Boötes-HiZELS: an optical to near-infrared survey of emission-line galaxies at $z = 0.4$–$4.7$

Jorryt Matthee,1,* David Sobral,2,1 Philip Best,3 Ian Smail,4 Fuyan Bian,5† Behnam Darvish,6 Huub Röttgering1 and Xiaohui Fan7

1Leiden Observatory, Leiden University, PO Box 9513, NL-2300 RA Leiden, the Netherlands
2Department of Physics, Lancaster University, Lancaster LA1 4YB, UK
3Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
4Centre for Extragalactic Astronomy, Department of Physics, Durham University, South Road, Durham DH1 3LE, UK
5Research School of Astronomy & Astrophysics, Mt Stromlo Observatory, Australian National University, Weston Creek, ACT 2611, Australia
6Cahill Center for Astrophysics, California Institute of Technology, 1216 East California Boulevard, Pasadena, CA 91125, USA
7Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA

Accepted 2017 June 20. Received 2017 June 16; in original form 2017 February 12

ABSTRACT

We present a sample of $\sim$1000 emission-line galaxies at $z = 0.4$–$4.7$ from the $\sim$0.7deg$^2$ High-$z$ Emission-Line Survey in the Boötes field identified with a suite of six narrow-band filters at $\approx 0.4$–$2.1$ μm. These galaxies have been selected on their Ly$\alpha$ (73), [O ii] (285), H$\beta$/[O iii] (387) or H$\alpha$ (362) emission line, and have been classified with optical to near-infrared colours. A subsample of 98 sources have reliable redshifts from multiple narrow-band (e.g. [O ii]–H$\alpha$) detections and/or spectroscopy. In this survey paper, we present the observations, selection and catalogues of emitters. We measure number densities of Ly$\alpha$, [O ii], H$\beta$/[O iii] and H$\alpha$ and confirm strong luminosity evolution in star-forming galaxies from $z \sim 0.4$ to $\sim 5$, in agreement with previous results. To demonstrate the usefulness of dual-line emitters, we use the sample of dual [O ii]–H$\alpha$ emitters to measure the observed [O ii]/H$\alpha$ ratio at $z = 1.47$. The observed [O ii]/H$\alpha$ ratio increases significantly from 0.40 ± 0.01 at $z = 0.1$ to 0.52 ± 0.05 at $z = 1.47$, which we attribute to either decreasing dust attenuation with redshift, or due to a bias in the (typically) fibre measurements in the local Universe that only measure the central kpc regions. At the bright end, we find that both the H$\alpha$ and Ly$\alpha$ number densities at $z \approx 2.2$ deviate significantly from a Schechter form, following a power law. We show that this is driven entirely by an increasing X-ray/active galactic nucleus fraction with line luminosity, which reaches $\approx 100$ per cent at line luminosities $L \gtrsim 3 \times 10^{44}$ erg s$^{-1}$.

Key words: galaxies: active – galaxies: evolution – galaxies: high-redshift – galaxies: luminosity function, mass function – galaxies: star formation.

1 INTRODUCTION

Understanding how and when galaxies grow their stellar mass and in some cases eventually stop forming stars are key goals of galaxy formation theory. However, since it is only possible to observe an individual galaxy at a single epoch, to assess their evolution it is crucial to homogeneously select equivalent samples of galaxies over a wide redshift range. Currently, different epochs in cosmic time are probed by different selections of galaxies. Moreover, the galaxy properties (such as star formation rates and estimates of dust attenuation) are measured with different tracers (e.g. Speagle et al. 2014). Therefore, it is important to understand whether local calibrations can be extrapolated to high redshift. This requires large samples of galaxies with a well understood selection function and a large dynamic range in galaxy properties.

Homogeneously selected samples of star-forming galaxies can be obtained with narrow-band (NB) surveys that are very efficient in selecting emission-line galaxies. Using different NBs, galaxies can be selected on a particular emission line across a range of redshifts with well-defined line-luminosity and equivalent width (EW) limits. For example, in specific windows from the optical to the near-infrared, ground-based NB surveys can select H$\alpha$, [O ii] and [O iii] emission-line galaxies up to $z \approx 2.6$ (e.g. Bunker et al. 1995; Malkan, Teplitz & McLean 1996; van der Werf, Moorwood & Bremer 2000;...
Ly et al. 2007; Geach et al. 2008; Tadaki et al. 2011; Lee et al. 2012; Drake et al. 2013; Sobral et al. 2013, 2015; Stroe & Sobral 2015). The Hα combination-line is a reliable tracer of star-formation rate on > 10 Myr time-scales (Kennicutt 1998) and is less sensitive to attenuation due to dust than other shorter wavelength tracers (e.g. Garn et al. 2010; Ibar et al. 2013; Stott et al. 2013). At redshifts z > 2.5, the most commonly used rest-optical emission lines are challenging to observe (but see e.g. Khostovan et al. 2015), while the rest-frame UV Lyman-α (Ly α) line, intrinsically the strongest emission line emitted in Hα regions is efficiently observed up to z ≈ 7 (e.g. Rhoads et al. 2000; Dawson et al. 2007; Ouchi et al. 2008; Lee et al. 2014; Matthee et al. 2015; Santos, Sobral & Matthee 2016), but is extremely sensitive to resonant scattering and dust attenuation (e.g. Hayes 2015).

Our High-z Emission-Line Survey (HiZELS; Geach et al. 2008; Best et al. 2013; Sobral et al. 2013) has been designed to observe multiple emission lines in different NBs simultaneously. Hence, Sobral et al. (2012) used observations with NB921 at ≈920 nm and NBH at ≈1620 nm to jointly observe [O III]λλ3727, 3729 and Hα at z = 1.47. At z = 2.2, matched NB surveys have observed (combinations of) Ly α+[O II]λλ392, 411 and [O III]λλ4959, 5007+Hα at z = 2.2 (Lee et al. 2012; Nakajima et al. 2012; Oteo et al. 2015; Matthee et al. 2016; Sobral et al. 2017). One of the advantages of this dual- (or multiple) NB technique is that identification of the specific emission line is secure, such that dual-emitters may be used to fine-tune colour selection criteria (in particular in fields where only limited multwave-length data are available). Another advantage is that various star formation rate (SFR) estimators, for example [O II] or (to lesser extent) Ly α, can be calibrated with joint Hα observations.

Here, we present the first results from Boötes-HiZELS, which is a survey of a central 0.7 deg$^2$ region in the Boötes field with a suite of six narrow-band filters, split into two sets: three red filters at ≈921, 1620 and 2120 nm from HiZELS that select rest-optical lines such as Hα,1 H β/[O III]$^2$ and [O II], complemented by three blue filters at ≈392, 411 and 501 nm that select Ly α emitters (LAEs). Using these narrow-band filters, we select samples of emission-line galaxies using their H α line at z = 0.4–2.2 and z = 0.8–4.7 with H β/[O III], [O II] and Ly α. These samples are used as targets for ongoing detailed spectroscopic follow-up studies.

This paper presents the selection and classification of line-emitters, their global properties such as number densities, the number of dual-NB emitters and X-ray detections. We compare our number densities to published luminosity functions (LFs) for samples in the range z ≈ 0.4–4.7 and we study [O III]–Hα emitters at z = 1.47. These emitters can be used to measure whether the observed [O III]/Hα ratio changes with redshift (e.g. Hayashi et al. 2013), which is essential for studies employing [O II] as a SFR indicator at z > 1 (e.g. Ly et al. 2012). We also use the available deep X-ray coverage to study the X-ray fractions of line-emitters.

We present the observations and archival data used in this survey in Section 2. The data reduction, characteristics and catalogue production and selection of emitters are presented in Section 3. Section 4 presents our procedure for classifying emission-line galaxies. We present the number densities of classed line-emitters and compare these to published LFs in Section 5. In Section 6, we investigate the properties of dual-NB line-emitters, the observed [O II]/Hα ratio at z = 1.47 and the X-ray fractions of Hα emitters (HAEs) and LAEs. Finally, Section 7 presents our conclusions.

We adopt a Λ cold dark matter (ΛCDM) cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$. Magnitudes are in the AB system measured in 3 arcsec apertures, unless noted otherwise.

## 2 OBSERVATIONS AND DATA

We observed a 0.7 deg$^2$ region in the Boötes field with six narrow-band filters (NB392, stV, NB501, NB921, NBH and NBs). The Boötes field was chosen for the availability of deep multwave-length data (see e.g. Lee et al. 2011; Bian et al. 2012, 2013; Beare et al. 2015) over a relatively large area, avoiding the galactic plane and its observability from La Palma and Hawaii. In addition to publicly available broad-band (BB) imaging in the U, B, R, I, J and K bands (described in Section 2.1), we also obtain the missing wave-length coverage with three broad-band filters g, z and H (see Table 1 for an overview).

### 2.1 Public/archival multwave-length data

The Boötes field has been imaged in the optical by the NOAO Deep Wide Field survey$^3$ in Bw, R and I (Jannuzi & Dey 1999) and by the LBT Boötes Field Survey in the U and Y bands (Bian et al. 2013). Near-infrared data in the J, H and Ks bands are available from the Infrared Boötes Imaging Survey (Gonzalez et al. 2010), although we do not use the H-band data as our data are deeper. The general characteristics of the archival data used in this paper are listed in Table 1. In addition, the field has been imaged in the X-ray by Chandra (Murray et al. 2005), in the UV by the GALEX Deep Imaging Survey (Martin et al. 2005), in the mid-infrared by Spitzer/IRAC (Ashby et al. 2009) and in the far-infrared by Herschel as part of the Herschel Multi-tiered Extragalactic Survey (Oliver et al. 2012). However, the X-ray, UV and mid- and far-infrared data are not explicitly used in the selection of line-emitters. In addition, Williams et al. (2016) presented deep low-frequency (150 MHz) radio observations in this field. Finally, spectroscopic follow-up of mostly X-ray-selected sources [and hence active galactic nucleus (AGN)] has been performed by Kochanek et al. (2012).

### 2.2 Optical observations

Optical observations in two narrow-band filters (NB392, NB501), a medium band filter (stV) and the g band were performed with the Wide Field Camera (WFC) on the 2.5-m Isaac Newton Telescope, part of the Roque de los Muchachos Observatory on the island of La Palma, Spain. WFC has a mosaic of four CCDs with a combined field of view of 0.3 deg$^2$ and a 0.33 arcsec pixel scale (see Table 1). The survey was designed with four pointings, each with a

---

1 We note that narrow-band Hα measurements measure the line-flux and EW of the combined Hα and [N II] doublet depending on the precise redshift. Therefore, a correction needs to be applied to measure Hα EWs and line-fluxes. For simplicity, we refer to Hα + [N II] emitters as Hα emitters from now on.

2 Typical photometric redshifts are not accurate enough to distinguish between H β line-emitters and a line-emitter with one of the [O III] lines. Moreover, depending on the specific redshift, we either detect H β, or one or two of the [O III] lines in the narrow-band filter. The majority of H β/[O III] emitters are [O III]λ5007 emitters, as this line is typically the stronger line [see Sobral et al. (2015) and Khostovan et al. (2015) for details]. Yet, to remind the reader of these caveats, we call these emitters H β/[O III] emitters throughout the paper.

3 http://noao.edu/noao/noaodeep/
Table 1. Description of the available (archival and new) multiwavelength data in Boötes-HiZELS, with narrow-band filters highlighted in bold. The abbreviations for the archival surveys are: LBFS – LBT Boötes Field Survey (Bian et al. 2013); NDWFS – NOAO Deep Wide Field Survey (Jannuzi & Dey 1999); IBIS – Infrared Bootes Imaging Survey (Gonzalez et al. 2010). $\lambda_c$ is the central wavelength of the filter and $\Delta \lambda$ is the width between the filter’s full width–maximum.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Telescope</th>
<th>Survey</th>
<th>$\lambda_c$ (nm)</th>
<th>$\Delta \lambda$ (nm)</th>
<th>FWHM (arcsec)</th>
<th>Exposure time (ks)</th>
<th>Dates</th>
<th>Depth (3σ, AB)</th>
<th>Coverage (deg$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U$</td>
<td>INT</td>
<td>This survey</td>
<td>359</td>
<td>54</td>
<td>1.2</td>
<td>12.4 ± 2.0</td>
<td>2013 June 6–10; 2014 February 27, March 1–8, 27</td>
<td>25.3 ± 0.78</td>
<td>0.54</td>
</tr>
<tr>
<td>NB392</td>
<td>INT</td>
<td>This survey</td>
<td>392</td>
<td>5.2</td>
<td>1.8</td>
<td>12.4 ± 2.0</td>
<td>2013 June 6–10; 2014 February 27, March 1–8, 27</td>
<td>24.3 ± 0.78</td>
<td>0.54</td>
</tr>
<tr>
<td>$B_k$</td>
<td>Mayall</td>
<td>NDWFS</td>
<td>464</td>
<td>110</td>
<td>1.4</td>
<td>3.8 ± 0.8</td>
<td>2013 June 6–10; 2014 March 5–7; 2016 June 11–13</td>
<td>25.4 ± 0.78</td>
<td>0.63</td>
</tr>
<tr>
<td>stV</td>
<td>INT</td>
<td>This survey</td>
<td>410</td>
<td>16</td>
<td>1.9</td>
<td>6.0 ± 0.0</td>
<td>2016 June 6–8</td>
<td>24.9 ± 0.78</td>
<td>0.82</td>
</tr>
<tr>
<td>$g$</td>
<td>INT</td>
<td>This survey</td>
<td>485</td>
<td>129</td>
<td>1.6</td>
<td>8.4 ± 0.1</td>
<td>2015 April 11, 12, 16, 17; 2016 June 5–7, 10, 12</td>
<td>24.7 ± 0.74</td>
<td>0.74</td>
</tr>
<tr>
<td>$R$</td>
<td>Mayall</td>
<td>NDWFS</td>
<td>602</td>
<td>160</td>
<td>1.1</td>
<td>1.0–2.1</td>
<td>2014 May 28, 29</td>
<td>24.3 ± 0.76</td>
<td>0.76</td>
</tr>
<tr>
<td>$I$</td>
<td>Mayall</td>
<td>NDWFS</td>
<td>754</td>
<td>170</td>
<td>1.1</td>
<td>2.16–2.52</td>
<td>2014 May 28, 29</td>
<td>24.0 ± 0.46</td>
<td>0.78</td>
</tr>
<tr>
<td>$z$</td>
<td>Subaru</td>
<td>This survey</td>
<td>878</td>
<td>113</td>
<td>0.8</td>
<td>1.0–2.1</td>
<td>2014 May 28, 29</td>
<td>23.1 ± 0.78</td>
<td>0.78</td>
</tr>
<tr>
<td>NB921</td>
<td>Subaru</td>
<td>This survey</td>
<td>919</td>
<td>13</td>
<td>0.8</td>
<td>1.0–2.1</td>
<td>2010 April 2–8</td>
<td>22.9 ± 0.78</td>
<td>0.78</td>
</tr>
<tr>
<td>$Y$</td>
<td>LBT</td>
<td>LBFS</td>
<td>984</td>
<td>42</td>
<td>0.8</td>
<td>1.0–2.1</td>
<td>2010 April 2–8</td>
<td>22.6 ± 0.78</td>
<td>0.78</td>
</tr>
<tr>
<td>$J$</td>
<td>NEWFIRM</td>
<td>IBIS</td>
<td>1300</td>
<td>190</td>
<td>1.0</td>
<td>1.2 ± 0.1</td>
<td>2010 April 2–6</td>
<td>22.1 ± 0.74</td>
<td>0.74</td>
</tr>
<tr>
<td>$H$</td>
<td>UKIRT</td>
<td>This survey</td>
<td>1600</td>
<td>200</td>
<td>0.8</td>
<td>1.5 ± 1.4</td>
<td>2010 April 2–6</td>
<td>22.1 ± 0.74</td>
<td>0.74</td>
</tr>
<tr>
<td>NBH</td>
<td>UKIRT</td>
<td>This survey</td>
<td>1620</td>
<td>21</td>
<td>0.8</td>
<td>1.0–2.1</td>
<td>2010 April 2–6</td>
<td>22.1 ± 0.74</td>
<td>0.74</td>
</tr>
<tr>
<td>$K$</td>
<td>NEWFIRM</td>
<td>IBIS</td>
<td>2260</td>
<td>280</td>
<td>1.2</td>
<td>20.2 ± 0.0</td>
<td>2010 April 8, 9, 14, July 18–23, 2011 February 16, 27, 28, March 9, 12, 16, 20, 22–26</td>
<td>22.3 ± 0.73</td>
<td>0.73</td>
</tr>
</tbody>
</table>

C-NE-NW-SE-SW dither pattern (with 30 arcsec offsets). Individual exposure times for narrow and medium-bands were either 0.2 or 1.0 ks, depending on whether the telescope could successfully guide on a star (since the auto-guider CCD is behind the filter, this is challenging for narrow-band filters in extragalactic fields) and the stability of the weather. The individual exposure times for the $g$ band were 0.6 ks.

Observations in the NB921 narrow-band filter and the $z$ filter were performed with Suprime-Cam (S-cam) on the 8.0-m Subaru telescope of the National Astronomical Observatory of Japan. S-cam consists of a mosaic of 10 CCDs with a combined field of view of 0.255 deg$^2$ with a 0.2-arcsec pixel scale. We imaged the field in the $z$ (NB921) filter with five (three) pointings. For NB921, we used individual 360-s exposures dithered either seven (two pointings) or six (one pointing) times. For $z$, we used individual 150-s exposures of the same pointings as NB921 dithered 14 times, and 3 times 100-s exposures in the other two pointings. Observations were done sequentially to avoid contamination of the emission-line sample by variable sources and/or supernova (i.e. Matthee et al. 2014).

2.3 Near-infrared observations

Near-infrared observations in $H$, NBH and NBK were performed with WFCAM on the UK Infrared Telescope (UKIRT) on Mauna Kea as part of the HiZELS (e.g. Sobral et al. 2013). WFCAM has a ‘paw-print’ configuration of four CCDs, with a total field of view of 0.21 deg$^2$ and a 0.4-arcsec pixel scale. The field was imaged with four pointings in a dither sequence of 14 exposures with small offsets. Due to the high sky background in the near-infrared, the individual exposure times were 10 s, 100 s and 60 s for $H$, NBH and NBK, respectively, to avoid saturation. In order to obtain the final depth, this dither sequence was typically repeated 9, 11 and 24 times for the respective filters.

3 DATA REDUCTION AND CATALOGUE PRODUCTION

3.1 Data reduction

3.1.1 Optical

We reduce data from the INT/WFC with a custom-made pipeline based on Python described in detail in Stroe et al. (2014) and Sobral et al. (2017) and we reduce Subaru/S-Cam data similarly with SUPFRED2 (Ouchi et al. 2004). In summary, we first bias subtract individual frames using a master bias from the median stack of bias frames for the corresponding night. We then create a master flat by median combining twilight flats and use it to flat-field the individual frames. Subsequently, we measure the full width half-maximum (FWHM) of the point spread function (PSF) using unsaturated stars in individually reduced frames with SExtractor (Bertin & Arnouts 1996), and reject frames with PSF FWHM above the chosen target FWHM listed in Table 1. This is particularly important for some exposures with the INT/WFC that have been observed in poor conditions. We then match the PSF of remaining frames before combining frames to the common mosaic by smoothing the images with a Gaussian kernel.

3.1.2 Near-infrared

Near-infrared data from UKIRT/WFCAM have been reduced using PHiZELS [see Sobral et al. (2009) and Sobral et al. (2013) for further details]. We use a kernel-based method to combine exposures, with a PSF kernel for each band produced with the FRED2 (Ouchi et al. 2004) package, with a median stack of bias frames used as the zero exposure value. We then co-add exposures individually, and produce a master flat and combine frames using the PSF kernel. We then combine individual frames, and use the PSF kernel to flat-field the individual frames. Finally, we measure the FWHM of the PSF using unsaturated stars in individually reduced frames with SExtractor (Bertin & Arnouts 1996), and reject frames with PSF FWHM above the chosen target FWHM listed in Table 1. This is particularly important for some exposures with the INT/WFC that have been observed in poor conditions. We then match the PSF of remaining frames before combining frames to the common mosaic by smoothing the images with a Gaussian kernel.
full details). The steps are similar to the steps in the optical data reduction, except for dark subtraction instead of bias subtraction and the master flat that is based on an iterative self-flat method using the science frames themselves, instead of relying on twilight flats (see Sobral et al. 2013).

3.1.3 Astrometric alignment

The reduced frames are astrometrically registered to the 2-Micron All-Sky Survey (2MASS) point source catalogue (Skrutskie et al. 2006) with SCAMP (Bertin 2006). Frames are then co-added, resampled to a pixel scale of 0.33 arcsec and mapped to the Mosaic pointing with SWARP (Bertin 2010). We apply the same method for public data described in Section 2.1.

While extracting initial catalogues, we encountered significant astrometric distortions of up to 1.2 arcsec in the edges of the cameras of the public $B$, $R$ and $I$ data. These distortions significantly affect dual-mode photometry (described in Section 3.2.1). In order to obtain a more accurate astrometric solution for these data, we used the SCAMP software to remap the images to the SDSS DR7 to obtain a more accurate astrometric solution for these data, we used the SCAMP software to remap the images to the SDSS DR7.

3.1.4 Photometric calibration

We set the photometric zero-point (ZP) of the images to an arbitrary common ZP = 30 by matching the MAG-AUTO photometry in the combined images to the following available data: $g$ and $z$ are calibrated to SDSS and $H$ and $K$ to 2MASS. We then use the broad-bands available to calibrate the narrow-bands in the two following steps: first, we calibrated NB921 to $z$, NB91 and NBK are calibrated to $H$ and $K$, NB392 to $g$ from SDSS, and NB392 and stV to $B$ (after this first step, we have to correct for the fact that most narrow-band central wavelengths are not in the centre wavelength of the broad-band filters, which leads to a bias in line-flux measurements due to gradients in the continuum. This can be resolved by using colour information in adjacent broad-bands. For NB921, NB91 and NBK, we follow the corrections described in Sobral et al. (2013) and for NB392 we use the corrections from Matthee et al. (2016). We derive the following correction for stV: $\text{stV}_{\text{cor}} = 0.23(U - B_w) + 0.24$. For sources undetected in $U$ and $B_w$, we apply the median correction of +0.04. We do not apply a correction for NB501, as it is close to the centre of the $g$ band.

3.2 Catalogue production

3.2.1 Photometry

Photometry of the optical-NIR filters listed in Table 1 is performed with SExtractor in dual-image mode. We create six catalogues, each with one of the six narrow-bands as detection image. Photometry is measured within circular apertures with a diameter of 3 arcsec. For each narrow-band, we measure the narrow-band and the corresponding broad-band magnitudes from images with their PSF matched to the narrow-band imaging. We also measure the magnitudes in all broad-bands with their PSF matched to the g-band PSF (1.6 arcsec FWHM). The measurements with the PSF from the NB are used to select line-emitters and compute emission-line properties such as line-flux and EW. The other measurements are used for colour–colour selections.

We have produced a mask for each narrow-band individually, where we mask regions around bright, saturated stars, CCD bleeding, cross-talk in near-infrared detectors and regions with low signal-to-noise ratio (S/N) or incomplete coverage (e.g. Sobral et al. 2009; Santos et al. 2016).

3.2.2 Depths

We estimate the depth of images by measuring the standard deviation of the total counts in 100 000 apertures with a diameter of 3 arcsec placed at random (but avoiding sources) locations in our images. $\sigma$ depths range from $\sim 25$ AB magnitude in blue broad-band filters to $\sim 22$ AB magnitude in the near-infrared filters (see Table 1).

3.3 Selecting line-emitters

Line-emitters are selected based on two criteria: the narrow-band excess (the EW) must be high enough and the excess must be significant. For the narrow-band filters NB9392, stV, NB501, NB921, NBH and NBK, we use the corresponding broad-band filters $U$, $B$, $g$, $z$, $H$ and $K$. In order to convert the photometric narrow-band excess to observed EW, we convert magnitudes ($m_i$) to flux densities in each filter ($f_i$) with the standard AB magnitude convention:

$$f_i = \frac{c}{\lambda_{i,\text{centre}}} 10^{-0.4(m_i+48.6)} ,$$

where $c$ is the speed of light and $\lambda_{i,\text{centre}}$ is the central wavelength in each filter. Next, we use the following equations to convert the narrow-band and their corresponding broad-bands to EW:

$$\text{EW}_{\text{obs}} = \Delta\lambda_{\text{NB}} \frac{f_{\text{NB}} - f_{\text{BB}}}{f_{\text{BB}} - f_{\text{BB}} / \Delta\lambda_{\text{BB}}} .$$

Here, $f_{\text{NB}}$ and $f_{\text{BB}}$ are the flux densities in the narrow-band and broad-band and $\Delta\lambda_{\text{NB}}$ and $\Delta\lambda_{\text{BB}}$ the filter widths. In equation (2), the numerator is the difference in narrow-band and broad-band flux and the denominator is the continuum level, corrected for the contribution from the flux in the narrow-band. For sources without broad-band detection, we set the EW to a lower limit. This lower limit ranges from 550 Å for NB392 and NB501 to 2500 Å for stV depending on the width of the NB filter and the depth of the BB data used to measure the continuum. The lower limit is around $\sim 1200$ Å for near-infrared NBs.

The excess significance ($\Sigma$) quantifies whether a certain narrow-band excess is due to errors in the narrow-band and broad-band photometry or not. Hence, we follow the methodology presented in Bunker et al. (1995) and the equation from Sobral et al. (2013) to compute $\Sigma$:

$$\Sigma = \frac{1 - 10^{-0.4(BB-NB)}}{10^{-0.4(BB-NB)} \sqrt{\sigma_{\text{box,BB}}^2 + \sigma_{\text{box,NB}}^2}} ,$$

where BB is the broad-band magnitude used for the continuum estimate, NB is the narrow-band magnitude and ZP is the zero-point of the images. $\sigma_{\text{box}}$ is the root mean squared (rms) of background aperture values in the data of the respective filters (see Section 3.2.2).

The line-flux is computed using

$$f_{\text{line}} = \Delta\lambda_{\text{NB}} \frac{f_{\text{NB}} - f_{\text{BB}}}{1 - f_{\text{BB}} / \Delta\lambda_{\text{BB}}} .$$

We select line-emitters amongst narrow-band selected sources in all six narrow-band filters with the criterion that $\Sigma > 3$. However,
because each narrow-band has different filter characteristics, we do not apply a homogeneous excess (EW) selection threshold. For each filter, we apply the criterion that the observed EW is three times the standard scatter in observed EWs for sources detected at $>15\sigma$. This means that we apply EW $>30$, $130$, $50$, $30$, $85$, $80$ Å for NB392, stV, NB921, NB$\alpha$, NB$\beta$, and NB$\kappa$, respectively.

Before obtaining our final list of line-emitters, in each filter, we visually inspect all the sources in the narrow-band images for remaining spurious sources such as artefacts from bright stars, cosmic rays or misidentifications by SExtractor. This can happen when the noise properties vary strongly locally, which is the case in small regions of the coverage by the NB392, stV and NB921 filters.

Figure 1 shows the redshift ranges where our narrow-band filters sample the brightest emission lines seen in normal star-forming galaxies and AGN. By a combination of design and coincidence, the HiZELS narrow-band filters coincide with several different emissions and AGN. By a combination of design and coincidence, the brightest emission lines seen in normal star-forming galaxies.

4 CLASSIFYING LINE-EMITTERS

Fig. 1 shows the redshift ranges where our narrow-band filters sample the brightest emission lines seen in normal star-forming galaxies and AGN. By a combination of design and coincidence, the HiZELS narrow-band filters coincide with several different emission lines at specific redshifts. At $z = 1.47$, the NB921/NB$\beta$ combination is sensitive to the [O ii] and H$\alpha$ lines (Sobral et al. 2012). At $z = 2.23$, the Ly$\alpha$, [O iii] and H$\alpha$ lines fall in the NB392/NB$\beta$/NB$\kappa$ combination. At $z = 2.23$, the NB921 filter is also sensitive to C IV emission. The redshifts of line-emitters detected in several narrow-bands (dual-emitters) can be estimated accurately and we refer to them as $z_{\text{dualNB}}$ in the remainder of this paper. As can be seen in Table C1, dual-emitters are found as faint as $\sigma \approx 25$, three magnitudes fainter than typical available spectroscopic redshifts, which were mostly for X-ray-selected sources.

Line-emitters that have no existing spectroscopic redshift or are not detected as dual-emitters are classified using colour–colour selections tuned to identify Lyman and Balmer breaks at various redshift intervals. For the blue narrow-bands, we use colour selections to identify Ly$\alpha$ emitters. For the red filters, we use colour selections to identify H$\alpha$ emitters, H $\beta$/[O iii] emitters and [O ii] emitters (see also similar selections in Sobral et al. 2013; Khostovan et al. 2015).

The main strategy to devise colour criteria has been as follows: after removing stars (due to atmospheric features in the blue or the near-infrared, stars may be picked up with a narrow-band excess) using their uJk colours (e.g. Muzzin et al. 2013), we start with colour selections from the literature, which we slightly modify using the spectroscopically confirmed line-emitters and the dual-emitters.

Colour criteria are stated explicitly below and listed in Table 3. We summarize the number of emitters and classified line-emitters in Table 4.

4.1 Line-emitters in NB392

The narrow-band NB392 has specifically been designed to conduct a Ly$\alpha$ survey with a matched volume coverage to H$\alpha$ emitters identified with the HiZELS NB$\beta$ filter (H$\alpha$S1) at $z = 2.23$ in order to study the Ly$\alpha$ escape fraction and its dependencies on galaxy properties, as described in detail in Matthee et al. (2016) and Sobral et al. (2017).

We select 57 line-emitters with an excess criterion of EW$_{\text{obs}} > 30$ Å ($U$-NB392 $>0.45$). For LAEs at $z = 2.23$, this corresponds to EW$_{\text{obs}} > 9$ Å (it is possible to go to such low EWs because the width of NB392 is very narrow). Although Ly$\alpha$ surveys at $z \approx 2$–3 typically invoke a higher EW criterion of $\sim25$–$30$ Å (e.g. Ouchi et al. 2008; Nakajima et al. 2012), we found that such a selection results in missing the most luminous LAEs at $z = 2.2$ in the COSMOS and Ultra Deep Survey (UDS) fields (Sobral et al. 2017). This is because these sources are typically AGN, which have bright Ly$\alpha$ emission on the top of a bright UV continuum.

Using the spectroscopy available from AGES (Kochanek et al. 2012), we find eight Mg ii emitters at $z > 0.4$ and five line-emitters at $z > 1$ (including two LAEs at $z = 2.2$) (see Table 2). By matching the sample of line-emitters with the samples of line-emitters in NB$\beta$ and NB$\kappa$ (see below), we add four other robust...
LAEs at $z = 2.2$. Other line-emitters are classed using the criteria described in Table 3. We spectroscopically identify four interlopers ($\sim 15\pm 7$ per cent contamination, similar to the $10\pm 4$ per cent from Sobral et al. 2017). These comprise two C IV emitters at $z = 1.53$ and two AGN for which we measure Lyman-Werner and Lyman-Continuum radiation in the NB392 filter at $z = 3.16$ and $z = 3.57$. We also identify two dual-emitters that are missed by the colour–colour selection (see Fig. B1). This results in a final sample of 25 LAEs at $z = 2.2$.

4.2 Line-emitters in stV

The stV medium-band filter is used to identify LAEs at $z \approx 2.4$. Because the width of the filter is relatively broad, it is sensitive to line-emitters over a larger redshift space (and thus covers a larger volume), at the cost of being only sensitive to lines with high EW. We apply a selection criterion of $\text{EW}_{\text{obs}} > 130\,\text{Å}$ (which corresponds to $B_{\text{spec}} - \text{stV} > 0.54$). We note that due to the width of the filter, it is possible that multiple lines contribute to the observed EW and line-flux, such as the combination of Ly$\alpha + N\alpha$. It is therefore not straightforward to interpret measured EWs and line-fluxes and caution must be taken.

We find a total of 39 line-emitters, of which 15 have spectroscopic redshifts (see e.g. Table 2). As expected, these are not only dominated by LAEs at $z = 2.3$–2.45 but also contain high-ionization lines as C III] and C IV at $z \approx 1.1$–1.7. After removal of one spectroscopic contaminant (a CIV emitter at $z = 1.613$) selected with the colour criteria described in Table 3 and illustrated in Fig. B1, we obtain a sample of 16 LAEs.

4.3 Line-emitters in NB501

The NB501 filter is used to select Ly$\alpha$ emitters at $z = 3.1$. We apply $\text{EW}_{\text{obs}} > 50\,\text{Å}$ ($g - \text{NB501} > 0.45$), corresponding to a Ly$\alpha$ rest-frame EW of $> 12\,\text{Å}$.

We find a total of 65 line-emitters; of which only four have an archival spectroscopic redshift. This is because the majority of these line-emitters are faint with line-fluxes below $2 \times 10^{-16}\,\text{erg s}^{-1}\,\text{cm}^{-2}$. One spectroscopic confirmed line-emitter is a LAE, two are C IV emitters at $z = 2.24$ and $z = 2.26$ (these are the dual-emitters B-HiZELS_3 and B-HiZELS_15, Table C1, also detected as line-emitters in several other bands) and one is possibly [NeV] at $z = 0.426$.

LAEs are selected as relatively blue $U$ drop-outs (e.g. Hildebrandt et al. 2009) as described in Table 3 and illustrated in Fig. B2). One C IV emitter at $z = 2.24$ is misclassified as a LAE and is removed from the sample. This leads to a sample of 31 LAEs. We note that our EW criterion of $\text{EW}_{\text{obs}} > 12\,\text{Å}$ is somewhat lower than the typical criterion used for selections of LAEs ($\text{EW}_{\text{obs}} > 25\,\text{Å}$; e.g. Ouchi et al. 2008; Yamada et al. 2012). However, more than 90 per cent of the identified LAEs have $\text{EW}_{\text{obs}} > 25\,\text{Å}$. Contrary to the properties of LAEs at $z \sim 2$, the additional LAEs with low EW are all faint in their UV continuum. This indicates an evolution in the properties of luminous LAEs from $z = 2–3$, with an increasing Ly$\alpha$ EW with redshift at fixed Ly$\alpha$ luminosity. Very recently, four additional LAEs from this sample have been confirmed at $z = 3.1$ from our spectroscopic follow-up campaign (to be presented in Sobral et al., in preparation), including the brightest LAE in our sample with a Ly$\alpha$ luminosity of $\approx 10^{43.8}\,\text{erg s}^{-1}$ ($\sim 10 \times L_{\odot}$) at $z = 3.1$. Ouchi et al. (2008) in a 3 arcsec aperture and an $\text{EW}_{\text{obs}}$ of $\sim 150\,\text{Å}$. To the current surface brightness limit, it is extended over $\sim 5$ arcsec (40 kpc), and it may thus be classed a Ly$\alpha$ blob (e.g. Matsuda et al. 2004; Prescott et al. 2008; Dey et al. 2016). This follow-up spectroscopy also identifies two interlopers: a red [O II] emitter at $z = 0.35$ and a Mg II emitter at $z = 0.81$, which we have removed from the sample.

4.4 Line-emitters in NB921

While the NB921 filter has been used to select LAEs at $z = 6.6$ (e.g. Matthee et al. 2015), it is also used to select H$\alpha$, H$\beta$/[O III] and [O III] emitters at lower redshift (e.g. Ly et al. 2007; Drake et al. 2013; Sobral et al. 2013; Khostovan et al. 2015). We select 1161 line-emitters with the excess criterion of $\text{EW}_{\text{obs}} > 30\,\text{Å}$ (corresponding to $z< \text{NB921} > 0.3$).

As our sample of line-emitters is selected from relatively deep narrow-band imaging (compared to the other narrow-bands in this survey), it is dominated by sources with line-fluxes fainter than $2 \times 10^{-16}\,\text{erg s}^{-1}\,\text{cm}^{-2}$ ($\sim 94$ per cent of line-emitters), down to fluxes of $2 \times 10^{-17}\,\text{erg s}^{-1}\,\text{cm}^{-2}$. Because of this, the number of spectroscopic redshifts is limited to only seven, of which five are H$\alpha$ emitters at $z = 0.4$. However, the number of galaxies with a robust redshift due to emission lines in multiple narrow-bands is significantly higher (23) (see Table 2).

Amogst our sample of line-emitters, we use colour criteria (Fig. B3; based on Sobral et al. 2013) to identify H$\alpha$ emitters at $z = 0.40$, H$\beta$/[O III] emitters at $z = 0.83$ and [O III] emitters at $z = 1.47$ (see Table 3). We select 198 H$\alpha$ emitters, 304 H$\beta$/[O III] emitters and 277 [O III] emitters (see Table 4). Two Mg II emitters at $z = 2.26$ are misidentified as [O III] emitter, while one dual-emitter at $z = 1.47$ is misidentified as H$\beta$/[O III] emitters.
Table 3. Colour selection criteria used to classify line-emitters. These criteria are based on the expected positions of the Lyman and Balmer breaks [see for example the $BzK$ criterion from Daddi et al. (2004)]. These criteria are then fine tuned using spectroscopic and dual-NB redshifts. In comparison to traditional criteria that use the $B$ band, we adjust the $B_w$ magnitude for the contribution from flux in the $U$ band. For samples at $z > 2.4$, we also include a colour criterion that removes very red objects for which the Lyman-break criterion has selected a strong Balmer break [see also Xue et al. (2017)]. The colour–colour selections are illustrated in the figures in Appendix B.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Emission line</th>
<th>Colour criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB392</td>
<td>Ly $\alpha$ $z = 2.2$</td>
<td>$(2B_w - U) - z &lt; 0.2 + 0.7(z - K)$</td>
</tr>
<tr>
<td>stV</td>
<td>Ly $\alpha$ $z = 2.4$</td>
<td>$U - B_w &gt; 0.3(B_w - g) + 0.2$ &amp; $g - I &lt; 1$</td>
</tr>
<tr>
<td>NB501</td>
<td>Ly $\alpha$ $z = 3.1$</td>
<td>$U - g &gt; 1$ &amp; $g - I &lt; 1.5$</td>
</tr>
<tr>
<td>NB921</td>
<td>H $\alpha$ $z = 0.40$</td>
<td>$(2B_w - U) - I &gt; 0.4 + 0.4(Z - H)$ &amp; $B_w - R &gt; 1.5(R - I)$</td>
</tr>
<tr>
<td>[O~III]</td>
<td>$z = 0.80$</td>
<td>$(2B_w - U) - I &gt; 0.4 + 0.4(Z - H)$ &amp; $B_w - R &gt; 1.3(R - I)$</td>
</tr>
<tr>
<td>[O~III]</td>
<td>$z = 1.47$</td>
<td>$(2B_w - U) - I &lt; 0.4 + 0.4(Z - H)$</td>
</tr>
<tr>
<td>NBH</td>
<td>$z &gt; 1$</td>
<td>$(2B_w - U) - z &lt; 0.4 + 0.8(z - K)$ or $z - K &gt; 2$</td>
</tr>
<tr>
<td></td>
<td>H $\alpha$ $z = 1.47$</td>
<td>$z &gt; 1$ &amp; $J - K &lt; 2.1(I - J)$</td>
</tr>
<tr>
<td></td>
<td>[O~III]/H$\beta$ $z = 2.23$</td>
<td>$z &gt; 1$ &amp; $K - J &gt; 2.1(I - J)$</td>
</tr>
<tr>
<td></td>
<td>[O~III] $z = 3.3$</td>
<td>Not H $\alpha$ or [O~III]/H$\beta$ in NBH &amp; $U - g &gt; 1$ &amp; $g - I &lt; 1.5$</td>
</tr>
<tr>
<td>NBK</td>
<td>$z &gt; 1$</td>
<td>$(2B_w - U) - z &lt; (z - K) - 0.05$ or $z - K &gt; 2$</td>
</tr>
<tr>
<td></td>
<td>H $\alpha$ $z = 2.23$</td>
<td>$z &gt; 1$ &amp; $U - R &lt; 2$</td>
</tr>
<tr>
<td></td>
<td>[O~III]/H$\beta$ $z = 3.2$</td>
<td>$z &gt; 1$ &amp; $U - g &gt; 1$ &amp; $g - I &lt; 1.5$</td>
</tr>
<tr>
<td></td>
<td>[O~III] $z = 4.7$</td>
<td>Not H $\alpha$ or [O~III]/H$\beta$ in NBK &amp; $g - I &gt; 1.5$</td>
</tr>
</tbody>
</table>

Due to their faintness, 359 out of the 1161 line-emitters are not detected in a sufficient number of broad-bands required for classification and can thus not be classed. We expect that most of these sources are faint H $\alpha$, H $\beta$/[O~III] or [O~III] emitters. Based on the fraction of emitters in different classifications as a function of line-flux, we expect an increasing fraction of [O~III] emitters at low line-fluxes (see also Sobral et al. 2012). As illustrated in the left-hand panel of Fig. 2, the majority of sources indeed has $B_w - R$ colours similar to [O~III] emitters (but could not be classed due to their faintness in other broad-band filters). We discuss this ‘identification incompleteness’ further in Section 5.1.3.

4.5 Line-emitters in NBH

We select line-emitters detected in the NBH filter with a narrow-band excess of EW $> 85$ Å (corresponding to H $\alpha$ – NBH $> 0.3$). Since the near-infrared detectors of UKIRT/WFCAM contain significant amounts of cross-talk, we perform careful visual inspections of our sample of line-emitters, resulting in a sample of 301 line-emitters.

While the sample of line-emitters includes nine sources with spectroscopic redshifts (six H $\alpha$ at $z = 1.4$ and three H $\beta$/[O~III] at $z = 2.2$), the NBH line-emitters are particularly suitable for identifying line-emitters with the dual-NB technique. These robustly identified line-emitters are used to adapt the colour selection criteria from Sobral et al. (2013) for the data available in this field. Using the criteria listed in Table 3, we select 77 H $\alpha$ emitters at $z = 1.47$, 72 H $\beta$/[O~III] emitters at $z = 2.2$ and 6 [O~III] emitters at $z = 3.3$ (see Table 4). 99 sources are classed as low-redshift interlopers and 39 sources are too faint to be detected in the required broad-bands. Prior to the final identification, four spectroscopically confirmed H $\beta$/[O~III] emitters were classed as H $\alpha$ emitters, while five H $\alpha$ emitters were classed as H $\beta$/[O~III] emitter. These misidentified emitters are typically very luminous and likely AGN, such that their colours are anomalous (see Fig. B4). There are no such identified contaminants amongst the fainter dual-emitters.

4.6 Line-emitters in NBK

We select line-emitters detected in the NBK filter with EW $> 80$ Å (corresponding to K – NBK $> 0.23$). In total, after visual inspections, we find 255 line-emitters, of which 18 have a spectroscopic redshift (including eight H $\alpha$ at $z = 2.23$) and 20 are dual-emitters (all H $\alpha$ at $z = 2.23$). Based on these robust redshifts and the colour selection criteria listed in Table 3, we select 77 H $\alpha$ emitters at $z = 2.2$, 11 H $\beta$/[O~III] emitters at $z = 3.2$ and 2 [O~III] emitters at $z = 4.7$ (see Table 4). 110 line-emitters are at $z < 1.5$ and 55 line-emitters are too faint to be classified. We have not identified any spectroscopically confirmed contaminants before the final classification. However, the colour–colour criteria missed two X-ray-detected dual-emitters at $z = 2.23$, as illustrated in Fig. B5.

5 NUMBER DENSITIES

5.1 Method

We measure the number densities of LAEs at $z = 2.2$, 2.4 and 3.1, H $\alpha$ emitters at $z = 0.4$, 1.47 and 2.23, H $\beta$/[O~III] emitters at $z = 0.8$, ...
J. Matthee et al.

Table 5. Survey volumes and flux completenesses for the various line-emitters in this survey.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Emission line</th>
<th>Volume (10^5 Mpc^3)</th>
<th>50 per cent completeness (erg s^{-1} cm^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB392</td>
<td>Ly α z = 2.2</td>
<td>2.8</td>
<td>1.3 × 10^{-16}</td>
</tr>
<tr>
<td>stV</td>
<td>Ly α z = 2.4</td>
<td>9.5</td>
<td>4.7 × 10^{-16}</td>
</tr>
<tr>
<td>NB501</td>
<td>Ly α z = 3.1</td>
<td>7.2</td>
<td>1.1 × 10^{-16}</td>
</tr>
<tr>
<td>NB921</td>
<td>H β z = 0.4</td>
<td>0.2</td>
<td>1.0 × 10^{-16}</td>
</tr>
<tr>
<td></td>
<td>[O III] z = 0.8</td>
<td>1.2</td>
<td>1.0 × 10^{-16}</td>
</tr>
<tr>
<td></td>
<td>[O III] z = 1.47</td>
<td>1.7</td>
<td>1.0 × 10^{-16}</td>
</tr>
<tr>
<td>NBH</td>
<td>H β z = 1.47</td>
<td>2.5</td>
<td>1.3 × 10^{-16}</td>
</tr>
<tr>
<td></td>
<td>[O III] z = 2.2</td>
<td>5.2</td>
<td>1.3 × 10^{-16}</td>
</tr>
<tr>
<td>NBK</td>
<td>H α z = 2.2</td>
<td>2.7</td>
<td>0.5 × 10^{-16}</td>
</tr>
</tbody>
</table>

2.2, 3.2 and [O II] emitters at z = 1.47, 3.3, 4.7 as a function of their line luminosity, in narrow luminosity bins (0.2–0.3 dex in this analysis). The luminosity is calculated using the line-flux (Section 3.3) and assuming the luminosity distance corresponding to the redshift of peak filter transmission for the relevant emission line. We calculate the comoving volume for each line/filter combination using the redshifts of half peak transmission (see Table 5). For H β/[O II], we compute the volume following Khostovan et al. (2015), who uses only the volume probed by the [O II]_{λ5007} line. We refer to this work and Sobral et al. (2015) for a detailed discussion on the contribution of H β and [O II]_{λ6363}. Luminosity-binned number densities were calculated by dividing the number of sources in each bin by the comoving volume, and then correcting these (as described in the following subsections) for the effects of the filter profile, flux incompleteness and identification incompleteness. Uncertainties on these number densities were estimated using Poissonian errors. To be conservative, we add in quadrature 20 per cent of the flux completeness correction and 20 per cent of the identification-incompleteness correction (in the case of the red narrow-bands) to the error of each bin. We only show bins with >40 per cent flux completeness.

5.1.1 Filter profile correction

As described in Khostovan et al. (2015) and Sobral et al. (2013, 2015), observed number densities have to be corrected for the fact that the filter transmission curves are not a perfect top-hat. Because of this, luminous sources may be observed as faint sources if they lie at a redshift corresponding to the wings of the filter. Furthermore, at fixed flux-limit, fainter sources can only be observed over a smaller volume than more luminous sources. Following the method described in these papers, we compute the number density corrections using a simulation. This simulation assumes that sources are distributed randomly in redshift space and computes their observed luminosities based on the relevant filter transmission. We then obtain a volume correction for each luminosity bin. These corrections typically increase the number densities of the most luminous bins by at most 0.3 dex, while the number densities of fainter bins stay constant, or are decreased by at most 0.05 dex.

5.1.2 Detection flux completeness

The flux completeness of our selection is measured as a function of line-flux as follows: for the relevant line, we select galaxies that are not selected as a line-emitter, but do fulfil the colour criteria from Section 4. We then artificially add line-flux (starting from 10^{-18} erg s^{-1} cm^{-2} in steps of 0.05 dex) and recompute the line-excess and excess significance for each step. After each step, we measure the fraction of sources that would be selected as line-emitter with the added line-flux. We tabulate the 50 per cent completeness in Table 5. Most narrow-band selections are 50 per cent complete at ∼1 × 10^{-16} erg s^{-1} cm^{-2}, with the exception of stV, which is only sensitive to brighter emission lines.

5.1.3 Identification incompleteness

For the red narrow-bands, we also take into account that the broadband data are not deep enough for a robust classification of all faintest line-emitters, which we call identification incompleteness. We estimate corrections for this effect as follows: for each narrow-band filter, we measure the fraction of line-emitters that is classed...
We show the measured LF of LAEs at $z \approx 2.2$ and $z \approx 3.1$. The power law like behaviour at the bright end is due to the contribution from AGN (for which we provide a fit in Section 5.2.1). The yellow points show an estimate of the contribution from Type I AGN, based on the UV LF combined with a Lyα of 80 Å. At $z \approx 2.2$, we find good agreement between the LF of LAEs in B-HiZELS and the LF we measured in Sobral et al. (2017) and to the survey from Konno et al. (2016). The number density of LAEs at $z = 3.1$ is similar to that measured by Ouchi et al. (2008) in the UDS field.

as either Hα, H β/[O III] or [O II] emitter or as a lower redshift source, as a function of line-flux and assume that this fraction can be extrapolated to the line-fluxes of the sources that are not classable.

We find that for line-emitters in NB921 the fraction of classed Hα, H β/[O III] and [O II] emitters is 25 ± 5, 35 ± 5 and 40 ± 4 per cent, respectively, at fluxes <6.3 × 10$^{-17}$ erg s$^{-1}$ cm$^{-2}$ and 42 ± 10, 38 ± 10 and 20 ± 8 per cent, respectively, for fluxes between 6.3 × 10$^{-17}$ and 4 × 10$^{-16}$ erg s$^{-1}$ cm$^{-2}$ (see Fig. 2). This is expected, as sources with fainter fluxes are expected to be at higher redshift. For line-emitters in NB54, the corresponding fractions are 25 ± 5, 25 ± 7 and 4 ± 2 per cent at fluxes below 4 × 10$^{-16}$ erg s$^{-1}$ cm$^{-2}$. This means that ~40 per cent of the unclassed sources is likely at $z < 1$. Above this flux, all sources are classed. These fractions are in agreement with the estimate from Sobral et al. (2012). Finally, for line-emitters in NB14, we estimate that below a flux of 1.5 × 10$^{-16}$ erg s$^{-1}$ cm$^{-2}$ a fraction of 40 ± 8 per cent of the line-emitters is Hα, 7 ± 3 per cent is H β/[O III], while 55 ± 6 per cent is at low redshift. All sources with a larger line-flux have been classed. We note that maximally 40 per cent of the sources in a flux bin are unclassed. This maximum occurs in the faintest bin of the NB921 line-emitters (see Fig. 2). The typical fraction of unclassed sources at the discussed flux levels is 20 per cent.

We use the estimates described above to obtain the identification incompleteness for each luminosity bin for the relevant emission line.

5.2 Comparison with previous surveys

5.2.1 Lyman-α emitters at $z = 2.2$–3.1

We show the measured LF of LAEs at $z = 2.2$–2.4 and $z = 3.1$ in Fig. 3. The depth of our data allows us to constrain the LF to $\approx L^*$.

We find good agreement with earlier results from Sobral et al. (2017) and those from Konno et al. (2016) in different survey fields and slightly different colour criteria (see also An et al. 2016). All surveys indicate that the Ly α LF at $z \approx 2.2$ deviates from a Schechter function at bright luminosities. We note that all LAEs at $z = 2.2$ with a luminosity above 10$^{44}$ erg s$^{-1}$ are either spectroscopically confirmed or have a dual-NB redshift. As discussed in Sobral et al. (2017), the power-law behaviour of the LF is likely due to the contribution of AGN in addition to the normal Schechter function. Indeed, most (~80 ± 40 per cent) luminous LAEs ($L_{\text{Ly} \alpha} > 10^{43}$ erg s$^{-1}$) are AGN (either due to X-ray detection or C IV detection in NB501). We fully explain this in Section 6.4.

Due to its larger probed cosmic volume, the stV filter is mostly sensitive to very luminous LAEs. Although all LAEs with a luminosity above 10$^{44}$ erg s$^{-1}$ at $z = 2.4$ are spectroscopically confirmed, we expect that the sample with luminosities 10$^{43} – 44$ erg s$^{-1}$ is contaminated, as the spectroscopic follow-up at these fluxes is not complete. Most importantly, we expect contaminants to be emission lines that are associated with AGN activity such as C IV, C III] and He II at $z = 1.15$–1.65 (e.g. Stroe et al. 2017), which are challenging to identify with these colour–colour selections. We estimate the contamination at these flux levels by mimicking the selection of this survey in a similar medium band in the COSMOS field (IA427, Santos et al., in preparation). We select LAEs at $z \approx 2.5$ with the same criteria (including broad-band depths) and estimate the number of interlopers using the most recent photometric redshifts (Laigle et al. 2016) and a compilation of spectroscopic redshifts. We find that at luminosities $\sim 10^{44} – 44$ erg s$^{-1}$, there is a non-negligible contamination due to C IV, C III] and He II emitters of 20±10 per cent.

The plotted number densities are corrected for these contamination rates. We combine the $z = 2.2$–2.4 data to fit a power-law function to the number density of LAEs at the bright end ($L_{\text{Ly} \alpha} > 10^{43}$ erg s$^{-1}$), which results in $\log_{10}(\Phi) = 27.5^{+0.3}_{-0.4} - 0.74^{+0.01}_{-0.01} \log_{10}(L_{\text{Ly} \alpha})$, with a reduced $\chi^2$ of 1.1. This fit is slightly shallower than the power law fitted by Sobral et al. (2017) based on a smaller volume, but consistent within 1σ.

We estimate the contribution of broad-line Type I AGN to the Ly α LF at $z \approx 2.2$ based on the UV LF of Type I AGN at 2.0 < $z$ < 2.5 from Bongiorno et al. (2007) and the typical UV slope and Ly α EW of these AGN. Assuming $f_o \propto \lambda^{-1.5}$ and Ly α EW$_0 = 80$ Å (e.g. Vanden Berk et al. 2001; Hunt et al. 2004), we convert the number densities as a function of $M_{\text{H}0}$ to number densities as a function of Ly α luminosity. As shown in Fig. 3, it is clear that the number density of LAEs is higher than the number density of Type I
AGN at fixed Ly α luminosity. This indicates that only a fraction of the luminous LAEs are likely Type I AGN. This estimate suggests that at Ly α luminosities $10^{43} – 44$ erg s$^{-1}$ the fraction of Type I AGN is only $\sim$10 per cent, while the fraction is $\sim$20–30 per cent at higher Ly α luminosities. Because the AGN LF at the faintest UV magnitudes is relatively flat, these fractions do not depend strongly on the assumed values of the Ly α EW or UV slope. The low Type I AGN fraction indicates that the majority of luminous LAEs are narrow-line Type II AGN (see also Section 6.4, or star-forming galaxies.

At $z = 3.1$, we find that the Ly α LF agrees well with that from Ouchi et al. (2008), who performed a deep Ly α survey over a similar area. Compared to similar NB501 data in the COSMOS field (with deeper ancillary data and relatively more spectroscopic follow-up; Matthee et al., in preparation), we also find that the fraction of line-emitters (with similar line-flux and EW distributions) that are classed as LAE is similar: $51 \pm 0.9$ per cent in Boötes against $46 \pm 0.7$ per cent in COSMOS. This also confirms evolution in $L_\lambda$ between $z = 2.2–3.1$ from $L_{\lambda, 3\mu} \approx 4 \times 10^{41} \mathrm{erg s}^{-1}$ to $L_{\lambda, 3\mu} \approx 9 \times 10^{42} \mathrm{erg s}^{-1}$. The number density of LAEs in the brightest bin (three out of the four sources in this bin are spectroscopically followed-up and confirmed) lies above the Schechter fit from Ouchi et al. (2008) (similar to the actual data points from that survey), indicating the presence of AGN amongst these luminous sources, similar to $z \sim 2$.

Indeed, we find evidence for AGN activity for most LAEs in the most luminous bin, either due to an X-ray detection or due to the detection of high ionization emission lines as [Ne IV] $λ\lambda 3961, 4047$ or broad Si IV and C IV absorption features in the spectrum (Sobral et al. in preparation).

### 5.2.2 Hα emitters at $z = 0.4–2.2$

We show the number densities of Hα emitters as a function of their observed Hα luminosities. The Hα luminosities are corrected for the contribution due to [N II] following a method based on observed Hα+[N II] EW (Sobral et al. 2012). Hα luminosities are not corrected for attenuation due to dust and we compare our results with dust-uncorrected values from the literature. In case dust-uncorrected values are not provided, we convert dust-corrected values back using the prescriptions outlined in the relevant papers.

As illustrated in Fig. 4, we find that the Hα LF at $z = 0.4$, 1.47, $z = 2.23$ are generally in good agreement with the number densities in the UDS+COSMOS parts of the HiZELS survey from Sobral et al. (2013). Within the errors, the LF agrees well with the fitted relations from Drake et al. (2013) and Ly et al. (2007). At $z = 2.23$, the number densities complement the number densities at fainter luminosities from Lee et al. (2012). This confirms strong evolution in $L_{\lambda, 421}$ from $z = 0.4$ to $z = 2.23$. We note that at $z = 0.4$ there could be some contamination at the faintest luminosities due to identification incompleteness (see Section 5.1.3). At $z = 1.47$, the luminosities seem to be systematically higher by $\approx$0.1–0.15 dex, increasing slightly with luminosity. This offset can partly be explained by different apertures used in the photometry. While Sobral et al. (2013) uses 2 arcsec apertures for all measurements above $z > 0.5$, we use 3 arcsec measurements. Redoing the measurements with 2 arcsec apertures (smaller symbols in Fig. 4) results in good agreement at our faintest luminosities and reasonable agreement (within the error bars) at higher luminosities. At faint luminosities, the luminosity difference between the two apertures is typically 0.14 dex, while it is typically 0.1 dex at high luminosities. The highest luminosity bins at $z = 1.47–2.23$ show number densities diverging from a Schechter function, contributing to the difference as well. The sources in these bins are all spectroscopically confirmed or have dual-NB redshifts and most are X-ray detected, as indicated in the corresponding panels. We discuss this in more detail in Section 6.4.

Compared to the grism results at $0.3 < z < 0.9$ from Colbert et al. (2013), the number densities at $z = 0.4$ are offset (mostly in terms of luminosity). This can simply be explained by the evolution in the typical Hα luminosity between $z = 0.4$ and the median redshift of the Colbert et al. (2013) sample of $z \approx 0.6$, as log $L_{\lambda, 421}$ increases with $0.45 \times z$ over this redshift range (Sobral et al. 2013). The number densities at $z = 1.47$ are in good agreement with the grism results at $0.9 < z < 1.5$, even though the median grism redshift is $z \approx 1.2$. This indicates that there is little evolution in $L_{\lambda, 421}$ between $z = 1.47$ and $z \approx 1.2$.

#### 5.2.3 H/β[O III] emitters at $z = 0.8–3.2$

We also compare our identification of H/β[O III] at $z = 0.8$, 2.2, 3.2 with the analysis from Khostovan et al. (2015) in the COSMOS and UDS fields.

As illustrated in Fig. 4, the number densities of H/β[O III] emitters at $z = 0.8$ are in good agreement with those from Khostovan et al. (2015), and higher than those from Ly et al. (2007) and Drake et al. (2013), which could be due to cosmic variance or systematics such as different apertures and estimates of volume and completeness. Using a large 10 deg$^2$ H/α [O III] and [O III] survey, Sobral et al. (2015) estimated empirically that the uncertainty in $L_\star$ and $\Phi_\star$ due to cosmic variance over the volume probed in these surveys at $z = 0.8$ is $\approx$40–50 per cent. Such variance could easily explain the observed differences. At $z = 2.2$, the number densities are systematically higher in luminosity compared to the literature results. Similarly as in Section 5.2.2, we find that this is partly due to an aperture effect.

As expected, the difference in luminosities measured with different apertures is slightly smaller at $z = 2.2$ than at $z = 1.47$, with a typical luminosity difference of 0.11 dex. As a consequence, even when matching apertures to Khostovan et al. (2015), we still find an offset at fainter luminosities, which we attribute to cosmic variance. Although the number of H/β[O III] emitters at $z = 3.2$ is limited, their number densities agree well with those from Khostovan et al. (2015).

Unlike the Hα number densities, the number densities of Hβ/[O III] emitters are in good agreement with those from Colbert et al. (2013), which could indicate that there is less evolution in the Hβ/[O III] LF than in the Hα LF between 0.7 < $z < 1.5$. However, this could also be due to the contribution of H β emitters (see Sobral et al. 2015 and Khostovan et al. 2015 for detailed discussions). Except for luminosities $>10^{42} \mathrm{erg s}^{-1}$, the number densities of H/β[O III] emitters at $z = 0.8$ are a factor 30–100 higher (at fixed [O III] luminosity) than the number densities of Type II AGN at $z \approx 0.71$ (Bongiorno et al. 2010).

#### 5.2.4 [O III] emitters at $z = 1.47, 3.3, 4.7$

Fig. 5 compares the number density of [O III] emitters at $z = 1.47, 3.3, 4.7$ to the other published results. At $z = 1.47$, the number densities agree reasonably well with Drake et al. (2013) and Khostovan et al. (2015), except for the faintest bin, although identification incompleteness is significant in this bin. At the bright end, the Schechter fit from Ly et al. (2007) indicates a lower number density, potentially due to a lack of bright sources in a small survey volume.
Figure 4. Left column: measured H$\alpha$ LFs at $z = 0.4, 1.47, 2.2$. H$\alpha$ luminosities are corrected for the [N II] contribution using a relation with H$\alpha$+[N II] EW (Sobral et al. 2012), but are not corrected for dust. At $z = 0.4$, the LF is compared to the narrow-band survey from Ly et al. (2007) in the Subaru Deep Field (SDF) field and Drake et al. (2013) in the UDS field and with the survey from Lee et al. (2012) at $z = 2.2$. At all redshifts, the number densities are compared to the HiZELS survey results in the UDS+COSMOS fields from Sobral et al. (2013). We also compare the LFs with those measured in a blind grism survey by Colbert et al. (2013). Overall, there is reasonable agreement. The luminosity-offset at $z = 1.47$ may be explained by aperture effects (see Section 5.2.2). The brightest bin at $z = 2.2$ contains the same AGN as in the brightest bin of the H$\alpha$ LF at $z = 2.2$.

Right column: measured H$\beta$/[O III] LFs at $z = 0.8, 2.2, 3.2$, compared to Ly et al. (2007) and Drake et al. (2013) at $z = 0.8$ and to Khostovan et al. (2015) and Colbert et al. (2013) at higher redshift. There is a luminosity-offset at $z = 2.2$ that is partially due to a larger aperture measuring a higher luminosity by $\approx 0.14$ dex (this is the same filter as the H$\alpha$ LF at $z = 1.47$). The brightest bin at $z = 2.2$ contains the same AGN as in the brightest bin of the H$\alpha$ LF at $z = 2.2$.
We note that the sources in the brightest bin are not spectroscopically confirmed and thus could be interlopers (for this reason, these points have a lighter colour in Fig. 5). Although the number of [O II] emitters in our samples at \(z = 3.3\) and \(z = 4.7\) is limited to a handful, their number densities are slightly higher than Khostovan et al. (2015), potentially indicating either contamination or cosmic variance. A further hint of contamination in this sample is that some have relatively low colour-excess (Fig. 6), which is unexpected for high-redshift sources, although this would also be consistent with a drop in typical EWs for [O II] emitters (Khostovan et al. 2016).

6 PROPERTIES OF LINE-EMITTERS

6.1 Dual-emitters

In total, we detect 42 line-emitters that are line-emitters in multiple narrow-bands. We list the coordinates, redshifts and band magnitude of these line-emitters in Table C1. The majority (20) of dual-emitters are \(H\alpha + \text{[O II]}\) emitters at \(z = 1.47\) detected in NB921 and NB81, followed by 17 \(H\alpha + \text{[O II]}\) emitters at \(z = 2.23\), of which two are also detected in Ly\(\alpha\), three in C IV and one in Mg II. Three galaxies are identified as LAE in NB392 at \(z \approx 2.2-2.3\) and are also detected in either NB81 ([O III]) or NB85 (H\(\alpha\)), of which one is also detected in NB501 (C IV).

6.2 The most luminous \(H\alpha\) emitters at \(z = 2.23\)

B-HiZELS_1 is the most luminous \(H\alpha\) emitter known from HiZELS at \(z = 2.23\) (i.e. Sobral et al. 2016) and also detected as Ly\(\alpha\) and [O III] emitter. Although its high luminosity \((L_{\text{H}\alpha} = 7.9 \times 10^{43} \text{ erg s}^{-1})\) suggests that it is an AGN, it is X-ray undetected \((L_X < 3 \times 10^{44} \text{ erg s}^{-1})\). There is also a dual-emitter (B-HiZELS_27), detected in [O III] and \(H\alpha\) at the same redshift only 6 arcsec away (a projected distance of \(\sim 50\) kpc). This source has an estimated \(H\alpha\) EW of \(\gtrsim 400 \text{ Å}\) and [O III] EW \(\gtrsim 375 \text{ Å}\). This places it at the very high end of the \(H\alpha\) EW distribution at \(z = 2.2\) (Fumagalli et al. 2012; Sobral et al. 2014), and the galaxy is thus likely a low-mass extreme emission-line galaxy (e.g. van der Wel et al. 2011). These strong emission lines could indicate that this galaxy may be undergoing high interaction-induced SFR combined with little extinction due to dust, or is a shocked gas cloud.

The second most luminous \(H\alpha\) emitter at \(z = 2.2\) is B-HiZELS_15 at \(z = 2.244\) \((L_{\text{H}\alpha} = 3.6 \times 10^{43} \text{ erg s}^{-1})\). We also detect [O III], \(H\alpha\) and C IV emission lines (there are no Ly\(\alpha\) observations at its position). Although B-HiZELS_15 also has a neighbouring galaxy (at \(z = 2.242\) and a projected separation of \(\sim 50\) kpc) and the \(H\alpha\) luminosity is only a factor of 2 lower than that of B-HiZELS_1, several other properties are different. B-HiZELS_15 is X-ray detected, has a higher \(H\alpha\) EW \((360 \text{ Å versus 120 Å})\) and is more than three magnitudes fainter in the optical and NIR continuum. This indicates a diversity in the properties of luminous \(H\alpha\) emitters, similar to the results from Sobral et al. (2016).

6.3 [O II]–\(H\alpha\) view at \(z = 1.47\)

One strength of the Boötes-HiZELS survey is our sample of dual-emitters that can be used to study the relation between different star-formation rate indicators at \(z = 1.47\) and \(z = 2.23\), such as [O III], \(H\alpha\) and continuum tracers such as the rest-frame UV, FIR and radio. Compared to \(H\alpha\), the [O III] emission line and UV continuum are more sensitive to dust attenuation and effects from metallicity and gas density (e.g. Kennicutt 1998; Jansen, Franx & Fabricant 2001; Ly et al. 2012), which may all evolve with redshift. We exploit this sample to derive the observed [O III]/\(H\alpha\) ratio at \(z = 1.47\) and compare it to a reference sample from SDSS at \(z = 0.1\), to test claims based on smaller samples by e.g. Hayashi et al. (2013) and Sobral et al. (2012).

We combine the sample of dual-emitters at \(z = 1.47\) in Boötes with those from HiZELS in the UDS and COSMOS field (see Sobral et al. 2013 for details), and remove any source that is detected in the X-rays. In total, this results in a sample of 340 dual-emitters at \(z = 1.47\). The majority of these are dominated by faint emitters observed in the deeper imaging in COSMOS. \(H\alpha\) luminosities are corrected for the contribution from the adjacent [N II] doublet using the relation with EW described in Sobral et al. (2012) (see also Sobral et al. 2015 for a spectroscopic validation). As a comparison sample at low redshift, we use a sample of emission-line
Figure 6. Narrow-band excess diagrams in NB392, stV, NB501, NB921, NB_H and NB_K. In grey, we show all detected sources, while blue points are sources selected as line-emitters. The horizontal dashed line shows the imposed EW selection cut, while the solid line shows the excess significance criteria for the typical depth of the survey. In the three blue filters, we mark Lyα selected sources with a green square. In the three red filters, we mark Hα emitters with a red square, Hβ/[O III] emitters with a yellow pentagon and [O II] emitters with a blue diamond. We note that we compute the excess significance locally, such that some sources may lie above the selection line, but are not selected as line-emitters because they are in shallower regions. It can be seen that LAEs detected in NB392 and NB501 are typically identified if a line-emitter has a high excess and faint magnitude (because most are likely faint star-forming galaxies with high EW), while this is not the case for LAEs identified in stV (which are typically bright AGN). In NB921, it can clearly be seen that most unidentified line-emitters are amongst the faintest magnitudes and that there is a clear trend that higher redshift line-emitters are fainter and have higher observed EWs. In NB_H and NB_K, Hα emitters and Hβ/[O III] emitters have similar narrow-band magnitudes, but Hβ/[O III] emitters tend to have higher excess because they are at higher redshift.
This indicates that, even though the spread in values is relatively large ($\approx 0.4$–$0.5$ dex), the median observed $[\text{O}~\II]/H\alpha$ ratio increases slightly, but statistically significantly, between $z = 0.1$–$1.47$.

We test whether the observed difference can be caused by systematic errors. At $z = 1.47$, there is a systematic uncertainty due to the relative filter transmissions at the different wavelengths, which leads to an increase in the scatter and a small bias towards higher $[\text{O}~\II]/H\alpha$ values. Based on the simulation that is discussed in detail in Sobral et al. (2012), we estimate that this systematic increase is only of the order of $\approx 5$ per cent, insufficient to explain the offset of the median ratio. If we remove AGN in the SDSS sample using the BPT criterion as defined in Kauffmann et al. (2003), we find $[\text{O}~\II]/H\alpha = 0.42 \pm 0.01$. Finally, if we fully mimic the $H\alpha$ measurement (and its correction for the contribution of the $[\text{N}~\II]$ in the narrow-band), we measure $[\text{O}~\II]/H\alpha = 0.45 \pm 0.01$. Thus, none of these effects can explain the observed difference, but they further highlight that the evolution is small, and thus only our large statistical sample can measure evolution.

A higher observed $[\text{O}~\II]/H\alpha$ ratio is expected when there is less attenuation due to dust, since $[\text{O}~\II]$ is attenuated more than $H\alpha$ (e.g. Reddy et al. 2015). For example, it could be that galaxies at $z = 1.47$ are less dusty. Indeed, if we restrict the sample of local galaxies to those with $A_{H\alpha} < 1.3$ (median $A_{H\alpha} = 0.82$, compared to a median $A_{H\alpha} = 0.91$ for the full sample), we find a similar observed $[\text{O}~\II]/H\alpha$ ratio of $0.49 \pm 0.01$. However, results from Herschel stacking of $H\alpha$ emitters at $z = 1.47$ (Thomson et al. 2017; see also Ibar et al. 2013) indicate that their extinction properties are similar to local galaxies, with a similar relation between stellar mass and $A_{H\alpha}$ (Garn & Best 2010). We note that because the samples are matched in $L/L_{H\alpha}$, there are likely no significant mass differences between the samples (e.g. Sobral et al. 2014). A more detailed analysis of the extinction properties of this sample is beyond the scope of this paper. Finally, another explanation is that the SDSS fibre measurements are biased towards higher extinction (and thus lower $[\text{O}~\II]/H\alpha$ ratios), because they measure the line-ratios in the central $3$–$4$ kpc of galaxies, which are observed to be dustier/more evolved (e.g. Sánchez et al. 2014), while the $3$ arcsec measurements at $z = 1.47$ measure flux out to radii of $8$–$13$ kpc (depending on UDS/COSMOS or Boötes). Therefore, the observed offset between $z = 0.1$ and $z = 1.47$ could also be an observational effect due to dust, age and/or metallicity gradients within galaxy. These observational issues can be overcome with large IFU or matched NB surveys in the local Universe, as for example the J-PAS project (Benítez et al. 2014).

### 6.4 X-ray fraction & the power-law component of the LF

We investigate the AGN fractions of $H\alpha$ emitters at $z = 1.47$ and $z = 2.23$ and LAEs at $z = 2.4$ by matching our samples to source catalogue from X-ray (Chandra, $0.5$–$7.0$ keV, depth $7.8 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$, $1$ arcsec resolution and matching radius, Kenter et al. 2005). In addition, we include the $H\alpha$ emitters at $z = 1.47$ and $z = 2.23$ in the COSMOS field from Sobral et al. (2013) and match these with the Chandra COSMOS point source catalogue ($0.5$–$7.0$ keV, $5.7 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$; Elvis et al. 2009); see also Calhau et al. (2017) for their detailed properties. These X-ray flux limits correspond to luminosity limits of $0.3$–$3 \times 10^{45}$ erg s$^{-1}$. If such an X-ray luminosity would have its origin in star formation, it would require SFRs of $> 10^{5} - 5 M_{\odot}$ yr$^{-1}$ (e.g. Lehmer et al. 2016), which is unlikely. This clearly indicates an AGN origin of all X-ray detections discussed in this section.
In total, we detect 21 HAEs in the X-ray, of which 10 are at \( z = 1.47 \) and 11 are at \( z = 2.23 \) and half of the X-ray-detected HAEs are in Boötes. We find that the detection rate depends strongly on the \( H_\alpha \) luminosity (see Fig. 8). This has also been observed using spectroscopic follow-up by Sobral et al. (2016), who found that the majority (80 \pm 30 per cent) of luminous HAEs are broad-line AGN. Relatively independent of redshift, roughly half of the most luminous HAEs are X-ray detected. Note that the other half may easily be undetected due to the short duty cycle of X-ray AGN (e.g. Shankar, Weinberg & Miralda-Escudé 2009; Fiore et al. 2012), although it could also indicate that roughly half of the luminous HAEs are optically thick to X-rays. By combining the data points above \( L^* \) at \( z = 1.47–2.23 \), we find a best-fitting \( f_X = 0.57 \pm 0.12 \log_{10}(L_{H_\alpha}/10^{43} \text{ erg s}^{-1}) + 0.25 \pm 0.06 \) that we illustrate in Fig. 8.

We combine the sample of LAEs at \( z = 2.2–2.4 \) identified with the NB392 and the stV filter to investigate the X-ray fraction of LAEs as a function of luminosity. Out of the 41 LAEs, eight are X-ray detected (\( L_X > 3 \times 10^{44} \text{ erg s}^{-1} \)). The X-ray fraction of LAEs increases strongly with line luminosity, from \( \approx 0 \) per cent at \( L_{Ly\alpha} \approx 100 \) per cent at \( L_{Ly\alpha} \approx 100 \times 10^{44} \text{ erg s}^{-1} \). We note that the \( Ly\alpha \) luminosities at which the X-ray fraction exceeds 20 per cent correspond to the luminosities at which the number densities start to deviate from a Schechter function, as observed in Konno et al. (2016), Sobral et al. (2017) and this work (Fig. 3). For both \( H_\alpha \) and \( Ly\alpha \), the X-ray fraction increases above \( L^* \). For \( Ly\alpha \), we find a best-fitting relation of \( f_X = 0.41 \pm 0.15 \log_{10}(L_{Ly\alpha}/10^{43} \text{ erg s}^{-1}) + 0.25 \pm 0.06 \) that we illustrate in Fig. 8.

7 CONCLUSIONS

We presented the first results from the Boötes-HiZELS survey, which uses six narrow-bands to select emission-line galaxies from \( z = 0.4–4.7 \) in a 0.7 deg\(^2\) region in the Boötes field. We describe the observations, data-reduction, extraction of catalogues and selection of line-emitters, and how multiwavelength data has been used to classify different populations of line-emitters. The main results are:

(i) We identify 362 candidate \( H_\alpha \) emitters (HAEs) at \( z = 0.4, 1.47, 2.23, 387 \) \( H_\beta/[O \text{ III}] \) emitters at \( z = 0.8, 2.23, 3.3, 285 \) \( O \text{ II} \) emitters at \( z = 1.47, 3.3, 4.7 \) and 73 \( Ly\alpha \) emitters (LAEs) at \( z = 2.23, 2.3, 3.1 \).

(ii) Using a suite of matched narrow-band filters, we identify 42 galaxies with emission lines in multiple narrow-bands, providing 22/18 new robust redshift identifications of \([O \text{ II}]/H_\alpha \) and \([O \text{ III}]/H_\alpha \) emitters at \( z = 1.47–2.23 \), without pre-selection on AGN activity or \( I \)-band magnitude (see Section 6 and Table C1). 56 additional line-emitters have a spectroscopic redshift.

(iii) In general, the number densities of line-emitters as a function of luminosity we derive agree remarkably well with LFIs observed in other survey fields (Section 5; Figs 3–5), confirming strong evolution in \( L_{Ly\alpha} \) from \( z = 0.4–2.2 \) and evolution in \( L_{Ly\alpha} \) from \( z = 2.2–3.1 \).

(iv) We confirm the result from Konno et al. (2016) and Sobral et al. (2017) that the LF of LAEs at \( z \approx 2.2 \) diverges from a Schechter function at the bright end, \( L_{Ly\alpha} > 10^{43} \text{ erg s}^{-1} \). At these luminosities, the LF follows \( f_{Ly\alpha}(\Phi) = 27.5 \pm 0.74 \log_{10}(L_{Ly\alpha}) \). Such a departure from a Schechter function is also clearly observed at the highest \( H_\alpha \) luminosities \( (L_{H_\alpha} > 10^{43.5} \text{ erg s}^{-1}) \) at \( z = 2.2 \) (Sections 5.2 and 5.2.2).

(v) Combining our sample of dual-emitters with those from the COSMOS and UDS fields from HiZELS, we compare the observed \([O \text{ II}]/H_\alpha \) ratio of 340 star-forming galaxies at \( z = 1.47 \) with those from a reference sample in the local Universe (Section 6.3). We measure a median ratio of \([O \text{ II}]/H_\alpha = 0.40 \pm 0.01 \) at \( z = 0.1 \) and \([O \text{ II}]/H_\alpha = 0.55 \pm 0.07 \) at \( z = 1.47 \). We find that the sample to sources with slightly higher S/N, see Fig. 7. The \( \approx 10 \) dex offset can potentially be attributed to a lower dust attenuation at \( z = 1.47 \), or biases in the fibre-measurements in the local Universe, which measure the ratio at the central 3–4 kpc of galaxies, while the measurements at \( z = 1.47 \) are integrated over \( >10 \) kpc.

(vi) By exploiting \textit{Chandra} X-ray data, we show that the \( H_\alpha \) and \( Ly\alpha \) luminosities at which the number densities start to diverge from pure Schechter form at similar luminosities to where the X-ray fractions start to increase, from 20 to \( \sim 100 \) per cent (Fig. 8). We also show that, under basic assumptions, the majority of luminous LAEs are not broad-line Type I AGN (Fig. 3), and more likely narrow-line Type II AGN.

The sample of identified line-emitters can be used to study various properties of star-forming galaxies. In particular, the...
relatively large sample of $\text{H}_\alpha$ emitters at $z = 1.5$–2.2 can be used to test various SFR indicators ($\text{H}_\alpha$, rest-UV, radio, FIR) in future papers.

ACKNOWLEDGEMENTS

We thank the referee for their constructive comments which helped improve the quality of this work. JM acknowledges the support of a Huygens PhD fellowship from Leiden University and JM and DS acknowledge financial support from a NWO/VENI grant awarded to David Sobral. IRS acknowledges support from STFC (ST/L00075X/1), the ERC Advanced Grant DUSTYGal (321334) and a Royal Society/Wolfson Merit Award. HR acknowledges support from the ERC Advanced Investigator programme NewClusters 321271. PNB is grateful to STFC for support via grant ST/M001229/1. BD acknowledges financial support from NASA through the Astrophysics Data Analysis Program (ADAP), grant number NNX12AE20G. We thank Ana Afonso, João Calhau, Leah Morabito, Iván Oteo, Sérgio Santos and Aayush Saxena for their assistance with observations. This work is based on observations obtained using the Wide Field Camera (WFCAM) on the 3.8-m United Kingdom Infrared Telescope (UKIRT), as part of the High-redshift(Z) Emission-Line Survey (HIZELS; U/CMP/3 and U/10B/07), using Suprime-Cam on the 8.2-m Subaru Telescope as part of programme S14A-086 and using the WFC on the 2.5-m Isaac Newton Telescope, as part of programmes 2013AN002, 2013BN008, 2014AC88, 2014AN002, 2014BN006, 2014BC118 and 2016AN001, using ISIS and AF2+WYFFOS on the 4.2-m William Herschel Telescope, as part of programmes 2016AN004 and 2016BN011 and using DEIMOS on the 10-m Keck II Telescope as part of programme C267D and on observations made with ESO Telescopes at the La Silla Paranal Observatory under ESO programme IDs 098.A-0819 and 179.A-2005. This work made use of images and/or data products provided by the NOAO Deep Wide-Field Survey (Jammuzi & Dey 1999) which is supported by the National Optical Astronomy Observatory (NOAO). NOAO is operated by AURA, Inc., under a cooperative agreement with the National Science Foundation. We have benefited greatly from the public available programming language PYTHON, including the NUMPY, MATPLOTLIB, PYFFTS, SCIPY and ASTROPy packages (Astropy Collaboration et al. 2013), the astronomical imaging tools SExTRACTOR, SWARP and SCAMP and the TOPCAT analysis program (Taylor 2013).

REFERENCES

Astropy Collaboration et al., 2013, AAP, 558, A33
Bertin E., Arnouts S., 1996, AAPS, 117, 393
Bongiorno A. et al., 2007, AAP, 472, 443
Bongiorno A. et al., 2010, AAP, 510, A56
Fiore F. et al., 2012, AAP, 537, A16
Hayes M., 2015, PASA, 32, e027
Kennicutt R. C., Jr, 1998, ARAA, 36, 189
Lee J. C. et al., 2012, PASP, 124, 782
Matsuda Y. et al., 2004, AJ, 128, 569
Muzzin A. et al., 2013, ApJS, 206, 8
Sánchez S. F. et al., 2014, AAP, 563, A49
Skrutskie M. F. et al., 2006, AJ, 131, 1163
Taylor M., 2013, Starlink User Note, 253
van der Werf P. P., Moorwood A. F. M., Bremer M. N., 2000, AAP, 362, 509

**Supporting Information**

Supplementary data are available at MNRAS online.

---

**APPENDIX A: Photometric Consistency Check**

In our catalogue production steps (Section 3.2), we only include objects in our catalogues that have a physically plausible NB excess. Because the BB covers the same wavelength as the NB, any flux in the NB must also be observed in the BB, otherwise the object is either unreal (such as a cosmic ray and artefacts) or variable (such as variable stars, supernovae or AGN). It is fairly straightforward to compute the faintest possible BB magnitude, given an NB magnitude:

$$BB_{max} = NB - 2.5\log_{10}\left(\frac{\lambda_{c,X}^2 \Delta \lambda_{BB}}{\lambda_{c,NB}^2 \Delta \lambda_{NB}}\right) + 0.5,$$

where $\lambda_{c,X}$ is the central wavelength of filter X and $\Delta \lambda_X$ is the width of filter X. We conservatively add 0.5 magnitude to take into account uncertainties in the photometry and relative filter transmissions. We remove any source for which the excess is larger than $BB_{max} - NB$. For example, for NB921 and z band, this equation results in $BB_{max} = NB + 3.4$. This means that if a source has a NB921 magnitude of 20, it must have a z magnitude of 23.4 or brighter. It is possible that the implied $BB_{max}$ is below the background. In that case, we exclude sources for which the BB is not detected at 2$\sigma$. This consistency check removes most spurious objects such as cosmic rays and detector artefacts.

---

**APPENDIX B: Colour–Colour Selections**

In this section, we illustrate the colour–colour selection criteria outlined in Table 3. In all figures (Figs B1–B5), line-emitters with secure redshift identifications from spectroscopy or dual-NB detections are shown with larger symbols. X-ray-detected AGN are shown with a star symbol.
Figure B1. Colour selection criteria used to select LAEs at $z = 2.2$ and $z = 2.4$. These are based on the BzK criterion from Daddi et al. (2004). The $B_w$ band magnitude is adjusted for the contribution to flux in the $U$ band. We highlight the sources with spectroscopic redshifts in larger symbols.

Figure B2. Colour selection criterion used to select LAEs at $z = 3.1$ (from NB501) and $[\text{OIII}]/H\beta$ at $z = 3.2$ (from NB_H), based on the $U$ drop-out criterion for Lyman-break galaxies at $z \approx 3$ from Hildebrandt et al. (2009). The $U - g$ colour identifies the Lyman break, while the $g - I$ criterion removes any sources for which the Balmer break is mimicked by a strong Balmer break (particularly important in the case a galaxy is very dusty).

Figure B3. Colour selection criteria used to distinguish H$\alpha$, $[\text{OIII}]/H\beta$ and $[\text{OII}]$ emitters amongst the line-emitters identified with NB921. The criterion in the left-hand panel identifies Balmer breaks at specific redshift intervals. Because this criterion cannot distinguish between $z = 0.4$ and $z = 0.8$, we use the additional $B_wRI$ colours to distinguish between a Balmer break between $B_w$ and $R$ (around 600 nm, or $z \approx 0.5$) and between $R$ and $I$ (around 700 nm, or $z \approx 0.75$).
Boötes-HiZELS: a \( z = 0.4–4.7 \) survey

Figure B4. Colour criteria used to classify line-emitters identified with the NB_H filter. The modified \( B_w zK \) criterion is used to distinguish \( z > 1 \) line-emitters from \( z < 1 \) line-emitters. We then distinguish between \( z = 1.47 \) and \( z = 2.2 \) based on the positions of Balmer breaks. At \( z \approx 1.5 \), the Balmer break lies around an observed 1000 nm, hence between \( J - I \) (note that we use \( I \) rather than \( z \) because \( I \) is deeper and broader, see Table 1). At \( z \approx 2.2 \), the Balmer break lies between the \( J \) and \( K \) bands. Note that several X-ray-detected H\( \alpha \) emitters at \( z = 1.47 \) mimic the colours of \( z = 2.2 \) [OIII]/H\( \beta \) emitters. These sources typically have high line-fluxes and their spectroscopic follow-up completeness is high. [OII] emitters at \( z = 3.3 \) are selected based on the position of their Lyman-break, similar to LAEs at \( z = 3.1 \) in Fig. B2.

Figure B5. Colour criteria used to classify line-emitters identified with the NB_K filter. Similarly to the line-emitters in the NB_H filter, we use the modified \( B_w zK \) criterion to select line-emitters at \( z > 1 \) (left-hand panel). We then distinguish those between H\( \alpha \) at \( z = 2.23 \) and [OIII]/H\( \beta \) emitters at \( z = 3.2 \) based on the positions of their Lyman breaks.

APPENDIX C: CATALOGUE OF DUAL-EMITTERS

Table C1. List of sources that are observed as dual-emitters (line-emitters in at least two narrow-bands). We present the coordinates, spectroscopic and dual-NB redshifts, \( I \)-band magnitudes and the list of emission lines that are detected. X-ray- and LOFAR-detected sources are marked. We note that because the coverage in NB392, stV and NB921 is not homogeneous, the number of Ly\( \alpha \) detections at \( z = 2.23 \) and [OII] at \( z = 1.47 \) is likely underestimated. An electronic version of this table is available online.

<table>
<thead>
<tr>
<th>ID</th>
<th>RA</th>
<th>Dec.</th>
<th>( z_{\text{dual-NB}} )</th>
<th>( z_{\text{spec}} )</th>
<th>I</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-HiZELS_1</td>
<td>14:33:19.29</td>
<td>+33:34:31.53</td>
<td>2.23</td>
<td>2.23</td>
<td>18.9</td>
<td>Ly( \alpha )+[OII]+H( \alpha )</td>
</tr>
<tr>
<td>B-HiZELS_2</td>
<td>14:32:58.85</td>
<td>+33:25:49.33</td>
<td>2.23</td>
<td>2.23</td>
<td>19.6</td>
<td>H( \alpha )+Ly( \alpha )+N( \alpha ), X-ray detected</td>
</tr>
<tr>
<td>B-HiZELS_3</td>
<td>14:31:41.51</td>
<td>+33:49:11.27</td>
<td>2.23</td>
<td>2.26</td>
<td>20.4</td>
<td>[OII]+H( \alpha )+CIV+Ly( \alpha ), X-ray detected</td>
</tr>
<tr>
<td>B-HiZELS_4</td>
<td>14:29:40.05</td>
<td>+33:33:32.13</td>
<td>2.23</td>
<td>2.27</td>
<td>20.6</td>
<td>[OII]+H( \alpha )+Mg( \alpha ), X-ray detected</td>
</tr>
<tr>
<td>B-HiZELS_5</td>
<td>14:32:01.52</td>
<td>+33:16:59.86</td>
<td>2.23</td>
<td>2.23</td>
<td>20.9</td>
<td>[OII]+H( \alpha )</td>
</tr>
<tr>
<td>B-HiZELS_6</td>
<td>14:30:38.29</td>
<td>+33:20:17.85</td>
<td>2.23</td>
<td>2.27</td>
<td>21.3</td>
<td>[OII]+H( \alpha ), X-ray detected</td>
</tr>
<tr>
<td>B-HiZELS_7</td>
<td>14:29:30.87</td>
<td>+34:05:44.85</td>
<td>2.23</td>
<td>2.27</td>
<td>21.7</td>
<td>[OII]+H( \alpha )</td>
</tr>
<tr>
<td>B-HiZELS_8</td>
<td>14:32:13.88</td>
<td>+33:25:57.48</td>
<td>2.23</td>
<td>2.27</td>
<td>21.9</td>
<td>[OII]+H( \alpha )+Ly( \alpha ), LOFAR detected</td>
</tr>
<tr>
<td>B-HiZELS_9</td>
<td>14:31:06.64</td>
<td>+33:46:19.18</td>
<td>2.23</td>
<td>2.23</td>
<td>22.1</td>
<td>[OII]+H( \alpha )</td>
</tr>
</tbody>
</table>
### APPENDIX D: EXAMPLE CATALOGUES OF LINE-EMITTERS

#### Table D1. First five entries in the catalogue of NB392 line-emitters. Coordinates are in J2000. Line-flux is in $10^{-16}$ erg s$^{-1}$ cm$^{-2}$. $EW_{\text{obs}}$ is in Å, where 99 entries mark sources without secure continuum measurement, and have $EW_{\text{obs}} > 550$ Å. Entries with 99 are undetected in I band. Flag_Class: 0: unclassed, 1: LAE at $z = 2.2$. A full version of this table is available online.

<table>
<thead>
<tr>
<th>ID</th>
<th>RA</th>
<th>Dec.</th>
<th>$EW_{\text{NB}}$</th>
<th>$EW_{\text{obs}}$</th>
<th>I</th>
<th>Flag_Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-HiZELS_NB392_1</td>
<td>217.945</td>
<td>33.310</td>
<td>1.3</td>
<td>136</td>
<td>22.2</td>
<td>0</td>
</tr>
<tr>
<td>B-HiZELS_NB392_2</td>
<td>218.017</td>
<td>33.316</td>
<td>1.9</td>
<td>119</td>
<td>20.1</td>
<td>0</td>
</tr>
<tr>
<td>B-HiZELS_NB392_3</td>
<td>217.739</td>
<td>33.340</td>
<td>1.2</td>
<td>158</td>
<td>23.6</td>
<td>1</td>
</tr>
<tr>
<td>B-HiZELS_NB392_4</td>
<td>218.056</td>
<td>33.366</td>
<td>2.1</td>
<td>–99</td>
<td>99</td>
<td>0</td>
</tr>
<tr>
<td>B-HiZELS_NB392_5</td>
<td>217.675</td>
<td>33.386</td>
<td>4.2</td>
<td>56</td>
<td>21.9</td>
<td>0</td>
</tr>
</tbody>
</table>

#### Table D2. First five entries in the catalogue of stV line-emitters. Coordinates are in J2000. Line-flux is in $10^{-16}$ erg s$^{-1}$ cm$^{-2}$. $EW_{\text{obs}}$ is in Å, where 99 entries mark sources without secure continuum measurement, and have $EW_{\text{obs}} > 2500$ Å. Entries with 99 are undetected in I band. Flag_Class: 0: unclassed, 1: LAE at $z = 2.4$. A full version of this table is available online.

<table>
<thead>
<tr>
<th>ID</th>
<th>RA</th>
<th>Dec.</th>
<th>Line-flux</th>
<th>$EW_{\text{obs}}$</th>
<th>I</th>
<th>Flag_Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-HiZELS_stV_1</td>
<td>218.239</td>
<td>33.305</td>
<td>64.3</td>
<td>97</td>
<td>17.2</td>
<td>0</td>
</tr>
<tr>
<td>B-HiZELS_stV_2</td>
<td>218.021</td>
<td>33.314</td>
<td>13.9</td>
<td>1131</td>
<td>22.6</td>
<td>0</td>
</tr>
<tr>
<td>B-HiZELS_stV_3</td>
<td>217.909</td>
<td>33.351</td>
<td>13.5</td>
<td>590</td>
<td>22.5</td>
<td>0</td>
</tr>
<tr>
<td>B-HiZELS_stV_4</td>
<td>218.053</td>
<td>33.354</td>
<td>6.4</td>
<td>207</td>
<td>22.3</td>
<td>0</td>
</tr>
<tr>
<td>B-HiZELS_stV_5</td>
<td>218.086</td>
<td>33.353</td>
<td>25.7</td>
<td>1079</td>
<td>21.7</td>
<td>1</td>
</tr>
</tbody>
</table>
Table D3. First five entries in the catalogue of NB501 line-emitters. Coordinates are in J2000. Line-flux is in $10^{-16}$ erg s$^{-1}$ cm$^{-2}$, EW$_{\text{obs}}$ is in Å, where $-99$ entries mark sources without secure continuum measurement, and have EW$_{\text{obs}} > 550$ Å. Entries with 99 are undetected in $I$ band. Flag_Class: 0: unclassed, 1: LAE at $z = 3.1$. A full version of this table is available online.

<table>
<thead>
<tr>
<th>ID</th>
<th>RA</th>
<th>Dec.</th>
<th>Line-flux</th>
<th>EW$_{\text{obs}}$</th>
<th>$I$</th>
<th>Flag_Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-HiZELS_NB501_1</td>
<td>217.635</td>
<td>33.366</td>
<td>14.9</td>
<td>198</td>
<td>19.9</td>
<td>0</td>
</tr>
<tr>
<td>B-HiZELS_NB501_2</td>
<td>217.923</td>
<td>33.820</td>
<td>13.7</td>
<td>64</td>
<td>20.4</td>
<td>0</td>
</tr>
<tr>
<td>B-HiZELS_NB501_3</td>
<td>217.619</td>
<td>33.558</td>
<td>7.8</td>
<td>391</td>
<td>23.3</td>
<td>0</td>
</tr>
<tr>
<td>B-HiZELS_NB501_4</td>
<td>218.127</td>
<td>33.666</td>
<td>7.2</td>
<td>$-99$</td>
<td>22.9</td>
<td>1</td>
</tr>
<tr>
<td>B-HiZELS_NB501_5</td>
<td>217.668</td>
<td>34.056</td>
<td>5.4</td>
<td>138</td>
<td>22.6</td>
<td>0</td>
</tr>
</tbody>
</table>

Table D4. First five entries in the catalogue of NB921 line-emitters. Coordinates are in J2000. Line-flux is in $10^{-16}$ erg s$^{-1}$ cm$^{-2}$. EW$_{\text{obs}}$ is in Å, where $-99$ entries mark sources without secure continuum measurement, and have EW$_{\text{obs}} > 1100$ Å. Entries with 99 are undetected in $I$ band. Flag_Class: 0: unclassed, 1: H$\alpha$ at $z = 0.4$, 2: H$\beta$/[O III] at $z = 0.8$, 3: [O II] at $z = 1.47$. A full version of this table is available online.

<table>
<thead>
<tr>
<th>ID</th>
<th>RA</th>
<th>Dec.</th>
<th>Line-flux</th>
<th>EW$_{\text{obs}}$</th>
<th>$I$</th>
<th>Flag_Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-HiZELS_NB921_1</td>
<td>217.417</td>
<td>33.559</td>
<td>3.9</td>
<td>40</td>
<td>20.5</td>
<td>0</td>
</tr>
<tr>
<td>B-HiZELS_NB921_2</td>
<td>217.990</td>
<td>33.277</td>
<td>0.3</td>
<td>142</td>
<td>24.6</td>
<td>0</td>
</tr>
<tr>
<td>B-HiZELS_NB921_3</td>
<td>217.831</td>
<td>33.437</td>
<td>0.3</td>
<td>59</td>
<td>23.7</td>
<td>3</td>
</tr>
<tr>
<td>B-HiZELS_NB921_4</td>
<td>218.220</td>
<td>33.662</td>
<td>1.3</td>
<td>101</td>
<td>22.8</td>
<td>3</td>
</tr>
<tr>
<td>B-HiZELS_NB921_5</td>
<td>217.799</td>
<td>33.691</td>
<td>0.3</td>
<td>70</td>
<td>23.9</td>
<td>3</td>
</tr>
</tbody>
</table>

Table D5. First five entries in the catalogue of NB$H$ line-emitters. Coordinates are in J2000. Line-flux is in $10^{-16}$ erg s$^{-1}$ cm$^{-2}$. EW$_{\text{obs}}$ is in Å, where $-99$ entries mark sources without secure continuum measurement, and have EW$_{\text{obs}} > 1200$ Å. Entries with 99 are undetected in $I$ band. Flag_Class: 0: unclassed, 1: H$\alpha$ at $z = 1.47$, 2: H$\beta$/[O III] at $z = 2.2$, 3: [O II] at $z = 3.3$. A full version of this table is available online.

<table>
<thead>
<tr>
<th>ID</th>
<th>RA</th>
<th>Dec.</th>
<th>Line-flux</th>
<th>EW$_{\text{obs}}$</th>
<th>$I$</th>
<th>Flag_Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-HiZELS_NBH_1</td>
<td>218.345</td>
<td>33.265</td>
<td>1.7</td>
<td>188</td>
<td>99</td>
<td>0</td>
</tr>
<tr>
<td>B-HiZELS_NBH_2</td>
<td>218.329</td>
<td>33.299</td>
<td>2.1</td>
<td>212</td>
<td>99</td>
<td>0</td>
</tr>
<tr>
<td>B-HiZELS_NBH_3</td>
<td>217.990</td>
<td>33.312</td>
<td>1.8</td>
<td>474</td>
<td>25.5</td>
<td>0</td>
</tr>
<tr>
<td>B-HiZELS_NBH_4</td>
<td>218.165</td>
<td>33.317</td>
<td>1.8</td>
<td>139</td>
<td>22.1</td>
<td>0</td>
</tr>
<tr>
<td>B-HiZELS_NBH_5</td>
<td>217.670</td>
<td>33.344</td>
<td>1.6</td>
<td>180</td>
<td>22.8</td>
<td>0</td>
</tr>
</tbody>
</table>

Table D6. First five entries in the catalogue of NB$K$ line-emitters. Coordinates are in J2000. Line-flux is in $10^{-16}$ erg s$^{-1}$ cm$^{-2}$. EW$_{\text{obs}}$ is in Å, where $-99$ entries mark sources without secure continuum measurement, and have EW$_{\text{obs}} > 1250$ Å. Entries with 99 are undetected in $I$ band. Flag_Class: 0: unclassed, 1: H$\alpha$ at $z = 2.23$, 2: H$\beta$/[O III] at $z = 3.2$, 3: [O II] at $z = 4.7$, 4: $z < 1$. A full version of this table is available online.

<table>
<thead>
<tr>
<th>ID</th>
<th>R.A.</th>
<th>Dec.</th>
<th>Line-flux</th>
<th>EW$_{\text{obs}}$</th>
<th>$I$</th>
<th>Flag_Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-HiZELS_NBK_1</td>
<td>218.080</td>
<td>33.261</td>
<td>0.8</td>
<td>121</td>
<td>22.3</td>
<td>4</td>
</tr>
<tr>
<td>B-HiZELS_NBK_2</td>
<td>218.345</td>
<td>33.265</td>
<td>1.1</td>
<td>$-99$</td>
<td>99</td>
<td>0</td>
</tr>
<tr>
<td>B-HiZELS_NBK_3</td>
<td>218.345</td>
<td>33.276</td>
<td>0.7</td>
<td>410</td>
<td>25.4</td>
<td>0</td>
</tr>
<tr>
<td>B-HiZELS_NBK_4</td>
<td>218.991</td>
<td>33.277</td>
<td>1.0</td>
<td>494</td>
<td>25.1</td>
<td>1</td>
</tr>
<tr>
<td>B-HiZELS_NBK_5</td>
<td>217.996</td>
<td>33.280</td>
<td>1.0</td>
<td>$-99$</td>
<td>24.8</td>
<td>1</td>
</tr>
</tbody>
</table>

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.