant line luminosity, labelled logarithmically. The luminosities chosen represent the edges of the bins used to create the fixed-volume luminosity function in Table 5. A bin is complete if all the objects between the bin edges are included in the sample. Candidate [O ii] emitters are highlighted in blue, stars are indicated by orange asterisks and objects with redshifts placing them out of range of the filter range are shown in red.](image)
4.4 Schechter fit

The fixed-volume luminosity function is fit with a Schechter function (Schechter 1976) of the form

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

To compute an appropriate Schechter function for the bright end of the luminosity function, a range of faint end slopes are assumed. For comparability, we vary \(\alpha\) over the same range as that assumed by Zhu et al. (2009) in their [O\,\text{II}] survey at 0.75 < \(z\) < 1.45: \(\alpha = -1.3 \pm 0.2\). For comparison, Takahashi et al. (2007) measured the faint-end slope of the [O\,\text{II}] luminosity function at \(z = 1.2\) in two fields finding \(\alpha = -1.41_{-0.15}^{+0.16}\) and \(-1.38_{-0.37}^{+0.40}\).

In Section 5, we look at how the luminosity function evolves from \(z = 1.2\) to 1.85. We emphasize that the range of \(\alpha\) assumed here has a minimal effect as this analysis is restricted to the bright portion of the luminosity function that is well fit, regardless of the assumed faint-end slope.

We fit the [O\,\text{II}] luminosity function at \(L > L_{\text{min}}\) with a Schechter function, assuming \(\alpha = -1.3 \pm 0.2\), using the maximum likelihood parametric fit method (Sandage, Tammann & Yahil 1979). The resulting best-fitting parameters are \(\log(L^\ast) = 42.00 \pm 0.06\) erg s\(^{-1}\) and \(\log(\phi^\ast) = -2.21 \pm 0.09\) Mpc\(^{-3}\). We note that increasing \(L_{\text{min}}\) produces fits within these errors but lowering \(L_{\text{min}}\) quickly departs from them, indicating that \(\log(L_{\text{min}}) = 41.74\text{ erg s}^{-1}\) is an appropriate completeness limit for the survey.

4.5 Filter correction

The fitted fixed-volume luminosity function is scaled to take into account the effects of filter shape. There are two considerations as follows.

(i) Flux loss due to filter transmission: ELGs with [O\,\text{II}] lines that fall in the filter wings have lower observed line fluxes due to the poor transmission. When computing the luminosity function, this results in a proportion of line objects systematically moving into fainter bins.

(ii) Variation of volume with line strength: Whilst a relatively faint emission line in the filter wings may fall below the detection threshold, a bright line will still be detectable. Brighter lines are therefore detectable over a wider filter width and correspondingly over a wider redshift range and a larger volume.

Simulations were run to quantify these effects. We considered a volume large enough to fully encompass the filter volume, including the filter wings. The volume was populated with objects with density and flux distributions according to a trial input luminosity function. We assumed the objects were homogeneously distributed with respect to redshift. The filter profile was then used to recover the observed simulated object luminosities. Different values of input \(\phi^\ast\) and \(L^\ast\) were iterated through until the output of the simulation matched the observed [O\,\text{II}] luminosity distribution.

The simulations indicate that the intrinsic observed luminosity function, assuming \(\alpha = -1.3 \pm 0.2\) is best-fitted with Schechter parameters of \(\log(L^\ast) = 42.05 \pm 0.06\) erg s\(^{-1}\) and \(\log(\phi^\ast) = -2.23 \pm 0.09\) Mpc\(^{-3}\).

Fig. 7 shows the observed [O\,\text{II}] luminosity function found in this study alongside the observed luminosity functions of equivalent [O\,\text{II}] studies at \(z = 1.2\). Black triangles show our binned luminosity function, calculated assuming a constant filter volume. The luminosity above which the survey is estimated to be complete (\(L_{\text{lim}}\)) is indicated by the vertical dotted line and the two bins that are significantly incomplete are highlighted as lower limits. The best-fitting Schechter function to the complete portion of the luminosity function is indicated with the black dashed line. The final observed filter-corrected luminosity function is shown in the solid black line. The HAWK-I limiting luminosity is indicated by the vertical dotted line. The observed luminosity functions reported by Takahashi et al. (2007) are shown in green, that of (Zhu et al. 2009) in blue and the Schechter fit of Ly et al. (2007) is shown in red. Note that none of the luminosity functions shown here has been corrected for obscuration.

5 EVOLUTION OF THE [O\,\text{II}] LUMINOSITY FUNCTION

Fig. 7 suggests the observed [O\,\text{II}] luminosity function evolves between redshift 1.2 and 1.85. To quantify this evolution, we compute the number density of [O\,\text{II}] emitters at a range of redshifts. We concentrate on the integrated number density of objects in the luminosity range in which our luminosity function is robust: \(\log(L_{\text{OII}}) > 41.74\text{ erg s}^{-1}\).

We find the number density of objects in the luminosity range \(\log(L_{\text{OII}}) > 41.74\text{ erg s}^{-1}\) at \(z = 1.85\) in this survey is \(\log(\rho_{\text{OII}} L_{\text{OII}}; 41.74) = -2.45 \pm 0.14\) Mpc\(^{-3}\). Fig. 8 shows this result alongside the equivalent number densities of Zhu et al. (2009) (\(z = 0.84, 1.00, 1.19\) and 1.35) in blue squares, Ly et al. (2007) (\(z = 0.91\) in red diamonds, and Takahashi et al. (2007) (\(z = 1.2\) in green squares).
and 1.18 in diamonds and Takahashi et al. (2007) (z = 1.2) in red crosses. Our measurement is indicated by the red triangle.

We fit the points (all but the two outliers) with a line, \( \log(\Phi[\log(L_{[O\alpha]} > 41.74, z)] = mz + c \), finding \( m = 0.69 \pm 0.089 \) and \( c = -3.72 \pm 0.11 \), this is over-plotted in green on the figure, along with the \( \pm \sigma \) fits. We find that the space density (\( \rho \)) of bright objects at \( z = 1.85 \) in the luminosity range \( \log(L_{[O\alpha]}) > 41.74 \) erg s\(^{-1}\) is a factor of 2 greater than the observed space density of \([O\alpha]\) emitters reported at \( z \sim 1.4 \); a comparable increase to that reported between \( z = 1.0 \) and 1.4.

### 6 THE STAR FORMATION RATE AT \( z = 1.85 \)

Two assumptions have to be made to convert the \([O\alpha]\) luminosity function found in this work into an SFR density: (i) the \([O\alpha]\) luminosities have to be corrected for internal extinction and (ii) a calibration has to be assumed between \([O\alpha]\) luminosity and SFR.

In Section 6.1 we explore the use of a ‘common’ obscuration correction to make the results comparable to the compilation of SFR measurements made by Hopkins (2004). In Section 6.2 we extend the analysis and independently estimate the extinction correction using a 24-\(\mu\)m flux and discuss the appropriate \([O\alpha]/H\alpha\) ratio.

#### 6.1 Common obscuration correction

Hopkins (2004) provides a compilation of SFR measurements made using a range of SFR indicators, corrected according to a common framework. In order to compare the measurement made here to the Hopkins compilation, we convert our luminosity density to SFR according to this common framework.

The first step towards computing the SFR is to calculate the total \([O\alpha]\) luminosity density, \( L_{[O\alpha]} \), at \( z = 1.85 \) by integrating the Schechter function:

\[
L_{[O\alpha]} = \int_0^{L_{[O\alpha]}} \Phi(L) L \, dL = \Phi^* L^* \Gamma(\alpha + 2),
\]

where \( \Gamma \) represents the gamma function.

Hopkins converts the \([O\alpha]\) luminosity density to \( H\alpha \) assuming \( L_{[O\alpha]}/L_{H\alpha,\text{obs}} = 0.45 \). The inferred \( H\alpha \) luminosity is then corrected for internal extinction, assuming \( A_{H\alpha} = 1.0 \) mag. Note that \( A_{H\alpha} = 1.0 \) mag corresponds to \( A_{[O\alpha]} = 1.86 \) using the O’Donnell (1994) galactic obscuration curve (\( R_e = 3.1 \)). Finally, \( L_{H\alpha,\text{corr}} \) is converted into an SFR density (SFRD) using the calibration of Kennicutt (1998):

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

The \([O\alpha]\) luminosity function derived in this work, corrected for filter effects [Schechter parameters: \( \alpha = -1.3 \pm 0.2, \log(L^*) = 42.05 \pm 0.06 \text{ erg s}^{-1}\) and \( \log(\phi^*) = -2.23 \pm 0.09 \text{ Mpc}^{-3} \)], implies an \([O\alpha]\) luminosity density of \( \log(L_{[O\alpha]}) = 39.93 \pm 0.08 \text{ erg s}^{-1} \). Accounting for \( A_{H\alpha} = 1 \) mag, this implies a SFRD of \( \rho_S = 0.38 \pm 0.06 \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3} \).

This result is plotted in red in Fig. 9, alongside other SFRD measurements derived from \([O\alpha]\) and corrected using the ‘common’ scheme at lower redshifts.

Whilst the application of a common obscuration correction is helpful for comparison with published literature (see Hopkins, 2004), it is an oversimplification. A more rigorous analysis can be carried out by measuring the obscuration directly. This is calculated and discussed in detail in Section 6.2. The final SFRD calculated in Section 6.2 is shown for completeness in orange in Fig. 9.

#### 6.2 Independent measure of \( A_{[O\alpha]} \) and \([O\alpha]/H\alpha\)

To independently estimate \( A_{[O\alpha]} \) for our sample, we look to the far-infrared. Kennicutt et al. (2009, hereafter K09) developed a set of empirical calibrations converting \([O\alpha]\) line luminosities into SFRs using 8, 24-\(\mu\)m or total infrared (TIR) fluxes as a tracer for the dust emission. They consider two samples of \( z = 0 \) galaxies; the Spitzer infrared nearby galaxies survey (SINGS) sample of 75 local galaxies with distances less than 30 Mpc, presented in Kennicutt et al. (2003) and 417 galaxies from the survey of integrated spectrophotometry described in Moustakas & Kennicutt (2006, hereafter MK06). The samples were selected to be representative of the wide range of morphologies, luminosities and dust opacities seen in the

---

**Figure 8.** Evolution of the observed \([O\alpha]\) luminosity function: evolution of the total number of bright objects per Mpc\(^{-3}\) in the luminosity range \( \log(L_{[O\alpha]}) > 41.74 \). The dashed lines indicate the best and \( \pm \sigma \) fits given by the equation \( \log(\Phi[\log(L_{[O\alpha]}) > 41.74, z]) = mz + c \).

**Figure 9.** A compilation of SFR measurements using the \([O\alpha]\) line, assuming a constant obscuration correction, \( A_{H\alpha} = 1 \) mag. \([O\alpha]\) measurements from the compilation of Hopkins (2004) are shown in grey, overlaid with the measurements of Hippelein et al. (2003) (purple), Takahashi et al. (2007) (green) and Zhu et al. (2009) (blue). The red triangle shows the result from this work corrected using the same ‘common’ correction as applied to the lower redshift points (\( A_{H\alpha} = 1 \) mag). The orange triangle shows the same result, this time corrected using \( A_{[O\alpha]} = 0.98 \) mag (\( A_{H\alpha} = 0.52 \)), the mean obscuration of the \( z = 1.85 \) sample inferred from 24-\(\mu\)m fluxes (see Section 6.2).

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present-day galaxies. The combined sample includes objects ranging from dwarf irregulars to giant spirals and IR-luminous galaxies. Full details can be found in the respective survey papers. For these local galaxy samples, they find that the corrected [O\textsc{ii}] luminosity density is given by
\[
L[\text{O\textsc{ii}}]_{\text{cor}} = L[\text{O\textsc{ii}}]_{\text{obs}} + 0.016 L(8 \mu \text{m}),
\]
implying
\[
A_{\text{[O\textsc{ii}]}_{\text{cor}}} = 2.5 \log \left[ 1 + \frac{0.016 L(8 \mu \text{m})_{\text{obs}}}{L[\text{O\textsc{ii}}]_{\text{obs}}} \right].
\]

For galaxies at the redshift of this survey, 8-\mu m flux is redshifted to \sim 24 \mu m. Using the 24 \mu m fluxes from the MUSIC catalogue, we calculate values of \( A_{\text{[O\textsc{ii}]}_{\text{cor}}} \) for our sample. MUSIC contains measurements for 24 of the 26 [O\textsc{ii}] emitters in the survey, 16 of which are upper limits.

To compare our results with galaxies at \( z = 0 \), we derive the [O\textsc{ii}] obscuration values for the K09 and MK06 samples using the stellar-absorption-corrected H\alpha/H\beta ratios quoted in K09 and MK06. The ratios are converted to [O\textsc{ii}] obscurations using the same assumptions as detailed in K09; namely we assume an intrinsic H\alpha/H\beta ratio for Case B recombination of \( I(\text{H}\alpha)/I(\text{H}\beta) = 2.86 \) (electron temperature \( T_e = 10 000 \text{ K} \) and density \( N_e = 100 \text{ cm}^{-3} \)). The observed reddenings are then converted to [O\textsc{ii}] attenuation values (via H\alpha) using the O’Donnell (1994) extinction law, assuming \( R_V = 3.1 \).

Fig. 10(a) shows the distribution of \( A_{\text{[O\textsc{ii}]}_{\text{cor}}} \) with respect to the uncorrected [O\textsc{ii}] luminosity. The \( z = 0 \) SINGS and MK06 samples are shown in crosses and diamonds, respectively. The \( z = 1.85 \) results from this work are overplotted in blue triangles. For the \( z = 1.85 \) objects in our sample, values of \( A_{\text{[O\textsc{ii}]}_{\text{cor}}} \) derived from upper limits are indicated with arrows and the eight values of \( A_{\text{[O\textsc{ii}]}_{\text{cor}}} \) derived from positive detections at 24 \mu m are highlighted with squares for clarity.

Although the \( z = 0 \) measurements of \( A_{\text{[O\textsc{ii}]}_{\text{cor}}} \) have a large dispersion, we find no evidence for a systematic variation of \( A_{\text{[O\textsc{ii}]}_{\text{cor}}} \) with the observed [O\textsc{ii}] luminosity. The mean of measurements with \( \log(L_{\text{[O\textsc{ii}]}_{\text{obs}}}) > 40.0 \) is \( A_{\text{[O\textsc{ii}]}_{\text{cor}} = 1.59 \pm 0.07 \text{ mag} \) with a dispersion of 0.8. Bifurcating the sample into \( 40.0 < \log(L_{\text{[O\textsc{ii}]}_{\text{obs}}}) < 41.0 \) and \( 41.0 < \log(L_{\text{[O\textsc{ii}]}_{\text{obs}}}) < 42.0 \) yields mean values of \( A_{\text{[O\textsc{ii}]}_{\text{cor}} = 1.42 \pm 0.1 \) and \( A_{\text{[O\textsc{ii}]}_{\text{cor}} = 1.80 \pm 0.10 \) (dispersions of 0.8 and 0.7 mag) for the fainter and brighter samples, respectively, consistent with no luminosity dependence. The mean values of each sample are indicated by the red solid lines in Fig. 10 and the red dotted lines indicate the error on the mean in each case.

Our galaxy sample at \( z = 1.85 \), however, has systematically lower levels of \( A_{\text{[O\textsc{ii}]}_{\text{cor}}} \) than the local Universe galaxies, with a mean \( A_{\text{[O\textsc{ii}]}_{\text{cor}} = 0.98 \pm 0.11 \text{ mag} \) and dispersion of 0.6 mag. This corresponds to \( A_{\text{H\alpha}} = 0.52 \) [O’Donnell (1994) extinction curve assuming \( R_V = 3.1 \)].

Selection effects may bias this result. For any given intrinsic luminosity, the survey is biased towards selecting objects with low obscuration: objects with high obscuration values may have observed [O\textsc{ii}] fluxes that fall below the selection threshold of the survey. To investigate the effect this would have on the measured mean \( A_{\text{[O\textsc{ii}]}} \) value, we replotted Fig. 10(a), correcting the observed luminosities for extinction using the measured obscuration corrections, this is shown in panel (b) of Fig. 10. The green line shows the maximum detectable value of \( A_{\text{[O\textsc{ii}]}} \) as a function of corrected luminosity. The mean obscuration of the SINGS and MK06 samples is 0.8 mag. Bifurcating the sample into 40 \text{ mag} with a dispersion of 0.6 mag. This corresponds to \( A_{\text{H\alpha}} = 0.52 \) [O’Donnell (1994) extinction curve assuming \( R_V = 3.1 \)].

Selection effects may bias this result. For any given intrinsic luminosity, the survey is biased towards selecting objects with low obscuration: objects with high obscuration values may have observed [O\textsc{ii}] fluxes that fall below the selection threshold of the survey. To investigate the effect this would have on the measured mean \( A_{\text{[O\textsc{ii}]}} \) value, we replotted Fig. 10(a), correcting the observed luminosities for extinction using the measured obscuration corrections, this is shown in panel (b) of Fig. 10. The green line shows the maximum detectable value of \( A_{\text{[O\textsc{ii}]}} \) as a function of corrected luminosity. The mean obscuration of the SINGS and MK06 samples is 0.8 mag. Bifurcating the sample into 40

Figure 10. (a) [O\textsc{ii}] extinction with respect to observed [O\textsc{ii}] luminosity for galaxy samples at \( z = 0 \) (MK06 and SINGS samples shown in diamonds and crosses, respectively) and \( z = 1.85 \) (HAWK-I shown with blue triangles). 16 of the 24 \( A_{\text{[O\textsc{ii}]}} \) at \( z = 1.85 \) were calculated from upper limit measurements of the 24-\mu m flux (indicated by the arrows). The eight measurements made from positive detections at 24 \mu m are highlighted with squares for clarity. Red and Blue solid lines indicate the mean \( A_{\text{[O\textsc{ii}]}} \) values of the combined MK06 and SINGS sample and the Hawk-1 sample respectively. Dotted lines indicate the error on the mean in each case. (b) [O\textsc{ii}] extinction with respect to obscuration-corrected [O\textsc{ii}] luminosity, where a correction has been made according to the measured obscuration values. The green line shows the maximum obscuration with respect to intrinsic luminosity that could be selected in our sample.
galaxies with observed [O II] fluxes brighter than the Hawk-I selection threshold is A([O II]) = 1.68, whereas the mean of all objects with log L([O II]) > 41.5 = 1.90. Therefore, applying the Hawk-I selection bias to the z = 0 sample would result in a ~12 per cent drop in the mean A([O II]) value. It is possible that this selection limit imposes more than the locally inferred 12 per cent bias on the z = 1.85 sample if a greater proportion of star formation is dust enshrouded at high redshift. This cannot be ruled out on the basis of the present study, although it is worth noting that we found no evidence for a population of bright, dust-enshrouded [O II] emitters (Section 4.3.2). Adopting the mean value of A([O II]) at z = 1.85 (A([O II]) = 0.98 ± 0.11, A(Ha) = 0.52) yields a SFRD of 0.24 ± 0.06 M⊙ yr⁻¹ Mpc⁻³. This is plotted in orange in Fig. 9. We have indicated this result as a lower limit to reflect the fact that a proportion of dusty [O II] emitters may be omitted from the sample due to the selection criteria.

In the above analysis we have assumed the widely used [O II]/Hα ratio of 0.45 (Kennicutt 1992, 1998). However, local surveys have suggested that the [O II]/Hα ratio is luminosity dependent (Jansen, Franx & Fabricant 2001) as well as dependent on metallicity and obscuration (Kewley et al. 2004). Hopkins et al. (2003) noted higher [O II]/Hα ratios in higher equivalent width systems. For a complete sample of 752 SDSS galaxies, they found [O II]/Hα = 0.23 but that this rose to 0.46 if an EW limit of EW(Hα) > 70 Å was imposed.

Applying the Jansen et al. (2001) empirical relation between rest-frame absolute B-band magnitudes and the [O II]/Hα ratio to our galaxy sample, we find a mean absolute B-band magnitude of B_B = −20.1 mag (J = 24.5 mag), corresponding to [O II]/Hα = 0.48 with an rms dispersion of 0.1. This is very close to the value (0.45) that we have assumed, and would result in a SFRD of 0.23 ± 0.06 M⊙ yr⁻¹ Mpc⁻³.

The discussion above highlights that the ‘common’ obscuration correction is an oversimplification of the problem. Upon measuring the obscuration of the objects we find a mean obscuration of A([O II]) = 0.98 mag (A(Ha) = 0.52), rather than A(Ha) = 1 as assumed in the common framework. However, given that we also find that a proportion of dusty emitters are omitted from the sample, the SFRD measurement based on the measured obscuration correction is likely to be a lower limit. It is reasonable to expect that the reality may be somewhere between the two measurements. Deeper data would enable this to be explored in more detail.

7 SUMMARY AND CONCLUSIONS

This study has used Science Verification Data from the ESO instrument HAWK-I to perform a high-redshift survey for [O II] emitters in the GOODS field. The [O II] λ3727 doublet is of particular interest to SFRD surveys in that it is visible to z ~ 5 in the near-infrared, compared to the z ~ 2.5 limit of Hα surveys. Recent advances in the calibration of the [O II] λ3727 doublet (see e.g. Kennicutt et al. 2009) have made it possible to use [O II] with greatly improved precision, facilitating homogeneous measurements of the SFRD of the Universe to be measured from z = 0 to z = 5 for the first time. At z = 1.85, this is the highest redshift [O II] survey to date. We have identified 26 [O II] emitters in a volume of 4138 Mpc³, to a 5σ flux limit of 1.5 × 10⁻¹⁷ erg cm⁻² s⁻¹. Our findings can be summarized as follows.

(i) The observed [O II] luminosity function at z = 1.85 can be fit by a Schechter function with log(L*) = 42.05 ± 0.06 erg s⁻¹ and log(φ*) = −2.23 ± 0.09 Mpc⁻³, assuming α = −1.3 ± 0.2; a representative range of high-z faint-end slopes, including the value reported by Takahashi et al. (2007) at z = 1.2. This range was also assumed by Zhu et al. (2009) in their survey of z = 1.2 [O II] emitters.

(ii) The space density (ρ) of bright [log(L([O II])obs) > 41.74] [O II] emitters at z = 1.85 is log(ρ) = −2.45 ± 0.14 Mpc⁻³, a factor of 2 greater than the observed space density of [O II] emitters reported at z ~ 1.4. This increase is comparable to that reported between z = 1.0 and 1.4 and we find that the [O II] number density evolution of objects in the range L([O II])obs > 41.74 can be fit by the function, log(ρ([log(L([O II])obs) > 41.74, z]] = m + c, finding m = 0.69 ± 0.089 and c = −3.72 ± 0.11.

(iii) We convert the [O II] fluxes into a SFRD using the ‘common’ extinction correction (A(Hα) = 1.0) and [O II]/Hα ratio (O II)/Hα = 0.45) employed by Hopkins (2004), finding a SFRD at z = 1.85 of ρs = 0.38 ± 0.06 M⊙ yr⁻¹. When compared to other reported values of the SFRD, calculated using the [O II] emission line and the ‘common’ conversion, our work suggests a three-fold increase in the SFRD between z = 1.4 and 1.85.

(iv) We independently estimate A([O II]) for each object using a rest-frame 8-µm flux (observed 24 µm) and the empirical calibrations of Kennicutt et al. (2009). The results indicate that the [O II] emitters we detect contain low levels of dust – the mean extinction of the sample being A([O II]) = 0.98 ± 0.11 with a dispersion of 0.6 (equivalent to A(Hα) = 0.52). This is almost half the value measured at z = 0.

(v) The possible explanations of the low dust content are as follows. (a) Selection effects: the survey could be missing bright, dusty [O II] emitters due to the equivalent-width threshold applied to the sample. This is unlikely as we find no evidence to indicate that the survey misses bright objects with low equivalent widths (Section 4.3.2). We do find, however, that selecting objects above a fixed observed [O II] flux threshold may account for some of the difference between our A([O II]) measurement at z = 1.85 and other measurements made at z = 0. This is because objects with high levels of obscuration fall below the observed [O II] flux threshold leading to an underestimation of the true value. We estimate that this bias results in an underestimation of the true mean by at least ~12 per cent. However, without deeper data, it is unclear whether the bias alone could account for the full (~50 per cent) reduction in dust obscuration which is seen between the z = 1.85 and unbiased z = 0 samples. (b) Cosmic Variance: the survey is relatively small L = 2.45 and other samples. (c) Reddening law: the K09 empirical calibration is likely to be a lower limit. It is reasonable to expect that the reality may be somewhere between the two measurements. Deeper data would enable this to be explored in more detail.

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