On the nature of Hα emitters at z ~ 2 from the HiZELS survey: physical properties, Lyα escape fraction and main sequence

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ABSTRACT
We present a detailed multiwavelength study (from rest-frame ultraviolet to far-infrared) of narrow-band selected, star-forming (SF) Hα emitters (HAEs) at z ~ 2.23 taken from the High-Redshift(Z) Emission Line Survey (HiZELS). We find that HAEs have similar properties and colours derived from spectral energy distributions as sBzK galaxies, and probe a well-defined portion of the SF population at z ~ 2. This is not true for Lyα emitters (LAEs), which are strongly biased towards blue, less massive galaxies (missing a significant percentage of the SF population). Combining our Hα observations with matched, existing Lyα data, we determine that the Lyα escape fraction (f_{esc}) is low (only ~4.5 per cent of HAEs show Lyα emission) and decreases with increasing dust attenuation, ultraviolet continuum slope, stellar mass and star formation rate (SFR). This suggests that Lyα preferentially escapes from blue galaxies with low dust attenuation. However, a small population of red and massive LAEs is also present, in agreement with previous works and indicating that dust and Lyα are not mutually exclusive.

Using different and completely independent measures of the total SFR, we show that the Hα emission is an excellent tracer of star formation at z ~ 2 with deviations typically lower than 0.3 dex for individual galaxies. We find that the slope and zero-point of the HAE main sequence at z ~ 2 strongly depend on the dust-correction method used to recover the SFR, although they are consistent with previous works when similar assumptions are made.

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

1 INTRODUCTION
A wide variety of multiwavelength surveys indicate that the rate at which galaxies form stars has changed with cosmic time, increasing by about one order of magnitude from z ~ 0 to z ~ 1–2, when the cosmic star formation had a likely maximum (Lilly et al. 1996; Pérez-González et al. 2005; Hopkins & Beacom 2006; Karim et al. 2011; Sobral et al. 2013). A similar behaviour is found for the specific star formation rate (sSFR) – the ratio between the star formation rate (SFR) and stellar mass – at a given stellar mass (Noeske et al. 2007; Dutton, van den Bosch & Dekel 2010; Magdis et al. 2010; Sobral et al. 2014). However, there is still some debate about the behaviour at z > 2–3, because there are several uncertain factors involved in the analysis, such as dust-correction factors or the contribution of emission lines in the determination of stellar mass (Bouwens et al. 2009, 2012; Stark et al. 2013; González et al. 2014).

In agreement with the evolution of the cosmic SFR, the molecular gas content of star-forming (SF) galaxies is also higher at z ~ 2 than at lower redshifts, although it is claimed that the star-formation efficiency does not strongly depend on cosmic epoch (Daddi et al. 2010; Tacconi et al. 2010; Magdis et al. 2012a, b). The implication...
of this is that the increase of the cosmic SFR density with redshift is most likely driven by an increase in the molecular gas mass fraction of galaxies. A change in morphology is also found, from disc-like shapes in the local Universe to clumpy, irregular or compact morphologies at \( z \sim 2 \) (Elmegreen et al. 2009; Malhotra et al. 2012; Swinbank et al. 2012a,b). Given these rapid changes in galaxy properties, it is important to ensure uniform selection of galaxy samples at different epochs.

Several selection criteria have been traditionally applied to select SF galaxies at \( z \sim 2 \): (1) the Ly\( \alpha \) narrow-band (NB) technique, which selects Ly\( \alpha \) emitters (LAEs) by sampling the redshifted Ly\( \alpha \) emission line with a combination of NB and broad-band filters (e.g. Ouchi et al. 2008); (2) the Lyman break technique, which selects Lyman-break galaxies (LBGs) by using colours that sample the redshifted Lyman break and includes a rest-frame ultraviolet (UV) colour to rule out low-redshift interlopers (Steidel et al. 2003); (3) the \( BzK \) criterion (Daddi et al. 2004), which selects SF \( BzK \) (\( sBzK \)) galaxies with a double colour selection criterion involving optical and near-infrared (NIR) bands; (4) the BM/BX criterion, which select galaxies within \( 1 < z < 3 \) with different combinations of optical broad-band filters (Adelberger et al. 2004). Other selection criteria are based on far-infrared/submillimetre (FIR/submm) or radio data (Chapman et al. 2005; Riechers et al. 2013), although these identify only the highest SFR systems. The NB technique has also been applied in the NIR regime with the aim to look for H\( \alpha \) emitters (HAEs) at \( z \sim 2 \) (Bunker et al. 1995; Moorwood et al. 2000; Kurk et al. 2004; Geach et al. 2008; Hayes, Schaerer & "Ostlin 2010b; Lee et al. 2012; An et al. 2014; Sobral et al. 2013; Tadaki et al. 2013). In this way, it is possible to also use H\( \alpha \) to select and study SF galaxies all the way from the local Universe up to \( z \sim 2 \) (with H\( \alpha \) moving from the optical into the \( K \) band). This is a much simpler, self-consistent and well-understood selection; see Sobral et al. (2013), which is the only work so far where H\( \alpha \) emission has been traced from optical to \( K \) band in a single data set/analysis.

In order to understand the nature of SF galaxies at the peak of galaxy formation and the bias and incompleteness of each selection criterion, it is necessary to compare the physical properties of the galaxy samples selected by the different techniques. This study is important for all evolutionary conclusions based on a given population of galaxies, such as mass–metallicity relations, gas fractions, morphologies, colours, dynamics, etc. (Stott et al. 2013a,b). Furthermore, it provides a way to interpret galaxy evolution studies based on Ly\( \alpha \) and Lyman-break techniques, the ones that can be applied at the highest redshifts.

A comparison of the properties of LAEs, LBGs and \( sBzK \) galaxies has been already done (Grazian et al. 2007; Ly et al. 2009, 2011; Pentericci et al. 2010; Haberzettl et al. 2012; Oteo et al. 2014). Haberzettl et al. (2012) found that the \( BzK \) criterion is useful to select galaxies at \( z \sim 2 \), but the samples are biased towards massive SF galaxies and those with red stellar populations. Grazian et al. (2007) report that the \( sBzK \) criterion is efficient at finding SF galaxies at \( z \sim 2 \) but is highly contaminated by passively evolving galaxies at red \( z-K \) colours. They also found that the Lyman-break criterion misses dusty starburst systems. Oteo et al. (2014) found that most LBGs can be selected as \( sBzK \) galaxies, but most of these do not meet the Lyman-break criterion because this criterion is biased towards blue and/or UV-bright galaxies. Furthermore, they found that \( sBzK \) galaxies are similar to SF galaxies solely selected by their photometric redshift, and therefore represent an adequate population to study the bulk of SF galaxies at \( z \sim 2 \). However, the \( sBzK \) criterion cannot be used to carry out evolutionary studies, unlike the Lyman-break, Ly\( \alpha \) or H\( \alpha \) criteria, because of the use of a given filter set for the galaxy selection. However, extensions to higher redshift have been proposed with other broad-band filters (Guo et al. 2012). Additionally, \( sBzK \) galaxies do not represent by themselves a purely SFR-selected sample, but have a more complicated selection function.

The main objective of this paper is to study the properties of a sample of HAEs at \( z \sim 2.23 \) selected from the High Redshift(\( Z \)) Emission Line Survey (HIZELS; Geach et al. 2008; Sobral et al. 2009b,a, 2012, 2013, 2014). HIZELS uses a set of NB filters in NIR bands to look for emission-line galaxies up to \( z \sim 9 \). The study of HAEs will also allow us to analyse the accuracy of the H\( \alpha \) emission as a proxy of SFR and the relation between SFR and stellar mass at \( z \sim 2 \). Combining the H\( \alpha \) observations with available, matched Ly\( \alpha \) data, we also study the Ly\( \alpha \) escape fraction and its relation to galaxy properties.

This paper is organized as follows. In Section 2, we present the data sets used, the selection of our sources, and how we analyse them. In Section 3, we study the nature of HAEs and compare them with LAEs, LBGs and \( sBzK \) galaxies to place HAEs into the context of SF galaxies at the peak of cosmic star formation. In Section 4, we study the population of galaxies with both Ly\( \alpha \) and H\( \alpha \) emission, and analyse the Ly\( \alpha \) escape fraction at \( z \sim 2 \). We examine in Section 5 the accuracy of H\( \alpha \) emission as a tracer of star formation at \( z \sim 2 \). In Section 6, we explore the location of our galaxies in an SFR–mass plane and discuss in detail the uncertainties in the determination of the slope of the main sequence (MS) of star formation at \( z \sim 2 \). Finally, the main conclusions of the work are summarized in Section 7.

Throughout this paper, all stellar masses and SFRs reported are derived by assuming a Salpeter initial mass function (IMF). We assume a flat universe with \(( \Omega_m, \Omega_{\Lambda}, h_0) = (0.3, 0.7, 0.7) \), and all magnitudes are listed in the AB system (Oke & Gunn 1983).

2 METHODOLOGY

2.1 Data sets

Because of the availability of multiwavelength data and NB Ly\( \alpha \) and H\( \alpha \) observations over an overlapping redshift range, we focus on the Cosmic Evolution Survey (COSMOS) field (Scoville et al. 2007). In order to sample the SEDs and to study the stellar populations of the galaxies analysed in this paper (see Section 2.2), we take optical to NIR photometry from Ilbert et al. (2013), mid-IR Infrared Array Camera (IRAC) and Multiband Imaging Photometer for \textit{Spitzer} (MIPS) data from the S-COSMOS (Sanders et al. 2007), and \textit{Herschel} Photodetector Array Camera and Spectrometer (PACS) and SPIRE data from the PACS Evolutionary Probe (PEP) and \textit{Herschel} Multitiered Extragalactic Survey (HerMES) projects, respectively (Lutz et al. 2011; Oliver et al. 2012). High-quality photometric redshifts for the studied galaxies are taken from Ilbert et al. (2013). \textit{GALEX} (Zamojski et al. 2007) and \textit{CHANTLA} (Elvis et al. 2009) data are also used.

2.2 Source selection

The main objective of this work is the analysis of the properties of NB-selected HAEs at \( z \sim 2.23 \). In some sections of this paper, we use a sample of LAEs, LBGs and \( sBzK \) galaxies at \( z \sim 2 \) to help us to understand the properties of HAEs and to place them into the context of the SF population at \( z \sim 2 \). In this section, we explain how all these galaxies were selected.
The samples of HAEs and LAEs are taken from Sobral et al. (2013) and Nilsson et al. (2009), respectively. LAEs and HAEs were selected via the NB technique, with an NB filter centred at 3963 Å (129 Å width) for LAEs and at 2.121 μm (210 Å width) for HAEs. In addition to the NB criterion, HAE selection requires identification of the detected emission line as H\(\alpha\) at \(z \sim 2.23\) rather than other line emitters at different redshifts. This selection includes a \(BzK\) cut to remove low-redshift interlopers, a Lyman-break-like cut to remove \(z \sim 3.3\) [O\(\text{ii}\)] emitters, and inclusion of double and triple line emitters from the combination of all H\(\text{ZELs}\) NB filters. It should be pointed out that the \(sBzK\) criterion applied to HAEs does not produce the loss of galaxies with unusual colours, but it is used to increase the completeness of the sample. Also, it might be possible that a small number of HAEs have been missed because of their extremely blue SEDs (similar to those for LBGs; see Section 3). However, this percentage is estimated to be very low due to the use of double and triple line detections, because blue HAEs would have very strong emission lines and low reddening, and thus be detectable in [O\(\text{ii}\)] or [O\(\text{iii}\)] as well as H\(\alpha\) (for more details, see Sobral et al. 2013).

Completeness analysis indicates that LAEs are 90 per cent complete down to a Ly\(\alpha\) flux of \(f_{\text{Ly}\alpha} \sim 6 \times 10^{-17} \text{erg cm}^{-2} \text{s}^{-1}\) (Nilsson et al. 2009) and HAEs are 90 per cent complete down to an H\(\alpha\) flux of \(f_{\text{H}\alpha} \sim 5.6 \times 10^{-17} \text{erg cm}^{-2} \text{s}^{-1}\) (Sobral et al. 2013). We recall at this point that the Ly\(\alpha\) and H\(\alpha\) NB filters used in Nilsson et al. (2009) and Sobral et al. (2013), respectively, select galaxies over an overlapping redshift range. The Ly\(\alpha\) filter is broader than the H\(\alpha\) filter in the redshift space, and therefore selects galaxies over a wider redshift range, with the redshift range of HAEs being fully included within the redshift range of LAEs. The great advantage is that it will be possible to study galaxies with both Ly\(\alpha\) and H\(\alpha\) emission, even if Ly\(\alpha\) has a velocity offset with respect H\(\alpha\) (see Section 4).

It is important to point out that among the whole sample of 187 LAEs of Nilsson et al. (2009), only 118 have a counterpart in the Ilbert et al. (2013) catalogue, which is the data set that we use for optical-to-NIR SED fits. This represents 63 per cent of the sample. The non-detections are mainly a consequence of the blue nature of these LAEs, which are clearly detected in \(U\), \(B\), \(r\) or \(i\) bands, but are very faint in \(z\) and redder bands. The non-detection in the NIR is an indication of their low stellar mass, being less massive than HAEs and other SF galaxies detected in the NIR. The significant number of LAEs without NIR counterparts indicates that the Ly\(\alpha\) technique tends to select low-mass, blue galaxies. Accurate SED fits cannot be carried out for those faint LAEs due to the lack of NIR information that is essential for age, stellar mass and redshift estimations. Stacking might be an alternative, but it has been reported that stacking in LAEs does not provide reliable estimations of the median properties of the population (Vargas et al. 2014). Therefore, we have decided not to include these LAEs in the analysis. This might bias our results because we only include in the final sample the most massive LAEs selected through the NB technique in Nilsson et al. (2009). We indicate the implications of this in the relevant sections of the paper.

Regarding HAEs, most have a counterpart in the Ilbert et al. (2013) catalogue, with only 8 per cent being undetected. The non-detections are mainly due to the faintness of that small population of HAEs in optical bands. At the same time, this is an indication that the HAE selection is also able to identify very dusty sources that might be missed in optical-based studies. We do not include the previous 8 per cent of faint HAEs in our analysis because their UV continuum cannot be well constrained. They represent a very low percentage of the total sample, and therefore their exclusion is not expected to affect significantly the conclusions presented in this work. However, it should be noted that due to their red colours (e.g. high dust extinction) they might be a significant proportion of dust-extinguished HAEs.

LBGs and \(sBzK\) galaxies are taken from Oteo et al. (2014). LBGs were selected with the classical dropout technique, where the near-ultraviolet (NUV) and \(U\) bands were used to sample the Lyman break at \(z \sim 2\) and a \(U-V\) colour was used to avoid contamination from low-redshift interlopers. Furthermore, non-detection in the GALEX far-ultraviolet (FUV) band was imposed. The \(BzK\) galaxies were selected using the criterion of Daddi et al. (2004), which picks up both SF galaxies (\(sBzK\) galaxies) and quiescent galaxies (\(pBzK\) galaxies). Because we are interested in galaxies dominated by star formation, we only consider \(sBzK\) galaxies for most of the analysis presented in this paper, although \(pBzK\) galaxies will be used for a comparison in some discussions. While LAEs and HAEs have a narrow redshift distribution as a result of their selection with NB filters, LBGs and \(sBzK\) have redshifts spanning typically \(1.5 < z < 2.5\) (Daddi et al. 2004; Oteo et al. 2014). Therefore, in order to carry out a fairer comparison with LAEs and HAEs at \(z \sim 2.23\), we additionally limit the photometric redshift of LBGs and \(sBzK\) galaxies to \(2.0 < z_{\text{phot}} < 2.5\). This redshift range has been selected to account for the uncertainties of photometric redshift determinations at \(z \sim 2.25\) (Ilbert et al. 2013). To avoid a possible presence of any low-redshift interlopers in the HAE and LAE samples, we also limit their photometric redshifts to the same range: \(2.0 < z_{\text{phot}} < 2.5\). Again, this range is chosen to account for the \(z_{\text{phot}}\) uncertainties.

We clean all samples of contamination from active galactic nuclei (AGNs) by removing all sources with X-ray CHANDRA detections (Elvis et al. 2009). It should be pointed out that the percentage of X-ray detections in our galaxies is low, less than 5 per cent in all four samples studied. Additionally, we use GALEX photometry (Zamojski et al. 2007) to clean our samples from low-redshift interlopers. At \(z \sim 2\), the Lyman break is redshifted out of the UV regime and therefore our galaxies cannot be detected in GALEX bands.

After all these considerations, we end up with a sample of 373 HAEs, 69 LAEs, 3751 LBGs and 13 194 \(sBzK\) galaxies. We note that out of all the samples, HAEs are the ones drawn from the smallest volume, followed by LAEs, LBGs and \(sBzK\) galaxies. Thus, the number of galaxies in each sample is largely driven by the different volumes. The number density of HAEs is \(4.8 \times 10^{-4} \text{Mpc}^{-3}\) down to \(\log (L_{\text{H}\alpha}) > 42.0\) and the number density of LAEs is \(1.6 \times 10^{-4} \text{Mpc}^{-3}\) down to \(\log (L_{\text{Ly}\alpha}) > 42.3\). The number density of LAEs obtained here is smaller than the value reported in Nilsson et al. (2009), mostly due to our inclusion of the criterion to clean the sample from lower-redshift interlopers and because we only include in the sample galaxies detected in the NIR. Furthermore, the value reported in Nilsson et al. (2009) was calculated over 28 per cent of the area covered by their observations, which in turn represents 2 per cent of the entire area of the COSMOS field. This makes their calculation very uncertain, due to the influence of cosmic variance. The number density of LBGs is \(3.1 \times 10^{-4} \text{Mpc}^{-3}\), and the number density of \(sBzK\) galaxies is the highest in our samples, \(1.1 \times 10^{-3} \text{Mpc}^{-3}\), due to the high number of sources selected. Note also that LBGs and \(sBzK\) have different, more uncertain SFR limits.

### 2.3 Analysis

In the rest-frame UV to NIR regime, we analysed the nature of our selected galaxies via the traditional SED-fitting technique,

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massive galaxies. If templates with no emission lines had been used, the stellar masses would have been overestimated. The UV continuum (and hence SFR UV) fluxes. It can be seen in this figure that the best-fitting templates including emission lines have fainter rest-frame optical continua, and therefore represent less of the fits. Our HAEs (and also LAEs) are selected for having strong Hα (and Lyα) emission. Therefore, it is expected that emission lines affect their observed fluxes. It can be seen in this figure that the best-fitting templates including emission lines have fainter rest-frame optical continua, and therefore represent less massive galaxies. If templates with no emission lines had been used, the stellar masses would have been overestimated. The UV continuum (and hence SFR UV) of the best-fitting templates does not change significantly when emission lines are included.

Figure 1. Examples of SED fit results for six randomly selected HAEs from our sample. These fits are representative of the whole sample of HAEs studied in this work. The best-fitting BC03 templates including emission lines are shown in orange, and best-fitting templates with no emission lines are in green. Red open squares are the observed photometric data. Because of the uncertain contribution of the Lyα emission, the U-band information has not been included in the fits. Our HAEs (and also LAEs) are selected for having strong Hα (and Lyα) emission. Therefore, it is expected that emission lines affect their observed fluxes. It can be seen in this figure that the best-fitting templates including emission lines have fainter rest-frame optical continua, and therefore represent less massive galaxies. If templates with no emission lines had been used, the stellar masses would have been overestimated. The UV continuum (and hence SFR UV) of the best-fitting templates does not change significantly when emission lines are included.

using Bruzual & Charlot (2003, hereafter BC03) templates. To this end, we used LEPHARE (Arnouts et al. 1999; Ilbert et al. 2006). We included the emission lines in the stellar population templates (Schaerer & de Barros 2009; de Barros, Schaerer & Stark 2014) because we are working with SF galaxies and, in fact, LAEs and HAEs are selected through their emission lines. The strength of the Lyα emission is more uncertain than other emission lines due to its resonant nature. Therefore, we do not include U-band information in the fits. This does not significantly change the values of the SED-derived properties, because the UV continuum is well sampled with the other filters. In this way, the filters used in the fits are: Subaru B1, V1, r1, i1, z1 and VISTA Y, J, H, Ks (Ilbert et al. 2009; McCracken et al. 2012). IRAC data for the IRAC-detected galaxies are also included (Sanders et al. 2007).

The BC03 templates used in this work were built by assuming an exponentially declining SFH and a fixed metallicity Z = 0.2 Z⊙. We considered time-scale τSFH values of 0.1, 0.2, 1.0, 2.0, 3.0 and 5.0 Gyr. We chose a fixed value for metallicity because this parameter tends to suffer from large uncertainties (see for example, de Barros et al. 2014). For age, we considered values ranging from 10 Myr to 3.4 Gyr, the age of the Universe at the median redshift of our galaxies. Age values were taken in steps of 10 Myr from 10 to 100 Myr, in steps of 20 Myr from 100 to 200 Myr, in steps of 50 Myr from 200 to 500 Myr, in steps of 100 Myr from 500 Myr to 1 Gyr, and in steps of 0.2 Gyr from 1.0 to 3.4 Gyr. Dust attenuation was included in the templates via the Calzetti et al. (2000) law and parametrized through the colour excess in the stellar continuum, E(B − V), for which values ranging from 0 to 0.7 in steps of 0.05 were considered.

Once the templates are fitted, the rest-frame UV luminosity for each galaxy was obtained from its normalized best-fitting template and converted to SFRUV via the Kennicutt (1998) calibration. Note that SFRUV is not corrected for dust attenuation. The UV continuum slope was obtained by fitting a power-law function to the UV continuum of each best-fitting template. Fig. 1 shows the SED fit results for six HAEs randomly selected from our sample. For reference, the best-fitting templates with no inclusion of emission lines (also fitted with LEPHARE) are also included. It can be seen that emission lines have a clear effect on the observed fluxes and the best-fitting rest-frame optical continuum emission. This is because the strongest rest-frame optical emission lines are sampled with some broad-band filters used in the fits: Hα is within the K band, [O III]5007 within the H band and [O II]3727 within the J band. While the rest-frame UV SEDs are similar in all the cases, fainter rest-frame optical continua are obtained when including the effect of emission lines. This translates into lower stellar masses and younger ages.

Among the whole sample of SF HAEs, only nine are individually detected in any of the Herschel bands. This represents a detection rate of 3 per cent. Interestingly, despite being very low, the percentage of Herschel detections is higher for HAEs than for LBGs (~0.7 per cent) or sBc:K galaxies (~0.5 per cent). This indicates that the Hα selection can recover not only relatively dust-free sources, but also highly dust-obscured sources. However, the comparison between the number of Herschel detections and physical properties is challenging because at z ~ 2 Herschel only selects the most extreme galaxies rather than normal SF galaxies. Source confusion is also a major problem when analysing the FIR emission of UV, optical or NIR-selected galaxies. We have attempted to identify source confusion by analysing the optical Advanced Camera for Surveys (ACS) images of the galaxies along with the MIPS 24-μm and Very Large Array (VLA) contours. As an example, see results in Fig. 2 for the three SPIRE 500-μm detected HAEs. The size of the images are ~0 arcsec on each side, slightly larger than the SPIRE 500-μm beam, the Herschel band with the largest point spread function (PSF). In the three cases, the location of the MIPS detection is coincident with a radio emission, indicating that there is no significant contribution of nearby FIR-bright sources that might contaminate the fluxes in the SPIRE bands. The contamination is even more unlikely in PACS bands, because their PSF is two to four times smaller than SPIRE beams. As a sanity check for SPIRE-detected sources, we have re-done the FIR SED fits including only their less-likely contaminated PACS photometry. The values obtained for the total IR luminosity, and hence for SFRIR, are in agreement with those including SPIRE data within the uncertainties (~0.1–0.2 dex). It should be pointed out that there are two LAEs individually detected in Herschel but they are also detected in X-ray and, consequently, have a likely
AGN nature and are not considered in this work (see Section 2.2 and Bongiovanni et al. 2010).

The IR SEDs of the FIR-detected galaxies are fitted with Chary & Elbaz (2001, hereafter CE01), Dale & Helou (2002), Polletta et al. (2007) and Berta et al. (2013) templates. As an example, we show in Fig. 3 the IR SEDs of the three HAEs detected in SPIRE 500-µm. The presence of the rest-frame 1.6-µm stellar bump (sampled with the IRAC bands at the redshift of our galaxies) is clear in the three galaxies, indicating that their SEDs are dominated by star formation. All the different templates fit well the IR SEDs of the galaxies, with similar values of \( \chi^2 \). We choose to report the results obtained with CE01 templates, as in many previous works in the literature. The best-fitting CE01 templates are integrated between rest-frame 8 and 1000 µm to derive total IR luminosities, \( L_{\text{IR}} \). These are then converted into SFR by using the Kennicutt 1998 calibration. The total SFR is then obtained by assuming that all the light absorbed by dust in the UV is re-emitted in the FIR: \( \text{SFR}_{\text{total}} = \text{SFR}_{\text{UV}} + \text{SFR}_{\text{IR}} \).

Because most galaxies are not individually detected in the FIR, we also performed stacking analysis in Herschel bands to study the FIR emission of Herschel-undetected galaxies; see, for example, Ibar et al. (2013) for stacking analysis in HAEs at \( z \sim 1.47 \). One single band near the peak of the dust SED is enough to estimate the total IR luminosity. We focused on the PACS 160-µm band for stacking, due to its relatively small beam, and employ the residual maps, as in many previous works. We stacked by using the publicly available IAS Stacking Library (Béthermin et al. 2010) and uncertainties in the stacked fluxes were derived by using bootstraps. For HAEs, we stacked in different bins of stellar mass [from \( \log (M_*/M_\odot) = 9.5–11 \text{ in bins of 0.5 dex} \] and dust-corrected H\( \alpha \)-derived SFR (SFR\( \text{H}_\alpha \)) [from \( \log (\text{SFR}_{\text{H}_\alpha}(M_\odot \text{yr}^{-1})) = 1.0 \text{ to 2.0 in bins of 0.5} \]). Those bins cover the whole range of values for those parameters. For sBzK galaxies, where the number of sources is high and allows stacking over more stellar mass bins, we stacked \( \log (M_*/M_\odot) = 9.8–11.6 \text{ in bins of 0.2 dex} \).

![Figure 2](http://mnras.oxfordjournals.org/)

**Figure 2.** Analysis of source confusion and contamination at FIR wavelengths from nearby sources in the three SPIRE 500-µm detected HAEs. The MIPS 24-µm (green) and VLA (yellow) contours are overplotted in the ACS I-band images of the galaxies. HAEs are located in the centre of each image. Images are 40 arcsec on each side, slightly larger than the SPIRE 500-µm beam, the Herschel band with the largest PSF. The VLA and MIPS detections, which have better spatial resolution than PACS and SPIRE, indicate that there is no significant contribution of possible nearby FIR-bright sources that might contaminate the HAE Herschel fluxes. The PSF of PACS bands is much smaller than the SPIRE PSFs, so contamination is even more unlikely.

![Figure 3](http://mnras.oxfordjournals.org/)

**Figure 3.** IR SEDs of the three SPIRE 500-µm detected HAEs as an illustration of the SED-fitting results for the Herschel-selected galaxies studied in this work. We plot the observed photometry in \( K_s \), the four IRAC bands, MIPS 24-µm, PACS and SPIRE. The best-fitting Chary & Elbaz (2001), Dale & Helou (2002) and Berta et al. (2013) templates are also shown, with the colour code indicated in the bottom-right legend. In the SED fits, a redshift of \( z = 2.23 \) has been assumed. The data provide a good sampling of the dust emission peak in HAEs at \( z \sim 2.23 \). Therefore, the integration of the best-fitting templates between 8 and 1000 µm provides an accurate determination of their total IR luminosities and, consequently, dust-corrected SFR. No significant difference is found for \( L_{\text{IR}} \) when using different templates. We choose to report results obtained with Chary & Elbaz (2001) templates, as in many previous works.
The nature of Hα emitters at $z \sim 2$

Fig. 4 shows the SED-derived dust attenuation, stellar mass, UV continuum slope and dust-corrected total SFR of our selected HAEs (orange-filled histograms). We include the distributions obtained for LAEs, LBGs and sBzK galaxies. These properties were obtained by fitting BC03 templates to the observed multiwavelength photometry (from B to IRAC bands, when available) of each galaxy. The BC03 templates were built by assuming an exponentially declining SFH and a fixed metallicity of $Z = 0.2 Z_\odot$. Emission lines were also included in the templates. Histograms have been normalized to their maxima in order to clarify the representations. The distributions indicate that HAEs and sBzK galaxies have similar stellar populations, both in the median values and in the range covered. HAEs have a very well-defined selection criterion, and therefore represent an excellent sample for studies of star formation at $z \sim 2$. LAEs are significantly biased towards blue, less massive and dust-poor galaxies.

Table 1. Stacked PACS 160-µm fluxes and their associated total IR luminosities for our sample of sBzK galaxies at $2.0 < z_{\text{phot}} < 2.5$.

<table>
<thead>
<tr>
<th>Stellar mass range</th>
<th>Stacked $f_{160 \mu m}$</th>
<th>log$(L_{IR}/L_\odot)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$9.8 \leq \log (M_*/M_\odot) &lt; 10.0$</td>
<td>0.53 $\pm$ 0.05 mJy</td>
<td>11.4 $\pm$ 0.1</td>
</tr>
<tr>
<td>$10.0 \leq \log (M_*/M_\odot) &lt; 10.2$</td>
<td>0.80 $\pm$ 0.06 mJy</td>
<td>11.5 $\pm$ 0.1</td>
</tr>
<tr>
<td>$10.2 \leq \log (M_*/M_\odot) &lt; 10.4$</td>
<td>1.00 $\pm$ 0.09 mJy</td>
<td>11.6 $\pm$ 0.1</td>
</tr>
<tr>
<td>$10.4 \leq \log (M_*/M_\odot) &lt; 10.6$</td>
<td>1.20 $\pm$ 0.12 mJy</td>
<td>11.7 $\pm$ 0.1</td>
</tr>
<tr>
<td>$10.6 \leq \log (M_*/M_\odot) &lt; 10.8$</td>
<td>1.23 $\pm$ 0.12 mJy</td>
<td>11.7 $\pm$ 0.1</td>
</tr>
<tr>
<td>$10.8 \leq \log (M_*/M_\odot) &lt; 11.0$</td>
<td>1.40 $\pm$ 0.17 mJy</td>
<td>11.8 $\pm$ 0.1</td>
</tr>
</tbody>
</table>

We only detected stacked fluxes for HAEs in the bin corresponding to the highest stellar mass [$10.5 \leq \log (M_*/M_\odot) < 11.0$, where 66 galaxies are included and the stacked flux is $f_{160 \mu m} = 1.4 \pm 0.3$ mJy, corresponding to log$(L_{IR}/L_\odot) = 11.8 \pm 0.1$] and highest SFR$_{160}$ [1.5 $\leq$ log(SFR$_{160}$) $<$ 2.0, where 166 sources are included and the stacked flux is $f_{160 \mu m} = 1.0 \pm 0.2$ mJy, corresponding to log$(L_{IR}/L_\odot) = 11.3 \pm 0.1$]. This is consistent with more massive SF galaxies being more affected by dust, in agreement with Garn & Best (2010), Sobral et al. (2012) or Ibar et al. (2013), although it could also be due to a pure scaling of the SED. We also stacked LAEs as a function of stellar mass (with the same bins as for HAEs), but no stacked detections are recovered, probably because of the low number of sources producing poor statistics and also the less dusty nature of LAEs (see also Section 3). In sBzK galaxies, we recover detections for 9.8 $< \log (M_*/M_\odot) < 11.0$ with more than 1000 galaxies in each bin. The recovered stacked fluxes are summarized in Table 1. The stacked PACS 160-µm fluxes were converted into $L_{IR}$ by using single-band extrapolations with CE01 templates and errors were obtained from the flux uncertainties. SFR$_{IR}$ were obtained with the Kennicutt (1998) calibration.

3 THE NATURE OF Hα EMITTERS AT $z \sim 2$

Fig. 4 shows the SED-derived dust attenuation, stellar mass, UV continuum slope and dust-corrected SFR of our HAEs at $z \sim 2$. It can be seen that HAEs can be either dust-poor (and have blue UV slopes) or dusty (and have red UV slopes) and have a wide range of stellar masses and dust-corrected SFR. This already indicates that our sample of SF HAEs, selected down to a fixed dust-uncorrected SFR, is not significantly biased towards any SED-derived property. The distributions of SED-derived properties of HAEs resemble those for sBzK galaxies, one of the classical populations traditionally used to study galaxy properties at $z \sim 2$. However, HAEs seem to have slightly higher stellar masses and SFR on average, probably due to their selection based on SFR. The distributions for HAEs contrast with those found for LAEs, which have much lower dust attenuation and stellar mass, and much bluer UV continuum slopes on average. This indicates that Lyα and Hα samples are formed, on average, with galaxies with different stellar populations (although the values obtained for LAEs are within the distributions found for HAEs). This suggests that the selection based on Lyα is much more biased than the selection in Hα and that using Lyα to select high-redshift galaxies might lead to the loss of a significant population at a given redshift (mostly the reddest and most massive galaxies). Fig. 4 shows that the sample of LBGs is also slightly biased towards galaxies with lower dust attenuation and bluer UV continuum slope, although the effect is not as strong as it is for LAEs.

Fig. 5 shows the relation between colour and stellar mass for our HAEs. We choose the $Y - K$ colour because it matches at $z \sim 2$ with the rest-frame $u - r$ colour traditionally used to define the blue cloud and the red sequence in the local Universe (see for example, Strateva et al. 2001). Defining a clear difference between the blue cloud and red sequence at $z \sim 2$ is challenging because of the low number of passive galaxies populating the red sequence. However, we consider here that $pBzK$ galaxies represent the prototype of passive galaxies populating the red sequence at $z \sim 2$. These galaxies are also represented in Fig. 5. HAEs cover a wide range of colours and stellar masses and thus they represent a diverse population with a range of properties. Hα selection only misses a small population of the bluest and least massive galaxies at $z \sim 2.25$. Some SF HAEs even have colours similar to $pBzK$ galaxies, as happens for obscured galaxies with intense, obscured star formation (Oteo et al. 2013b, 2014).

Interestingly, although most galaxies with Lyα emission have low dust attenuation and blue colours, there is a population of 12 red LAEs with log$(M_*/M_\odot) > 10.25$. Their stellar masses are as high as the most massive HAEs. All 12 red LAEs are detected in...
For reference, we also plot the location of the \(pBzK\) define the blue cloud and red sequence in local galaxies (Strateva et al. 2001). For reference, we also plot the location of the \(pBzK\) quiescent population (Daddi et al. 2004) and LAHAEs (see Section 4). We also represent the distributions of \(Y – K\) colour and stellar masses for each type of galaxy but not for LAHAEs, because of their low number. It can be clearly seen that HAEs are well distributed across a wide range of colours and stellar masses as are \(sBzK\) galaxies. However, LAEs and LBGs are the galaxies with the bluest colours and lowest masses, indicating the biased nature of those selections. LBGs and \(sBzK\) galaxies are distributed over a larger area because of their wider photometric redshift distributions. Most LAEs are blue and less massive, but there is a small population of LAEs with red colours. Although the number of such red LAEs is not high, it indicates that Ly\(\alpha\) emission can also escape from dusty, red systems, as previously reported from individual detections in FIR wavelengths.

IRAC and there is no indication of power-law-like mid-IR SED, so these red LAEs are SF galaxies rather than AGNs (note that AGN contamination in all our samples has been avoided by discarding galaxies with X-ray detection). This population represents a low fraction of the whole LAE sample, but it indicates that Ly\(\alpha\) emission can also escape from dusty, massive and red galaxies, as previously shown via optical colours (Stiavelli et al. 2001) and submm or FIR detections at different redshifts (Chapman et al. 2005; Oteo et al. 2012a,b; Casey et al. 2012; Sandberg et al. 2015). Ly\(\alpha\) surveys over larger areas would be needed to increase the samples of red and massive LAEs and to study in detail how and why Ly\(\alpha\) can escape from dusty galaxies.

It is also important to examine the overlap between HAEs and other populations of SF galaxies at \(z \sim 2.25\). In other words, what is the fraction of galaxies of a given type that could have been selected/missed through any of the other criteria? This study has already been carried out by Oteo et al. (2014) for LBGs, UV-selected and \(sBzK\) galaxies. They concluded that most LBGs can be also selected through the \(sBzK\) criterion and only 25 per cent of \(sBzK\) galaxies would have been selected as LBGs (mainly because of the bias of the Lyman-break selection towards UV-bright galaxies).

Consequently, \(sBzK\) galaxies are a better representation of the bulk of SF galaxies over \(1.5 < z < 2.5\) than LBGs.

Fig. 6 represents the classical colour–colour diagram employed to select high-redshift \(BzK\) galaxies, both SF and passively evolving (Daddi et al. 2004). Studying the location of our selected HAEs in such a diagram gives information about the overlap between those populations. Most HAEs can be also selected as \(sBzK\) galaxies. As commented in Section 2.2, this was expected for HAEs because a \(BzK\) selection was applied in Sobral et al. (2013) to the NB-selected HAEs to avoid contamination from low-redshift interlopers. HAEs cover the same range of colours as \(sBzK\) galaxies, confirming that they are not strongly biased towards either dust-obscured or dust-free objects. However, as suggested by Fig. 5, the \(H\alpha\) selection might miss the bluest galaxies (now in terms of their \(z – K\) colour) at \(z \sim 2.25\), as happens to \(sBzK\) galaxies. Actually, there is a subpopulation of blue LBGs with \(BzK = (z – K)_{AB} \leq 1\) that cannot be selected as \(sBzK\) galaxies.

Figure 5. Relation between the \(Y – K\) colour and stellar mass for our sample of HAEs at \(z \sim 2.25\). We also represent the location of LAEs, LBGs and \(sBzK\) galaxies selected in the same field. At the redshift of our galaxies, \(Y – K\) matches the rest-frame \(u – r\) colour used to study the colour distribution and to define the blue cloud and red sequence in local galaxies (Strateva et al. 2001). For reference, we also plot the location of the \(pBzK\) quiescent population (Daddi et al. 2004) and LAHAEs (see Section 4). We also represent the distributions of \(Y – K\) colour and stellar masses for each type of galaxy but not for LAHAEs, because of their low number. It can be clearly seen that HAEs are well distributed across a wide range of colours and stellar masses as are \(sBzK\) galaxies. However, LAEs and LBGs are the galaxies with the bluest colours and lowest masses, indicating the biased nature of those selections. LBGs and \(sBzK\) galaxies are distributed over a larger area because of their wider photometric redshift distributions. Most LAEs are blue and less massive, but there is a small population of LAEs with red colours. Although the number of such red LAEs is not high, it indicates that Ly\(\alpha\) emission can also escape from dusty, red systems, as previously reported from individual detections in FIR wavelengths.

Figure 6. Location of our HAEs at \(z \sim 2.25\) in the colour–colour diagram employed to look for \(BzK\) galaxies at \(z \sim 2\) (Daddi et al. 2007). We also represent the location of LAEs, LBGs and LAHAEs (see Section 4). The distributions of \(B – z\) and \(z – K\) colours are also represented for each type of galaxy but not for LAHAEs, because of the low number of galaxies in that sample. It can be seen that most LAEs, LBGs and HAEs can also be selected through the \(sBzK\) criterion. There is a small population of LBGs (and a less numerous sample of LAEs) that are missed through the \(sBzK\) criterion, indicating that it misses the bluest and youngest galaxies at \(z \sim 2\).
As commented above, the $U$ band might be affected by the uncertain strength of the Ly$\alpha$ emission. The top-left inset plot in Fig. 7 shows the region of the SED around the Ly$\alpha$ emission. It can be seen that the $U$-band magnitudes of HAEs, LBGs and sBzK galaxies agree well with the best-fitting templates. Therefore, in these galaxies, the equivalent width of the Ly$\alpha$ emission is not high enough to alter significantly the $U$-band fluxes. This indicates that HAEs, LBGs and sBzK galaxies do not have Ly$\alpha$ emission with high equivalent width, on average. This is not the case for LAEs. The median $U$-band flux of LAEs is brighter than that predicted by the templates, suggesting intense Ly$\alpha$ emission with high equivalent widths, as expected by their selection. These results indicate that the Ly$\alpha$ emission has high equivalent width only in a small sample of galaxies, reducing the chances of finding strong Ly$\alpha$ emission in a general population of SF galaxies at $z \sim 2$. Our selected LBGs have higher rest-frame UV luminosities than the other galaxies analysed in this work. Their lack of strong Ly$\alpha$ emission, on average, is thus in agreement with the results reported in Schaerer, de Barros & Stark (2011), who found that, at a given redshift, the Ly$\alpha$ emission is more common in galaxies with fainter UV magnitudes (see also Stark et al. 2010).

It should be pointed out that the comparison between the different samples presented in this paper is very dependent on the depth of the surveys used to select them. However, COSMOS is one of the deepest sets of multiwavelength data available. Therefore, it makes a good judgement of the biases that affect samples selected at $z \sim 2$ through the studied selection criteria for most deep extragalactic surveys. One alternative to overcome this limitation would be to use the lensing power of massive clusters of galaxies, as was done by Alavi et al. (2014), allowing us to detect galaxies much fainter than previous surveys at $z \sim 2$. However, this is not the traditional way of selecting LAEs, sBzK or HAEs as normally they are searched and analysed in well-known cosmological fields where a wealth of deep multiwavelength observations are available for their analysis.

**4 MATCHED Ly$\alpha$ AND H$\alpha$ EMITTERS: Ly$\alpha$ ESCAPE FRACTION AT $z \sim 2.23$**

Of special interest is the analysis of the galaxies that exhibit both Ly$\alpha$ and H$\alpha$ emission (Lyr$\alpha$-H$\alpha$ emitters, LAHAEs), not only because of the low number of such sources reported so far at $z \sim 2$, but also because they allow us to constrain the escape fraction of Ly$\alpha$ photons (Hayes et al. 2010a; Song et al. 2014). As indicated in Section 2.2, we can study LAHAEs because the Ly$\alpha$ and H$\alpha$ NB filters used in Nilsson et al. (2009) and Sobral et al. (2013) select galaxies within an overlapping redshift slice over the same region of the sky. The Ly$\alpha$ observations select galaxies over the redshift range $2.206 \lesssim z_{Ly\alpha} \lesssim 2.312$. The H$\alpha$ observations cover $2.216 \lesssim z_{H\alpha} \lesssim 2.248$. The Ly$\alpha$ observations cover a wider redshift range than the H$\alpha$ observations. Therefore, if HAEs had strong Ly$\alpha$ emission, they should have been detected in the Ly$\alpha$ filter.

In the overlapping region of the COSMOS field observed by the Ly$\alpha$ and H$\alpha$ NB filters, there are 158 HAEs and 146 LAEs.\(^1\) However, there are only seven galaxies in common between the two

\(^1\) We should point out that we include here the whole sample of LAEs, both detected and undetected in NIR wavelengths. The reason is that we are interested in the fraction of HAEs with Ly$\alpha$ emission, not in the SED-derived properties of galaxies with Ly$\alpha$ emission (for which only NIR-detected LAEs should be included; see Section 2.2). The seven LAHAEs have detection in NIR wavelengths, so good SED fits can be carried out.
samples. Therefore, only 4.5 per cent of HAEs have strong enough \( \text{Ly}\alpha \) emission to be selected as LAEs. This implies very low \( \text{Ly}\alpha \) escape fraction at \( z \sim 2 \) and agrees with Hayes et al. (2010a), who found six LAHAEs in their sample, implying an average \( \text{Ly}\alpha \) escape fraction of \( \sim 5 \) per cent. These results reinforce the different nature of the galaxies selected through the \( \text{H}\alpha \) and \( \text{Ly}\alpha \) NB techniques and highlight the low chance of finding galaxies with \( \text{Ly}\alpha \) emission, at least at \( z \sim 2.23 \). It should be remarked that the results of Hayes et al. are based on \( \text{Ly}\alpha \) observations about 10 times deeper than those used in this work. Similarly, the \( \text{H}\alpha \) survey in Hayes et al. (2010a) is about two times deeper than HiZELS. However, we cover in this work an area of the sky that is about 20 times higher than in Hayes et al. (2010a). Therefore, the results complement each other in different regimes of \( \text{Ly}\alpha \) and \( \text{H}\alpha \) brightness and area surveyed. We have explicitly indicated in Fig. 6 the location of LAHAEs. Among the seven joint detections, six have blue \( B-z \) colours compatible with almost flat UV continuum, whereas one of them has a red SED. Apart from the red LAHAE with SED-derived \( E_s(B-V) \sim 0.5 \), the remaining LAHAEs have a median dust attenuation of \( E_s(B-V) \sim 0.15 \). Their ages range between 1 and 900 Myr.

We derive the \( \text{Ly}\alpha \) escape fraction in our LAHAEs from the ratio between the intrinsic and observed \( \text{Ly}\alpha \) luminosities and assuming case B recombination, so the intrinsic \( \text{Ly}\alpha \) emission can be obtained from the intrinsic (dust-corrected) \( \text{H}\alpha \) luminosity. In order to make a fair comparison with previous works, the \( \text{H}\alpha \) luminosity is corrected for dust attenuation by using the SED-derived \( E_s(B-V) \):

\[
f_{\text{esc}} = \frac{L_{\text{obs}}(\text{Ly}\alpha)}{8.7 \times L_{\text{obs}}(\text{H}\alpha) \times 10^{0.4 E_s(B-V) \times 5 \times 3.1 }}.
\]

In equation (1), we have assumed that \( E_s(B-V) = E_s(B-V) \), as this has been reported in several previous works to happen at high redshift (see for example, Reddy & Steidel 2004; Erb et al. 2006; Reddy et al. 2010). However, it should be remarked that this has not been proven accurately, and will represent one of the major sources of uncertainties in our derived \( \text{Ly}\alpha \) escape fraction. This uncertainty affects not only our results but also the results reported in most previous works at similar redshifts, because a relation between \( E_s(B-V) \) and \( E_s(B-V) \) must be assumed.

In Fig. 8, we represent the \( \text{Ly}\alpha \) escape fraction as a function of the SED-derived dust attenuation, UV continuum slope, stellar mass and dust-corrected SFR_{H\alpha} for our LAHAEs at \( z \sim 2.23 \).

For comparison, we also represent the nine LAHAEs reported in Song et al. (2014) with both \( \text{Ly}\alpha \) and \( \text{H}\alpha \) emission (UV continuum slopes are not provided for individual galaxies in Song et al. 2014). To be consistent, we take the observed \( \text{Ly}\alpha \) and \( \text{H}\alpha \) fluxes and the SED-derived properties from Song et al. (2014) and then the \( \text{Ly}\alpha \) escape fraction is calculated with equation (1). However, we note that the selection criteria are not the same in both samples. Here we use the classical NB technique to look for LAEs and HAEs, whereas the LAEs in Song et al. (2014) were found through blind spectroscopy and then followed up with NIR spectroscopic observations. Actually, the \( \text{Ly}\alpha \) luminosities of the LAHAEs in Song et al. (2014) are higher than for the LAHAEs presented in this work. Despite these differences, the \( \text{Ly}\alpha \) escape fractions derived in both works agree well.

It can be seen from Fig. 8 that the \( \text{Ly}\alpha \) escape fraction decreases with increasing dust attenuation, as previously reported at similar and lower redshifts (Hayes et al. 2014; Atek et al. 2014; Song...
et al. 2014), and also with increasing (redder) UV continuum slope (a proxy for dust attenuation) and higher stellar mass and SFR. We also include in Fig. 8 the upper limits on the Ly$\alpha$ escape fraction in those LAEs whose Ly$\alpha$ is not detected. These upper limits have been calculated assuming a limiting Ly$\alpha$ EW of 80 Å (Nilsson et al. 2009). The upper limits indicate that the relations found for LAHAEs correspond to the upper envelope of the actual correlations. However, upper limits also indicate that the highest Ly$\alpha$ escape fraction seen at low dust attenuation and/or UV continuum slopes are not seen at higher dust attenuation and/or UV continuum slopes. These results indicate that Ly$\alpha$ emission preferentially escapes from blue, low-mass galaxies with low dust attenuation (with the exception of a low percentage of massive, red and dusty LAEs, as obtained in Section 3). This is in agreement with the SED-derived properties and colours found for LAEs in previous sections. It should be noted that the number of LAHAEs at $z \sim 2$ reported so far is low and, consequently, matched Ly$\alpha$–H$\alpha$ surveys over larger areas of the sky are needed to increase the number of LAHAEs and have more robust results with higher statistical significance.

5 H$\alpha$ SFR VERSUS UV AND UV+IR: A CONSISTENT VIEW

The H$\alpha$ emission is an excellent tracer of instantaneous star formation and calibrations between the SFR and the H$\alpha$ luminosity have been proposed in the literature (see for example, Kennicutt 1998). The H$\alpha$ emission is affected by dust attenuation (although to a much lesser extent than, for example, the UV). Therefore, in order to derive the total SFR from H$\alpha$, accurate dust-correction factors are needed. In the local Universe, where a significant percentage of galaxies can be detected in the FIR or their H$\alpha$ and H$\beta$ emissions can be measured, the dust-correction factors can be determined with acceptable accuracy. However, this is much more challenging for galaxies in the high-redshift Universe, complicating the determination of the total SFR.

In this section, we examine the robustness of the H$\alpha$ emission as a tracer of SFR at $z \sim 2.23$ for our HAEs. We first compare the results obtained from H$\alpha$ and UV estimates of the SFR when dust correction is not taken into consideration. This is shown in the left panel of Fig. 9. As can be seen, the two tracers of star formation give significantly different results, with the H$\alpha$-derived SFR being higher than that obtained from the rest-frame UV luminosity. The median values found are SFR$_{H\alpha}$ = 13.7 ± 9.0 M$_\odot$ yr$^{-1}$ and SFR$_{UV}$ = 7.4 ± 6.6 M$_\odot$ yr$^{-1}$, where the uncertainties represent the interquartile ranges.

In the right panel of Fig. 9, we show the comparison between H$\alpha$-derived and UV-derived SFRs when dust correction is included. We correct the rest-frame UV luminosities by using the relation between the dust attenuation and UV continuum slope derived in Heinis et al. (2013), as in Section 3. The dust correction of the H$\alpha$ luminosity has been derived by using the relation between stellar mass and dust attenuation of Garn & Best (2010), that has been suggested to be valid for HAEs at least up to $z \sim 1.5$ (Sobral et al. 2012; Ibar et al. 2013; Domínguez et al. 2013; Price et al. 2014). In the right panel of Fig. 9, it can be seen that there is a very good agreement between the UV-derived and the H$\alpha$-derived SFRs, despite these being calculated with completely different and independent estimators at

Figure 9. Comparison between the SFR derived from H$\alpha$ and rest-frame UV luminosities for our studied HAEs at $z \sim 2$. Left panel: results without dust correction. Right panel: results when dust correction is included. The H$\alpha$ luminosities are corrected by dust attenuation by using the local relation between dust attenuation and stellar mass (Garn & Best 2010), suggested to be valid at least up to $z \sim 1.5$ (Sobral et al. 2012). The rest-frame UV luminosities are corrected by using the dust attenuation derived with the Heinis et al. (2013) relation. In both panels, the filled red squares represent the median SFR$_{UV}$ in different bins of SFR$_{H\alpha}$ and filled cyan squares represent the median SFR$_{UV}$ in different bins of stellar mass. The solid lines are the one-to-one relations and the dashed lines are deviations of ±0.3 dex. PACS-detected and stacked HAEs are represented in the right panel by filled green and orange dots, respectively. The error bars in the right panel show a lower limit on the uncertainties of the results. For the dust correction applied to H$\alpha$ luminosity, this uncertainty comes from the scatter in the best-fitting relation found in Sobral et al. (2012). It should be pointed out that the uncertainties affecting the dust corrections in H$\alpha$ are much lower than those affecting the rest-frame UV continuum, as the latter is much more affected by dust.
different wavelengths. The difference between the two estimators is typically lower than 0.3 dex for individual galaxies. Furthermore, both estimations agree quite well when galaxies are averaged over different bins of Hα-derived SFR or stellar mass. This result shows the robustness of the Hα emission as a tracer of SFR at $z \sim 2$, which adds to the unbiased and well-understood selection function of the Hα NB method to find SF galaxies at different redshifts (Sobral et al. 2012).

Previous works have also analysed the accuracy of Hα to recover SFRs at high redshift (e.g. Erb et al. 2006; Reddy et al. 2010). They correct from dust attenuation derived from SED fitting, $E_A(B - V)$, and assuming $E_A(B - V) = E_A(B - V) - 0.4 \times E_A(B - V)$, where $E_A(B - V)$ is the reddening for nebular emission. They actually obtained that the traditionally employed relation $E_A(B - V) = 0.4 \times E_A(B - V)$ (Calzetti et al. 2000) produces Hα SFRs that overpredict those derived from the X-ray and dust-corrected UV emissions. Recently, Steidel et al. (2014) applied a relation between $A_{Hα}$ and $E_A(B - V)$ that depends on the value of $E_A(B - V)$. The main advantage of our dust-correction method for Hα emission is that we do not require any assumptions about the relationship between $E_A(B - V)$ and $E_A(B - V)$, which is still until debate and has been suggested to be redshift-dependent (Kashino et al. 2013). Instead, we use a relation between dust attenuation and stellar mass that has been reported to be valid at least up to $z \sim 1.5$ for HAEs (Sobral et al. 2012).

We also compare in the right panel of Fig. 9 the Hα-derived total SFR with the total SFR obtained with direct Herschel detections for the nine PACS/ SPIRE-detected HAEs. As can be seen, the Hα emission, after the dust correction has been included, is not able to recover the more accurate SFR derived with PACS detections. This is because, at $z \sim 2$, Herschel only detects the most extreme sources, for which our average dust-correction factor applied to the Hα luminosity is not high enough (due to very high internal obscuration) to reproduce the more accurate Herschel-derived SFR. This also happens to the dust-correction factors derived from the UV continuum slopes in high-redshift Herschel-selected galaxies (see for example, Oteo et al. 2013a; Rodighiero et al. 2014). Stacking as a function of the Hα-derived total SFR, we only recover one >3σ stacked detection, also represented in the right panel of Fig. 9. The total SFR derived from the PACS stacked flux is higher (by about ~0.3 dex) with respect to the Hα determination. This might indicate that the dust-correction factor used to correct the Hα emission is more uncertain for the most massive HAEs with the highest SFRs, although deeper FIR data would be needed to confirm this trend to more normal SF galaxies with lower SFR.

6 SFVERSUS STELLAR MASS REATION AND ITS UNCERTAINTIES AT $z \sim 2$

6.1 Main sequence for HAEs at $z \sim 2$

Most previous works agree that there is a relation between the SFR and stellar mass, commonly referred to as the main sequence (MS), where normal SF galaxies are located (see Speagle et al. 2014 for a recent compilation). The MS has been reported to exist from the local Universe up to high redshift and to be relatively independent of environment (Koyama et al. 2013). However, less is known about the values of its zero-point and slope at a given redshift. One of the main reasons is the lack of FIR detections for a representative population of SF galaxies at each redshift, which prevents accurate determinations of the total SFR. Even with the deepest FIR surveys carried out so far (see for example, Elbaz et al. 2011), only a very small fraction of the galaxies are detected in the FIR, mostly at the highest redshifts (Oteo et al. 2013a, 2014). Furthermore, it is claimed that most high-redshift FIR-detected galaxies are not normal SF galaxies, but likely have a starburst nature and are preferentially located above the MS (Rodighiero et al. 2011; Lee et al. 2013; Oteo et al. 2013a, 2014). Therefore, even with Herschel-selected galaxies, it is not possible to determine the slope and zero-point of the MS at high redshift.

Now that we have evidence from Section 5 that the Hα emission is a good tracer of star formation at $z \sim 2.23$, that Hα provides a clean, well-understood, SFR-selected sample (not biased to either just blue or just red galaxies), that HAEs are an excellent representation of the whole population of SF galaxies at $z \sim 2$ (Section 3), and that their stellar masses cover a wider range than many previous studies at $z \sim 2$, we can attempt to study the relation between SFR and stellar mass and its uncertainties by using our sample of HAEs. This is shown by the orange points in Fig. 10, with the best-fitting MS indicated by the red line.

The main caveat of the analysis of the MS with our sample of HAEs is that they are selected down to a fixed SFR$_{Hα - uncorr}$.
Actually, our PACS-detected sBzK galaxies have even higher SFRs than those in Oteo et al. (2014) due to the shallower PACS data in COSMOS (Lutz et al. 2011). When stacking as a function of stellar mass, we only recover one detection for HAEs, also represented in Fig. 10. The stacked point is in agreement with the Daddi et al. (2007) MS and it is located slightly above the MS for HAEs found in this work. This is compatible with the previous result that the SFR derived from stacking is slightly higher than that derived from Hα in the most massive HAEs. For comparison, we also show the stacked points corresponding to the sample of sBzK galaxies. Only the most massive sBzK galaxies are detected through stacking. The stacked points for sBzK galaxies agree very well with the extrapolation of the MS for log (M*/M⊙) ≤ 10.25 HAEs towards higher stellar masses. However, the most massive stacked sBzK galaxies have higher SFRs than the most massive HAEs. This difference might be because the dust-correction factor employed to recover the total SFR might not be accurate for the most massive galaxies. However, it could also be as a consequence of a different nature between HAEs and sBzK galaxies for the most massive objects. The latter would be supported by the shape of their UV-to-NIR SEDs (see Fig. 7), because massive HAEs are bluer than massive sBzK galaxies.

As already obtained in Section 3, galaxies selected through the Lyα technique tend to be less massive than HAEs. Furthermore, the Lyα selection allows us to probe down to lower dust-corrected SFRs. This can be used to extend the MS obtained for HAEs down to log (M*/M⊙) ~ 9. This is represented by the blue filled squares in Fig. 10. As in Section 3, the dust-corrected SFR for LAEs has been obtained by assuming the infrared excess (IRX–β) relation of Heinis et al. (2013). Interestingly, and despite the effect of our Hα selection on the MS slope, the point for LAEs agrees very well with the extrapolation of the HAE MS to lower stellar masses.

6.2 Uncertainties in the SFR–mass relation

In order to study the uncertainties involving the determination of the slope and zero-point of the HAE MS at z ~ 2 and to try to explain in more detail the differences found with previous works, we compare the SFR–mass relation when considering different methods used in the literature to obtain stellar mass and total SFR. We focus first on the dependence of the HAE MS upon the method used for determining stellar mass. This is shown in Fig. 11, where all the SFRs have been derived by correcting the rest-frame UV luminosity with the IRX–β relation of Meurer et al. (1999) for the sake of homogeneity with previous works that are referred to in this section. Therefore, the main difference would be only the determination of stellar mass. We include in Fig. 11 the MS when the stellar mass of HAEs is obtained through our method of SED fits with BC03 templates associated with exponentially declining SFHs and the inclusion of emission lines (blue open squares; see Section 2.3) and also (orange dots) those obtained using the calibration between sBzK photometry and stellar mass reported in Daddi et al. (2004) (see also Rodighiero et al. 2014). It can be clearly seen that the slope of the HAE MS depends upon the method used for deriving stellar mass, with the slope being lower when stellar masses are derived using SED fits with the inclusion of emission lines. The top-left inset plot of Fig. 11 compares the stellar masses derived with BC03 templates, including the effect of emission lines, with those derived using the Daddi et al. 2004 calibration. It can be seen that they are correlated but do not follow the one-to-one relation, explaining the difference in the MS.

When using the same dust-correction factors and method for stellar mass determination as in Daddi et al. (2007), we find a MS
It can be seen that they all follow quite well for HAEs and sBzK effect (see Section 6.1). We also plot in Fig. 11 the stacked points still slightly lower MS slope might be explained by the H\(\alpha\) and Daddi et al. (2004) calibration. Inset panels show the relation between stellar masses when different approaches are considered for their calculation: SED-Daddi et al. (2004) calibration. Inset panels show the relation between stellar masses and the rest-frame \(K\)-band luminosity for two different methods for stellar mass: SED fits with BC03 templates (green) and calibration with \(z\) and \(K\) magnitudes (Daddi et al. 2004) (blue). The black line would correspond to mass-to-light ratio equal to unity. Green and blue straight lines are fitted to the green and blue points, respectively. This figure indicates that dust-correction factors have a strong influence on the definition of the MS at \(z \sim 2\), both in the slope and zero-point.

Figure 12 shows the impact of different dust-correction factors in the definition of the HAE MS at \(z \sim 2\). With the aim of avoiding any uncertainty coming from the determination of stellar mass, we represent the SFR–mass relation by using the rest-frame \(K\)-band luminosity. This luminosity is a proxy of stellar mass (Dror\(y\) et al. 2004) and is a direct observable quantity that does not need any assumption or calibration in its determination. Three different methods for deriving the total SFR have been employed: dust-corrected \(H\alpha\) luminosity with the local dust–mass relation (red points); dust-corrected rest-frame UV luminosity with the IRX–\(\beta\) relation of Heinis et al. (2013) (orange filled dots); dust-corrected rest-frame UV luminosity with the IRX–\(\beta\) relation of Meurer et al. (1999) (blue filled dots). Note that the only differences in Fig. 12 are the methods adopted for deriving the total SFR. It can be seen that the MS is strongly affected by the different dust corrections, with the slope being steeper with the dust correction based on the Meurer et al. (1999) relation. The MSs derived from the \(H\alpha\) emission assuming the local dust–mass relation and from the rest-frame UV with the dust correction based on the relation of Heinis et al. (2013) are similar because of the agreement between both SFR indicators (see Fig. 9). For reference, we show in the inset panel of Fig. 12 the relation between stellar mass and rest-frame \(K\)-band luminosity for the two different assumptions for stellar mass determination used in the discussion above.

Summarizing, our results show that, despite evidence that the MS exists, it is a challenge to determine its slope and zero-points at each redshift. Their values depend on the methods employed to obtain stellar mass and total SFR. For given assumptions of these, consistent values can be determined provided that representative samples of sources such as NB-selected HAEs or sBzK galaxies are used for their characterization.
7 CONCLUSIONS

In this work, we have carried out a multiwavelength analysis (from the rest-frame UV to the FIR) of the SED of NB-selected, SF HAEs with the aim of analysing their physical properties and their importance for galaxy formation and evolution. We have also compared their physical properties with those derived for other classical populations of SF galaxies at their same redshift: NB-selected LAEs, LBGs and sBzK galaxies. The main conclusions of our work are the following.

(i) The HAE selection recovers the full diversity of SF galaxies at $z \sim 2$. Coupled with the simple and well-understood HAE selection (selecting SF galaxies down to a given dust-uncorrected SFR), which can be self-consistently applied at multiple redshift slices from the local Universe up to $z \sim 2.5$, HAEs represent an excellent sample to study galaxy evolution.

(ii) At the depth of the COSMOS data, only about 30 per cent of sBzK galaxies can be selected with the drop-out technique, whereas 95 per cent of LBGs can be selected with the sBzK criterion. Only 4.5 per cent of HAEs can be selected as LAEs. These results indicate that the Lyman-break and Lyα selections miss a relevant percentage of the SF population at the peak of cosmic star formation. LBGs and LAEs are biased towards blue, less massive galaxies. Although the precise numerical results will depend on the depth of the observations considered in the analysis, these results are important to interpret results at higher redshifts where only Lyα or Lyman-break selections can be applied. However, most LBGs and LAEs can be selected through the sBzK criterion. Only the bluest LAEs and LBGs would be missed, although this sample represents a very low percentage of the SF population at $z \sim 2$ and their exclusion would not significantly affect conclusions for galaxy evolution.

(iii) There is a significant percentage of LAEs that are not detected in optical and NIR broad-band filters even with the deep photometry used in this work. The non-detection indicates that these galaxies have a faint continuum but strong emission lines. Because of their non-detection, SED fits cannot be carried out for these galaxies and, consequently, their properties and, most importantly, their contribution to galaxy evolution studies, are unknown.

(iv) Although the Lyα criterion preferentially selects SF galaxies with low dust attenuation and low stellar mass (likely because of the resonant nature of the Lyα emission), there is also a small percentage of red and massive LAEs in our sample, even redder than any LBG in our LBG sample. This indicates that Lyα is also able to escape from dusty and massive galaxies, in agreement with previous work reporting Lyα emission in submm and FIR-selected samples. Because the number of red LAEs is low compared with the total population, surveys over wider areas are needed to study in detail the properties of these galaxies and to shed light on how Lyα can escape from these systems.

(v) The median SEDs of the galaxies studied in this work reveal that the Lyα emission is strong enough to affect the broad-band $U$ photometry only in LAEs. This result indicates that Lyα emission is not strong in LBGs, HAEs or sBzK galaxies on average, highlighting the low probability of finding Lyα emission in a general sample of selected SF galaxies.

(vi) Only 4.5 per cent of HAEs show detectable Lyα emission, implying low Lyα escape fraction at $z \sim 2$ in agreement with previous results. Additionally, we find that the Lyα escape fraction ($f_{\text{esc}}$) decreases with increasing SED-derived dust attenuation, the UV continuum slope, stellar mass and SFR. This suggests that Lyα preferentially escapes from blue galaxies with low dust attenuation, although a population of red LAEs is also present, indicating that dust and Lyα are not mutually exclusive.

(vii) By using completely different and independent methods to recover the total SFR, we find that the Hα emission is an excellent star formation tracer at $z \sim 2$ with deviations typically lower than 0.3 dex for individual galaxies. These deviations are close to zero when averaging the sample in stellar mass or SFR bins.

(viii) By using the Hα-derived SFR, we study the relation between SFR and stellar mass for our HAEs. We find a MS of star formation, but with a slope lower than the classical Daddi et al. (2007) relation. By fitting a linear function in the form $\log \text{SFR} = a + b \times \log (M/M_\odot)$, we obtain $a = -3.65 \pm 0.15$ and $b = 0.52 \pm 0.02$. We show that, in part, the lower slope with respect to previous works might be due to the different selection criteria. However, exploring the uncertainties in the slope and zero-point of the HAE MS, we find that they are very sensitive to both the dust-correction factors adopted to recover the total SFR and the way the stellar masses are determined. This largely explains the difference with previous works and represents the main uncertainty in the definition of MS at high redshift. This might apply to any sample of SF galaxies. Using the same methods for stellar mass calculation and dust correction as in Daddi et al. (2007), we find consistent results for the MS at $z \sim 2$ for our HAEs and also for sBzK galaxies whose total SFRs are obtained with a stacking analysis in Herschel bands.

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The nature of $H\alpha$ emitters at $z \sim 2.23$

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