The VIMOS VLT Deep Survey: Star formation rate density of Lyα emitters from a sample of 217 galaxies with spectroscopic redshifts 2 ≤ z ≤ 6.6*

P. Cassata1, O. Le Fèvre2, B. Garilli3, D. Maccagni3, V. Le Brun2, M. Scodellaro3, L. Tresse2, O. Ilbert2, G. Zamorani4, O. Cucciati2, T. Contini5, R. Bielby6, Y. Mellier6, H. J. McCracken6, A. Pollo7, A. Zanichelli8, S. Bardelli4, A. Cappi4, L. Pozzetti8, D. Vergani4, E. Zucca4

1 Department of Astronomy, University of Massachusetts, Amherst, MA 01003, USA e-mail: paolo@astro.umass.edu
2 Laboratoire d’Astrophysique de Marseille, UMR6110, CNRS-Université de Provence Aix-Marseille I, 38, rue Frééric Joliot-Curie, F-13388 Marseille cedex 13, France
3 IASF-INAF - via Bassini 15, I-20133, Milano, Italy
4 INAF-Osservatorio Astronomico di Bologna - via Ranzani 1, I-40127, Bologna, Italy
5 Laboratoire d’Astrophysique de Toulouse-Tarbes, Université de Toulouse, CNRS, 14 Av. E. Belin, 31400 France
6 Institut d’Astrophysique de Paris, UMR7095 CNRS, Université Pierre et Marie Curie, 98 bis Boulevard Arago, 75014 Paris, France
7 The Andrzej Sołtan Institute for Nuclear Studies, ul. Hoza 69, 00-681 Warszawa, Poland
8 INAF-IRA-INAF, Via Gobetti, 101, I-40129 Bologna, Italy

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ABSTRACT

Aims. The aim of this work is to study the contribution of the Lyα emitters to the star formation rate density (SFRD) of the Universe in the interval 2 < z < 6.6. Methods. We assembled a sample of 217 Lyα emitters (LAE) from the Vimos-VLT Deep Survey (VVDS) with secure spectroscopic redshifts in the redshift range 2 < z < 6.6 and fluxes down to F_α = 1.5 × 10^{-18} erg/s/cm^2. 133 Lyα emitters are serendipitous identifications in the 22 arcmin^2 total slit area surveyed with the VVDS-Deep and the 3.3 arcmin^2 from the VVDS Ultra-Deep survey, and 84 are targeted identifications in the 0.62 deg^2 surveyed with the VVDS-DEEP and 0.16 deg^2 from the Ultra-Deep survey. Among the serendipitous targets we estimate that 90% of the emission lines are most probably Lyα, while the remaining 10% could be either [OII]3727 or Lyβ. We computed the luminosity function and derived the star formation density from LAE at these redshifts. Results. The VVDS-LAE sample reaches faint line fluxes F(Lyα) = 1.5 × 10^{-18} erg/s/cm^2 (corresponding to L(Lyα) ~ 10^{41} erg/s at z ~ 3) enabling the faint end slope of the luminosity function to be constrained to α ~ −1.6 ± 0.12 at redshift z ~ 2.5 and to α ~ −1.7^{+0.2}_{−0.12} at redshift z ~ 4, placing on firm statistical grounds trends found in previous LAE studies, and indicating that sub-L^* LAE (L_{Lyα} < 10^{42} erg/s) contribute significantly to the SFRD. The projected number density and volume density of faint LAE in 2 ≤ z ≤ 6.6 with F_α > 1.5 × 10^{-18} erg/s/cm^2 are 33 galaxies/arcmin^2 and ~ 4 × 10^{-2} Mpc^{-3}, respectively. We find that the the observed luminosity function of LAE does not evolve from z=2 to z=6. This implies that, after correction for the redshift-dependent IGM absorption, the intrinsic LF must have evolved significantly over 3 Gyr. The SFRD from LAE is found to be contributing about 20% of the SFRD at z = 2 − 3, while the LAE appear to be the dominant source of star formation producing ionizing photons in the early universe z ~ 5 − 6, becoming equivalent to that of Lyman Break galaxies.

Key words. Cosmology: observations – Galaxies: fundamental parameters – Galaxies: evolution – Galaxies: formation

1. Introduction

The Lyα line is the strongest hydrogen emission line in the Universe, and it is observed in the optical range for galaxies at z > 2. It has thus naturally been used to search for high-z galaxies (Partridge&Peebles 1967; Djorgovski et al. 1985; Cowie &Hu 1998).

The Lyα emission in galaxies is thought to be produced by star formation, as the AGN contribution to the Lyα population at z < 4 is found to be less than 5% (Gawiser et al. 2006; Ouchi et al. 2008; Nilsson et al. 2009). However, the physical interpretation of the observed Lyα flux is not simple, because the Lyα photons are resonantly scattered by neutral hydrogen. Lyα photons can therefore be more attenuated than other UV photons, and they have an escape fraction that can depend on the spatial distribution of neutral and ionized gas, as well as on the velocity field of the neutral gas (Giavalisco et al. 1996; Kunts et al. 1998; Mas-Hesse et al. 2003; Deharveng et al. 2008 and references therein).
Lyα emitters (LAE) observed up to now are forming stars at rates of $\sim 1 \pm 10 M_\odot \text{yr}^{-1}$ (Cowie & Hu 1998; Gawiser et al. 2006; Pirzkal et al. 2007), and they have stellar masses as low as $10^8 \pm 10^9 M_\odot$ and ages $< 50 \text{Myr}$ (Pirzkal et al. 2007; Gawiser et al. 2007; Nilsson et al. 2009). However, Nilsson et al. (2007) find ages between 0.1 and 0.9 Gyr, and more recently Pentericci et al. (2007) and Finkelstein et al. (2009) point out that Lyα galaxies are a more heterogeneous family than young star-forming galaxies: they also find Lyα emitters with old stellar populations (ages of $\sim 1 \text{Gyr}$) and a wide range of stellar masses (up to $10^{10} M_\odot$).

Interestingly, a class of Lyα galaxies with rest-frame equivalent width $EW > 240 \AA$ has been found (Malhotra & Roads 2002; Shimasaku et al. 2006). Galaxies with such large EW cannot be explained by star formation with a Salpeter IMF, but must have a top heavy IMF, a very young age $< 10^7 \text{yr}$ and/or a very low metallicity. Many of these large EW objects are spatially extended, and thus are good candidates to be cooling clouds or primeval galaxies (Yang et al. 2006; Schauer 2008) and can give interesting clues about the first stages of star formation.

Together with studying the properties of Lyα galaxies at different redshifts, it is important to study the evolution of their luminosity function, comparing large and complete samples of Lyα galaxies at different redshifts. The most common technique used so far has been to build large samples from imaging in narrow band filters tuned to detect Lyα emission at $z \sim 2 - 9$ (Hu et al. 2004; Cuby et al. 2003; Tapken et al. 2006; Kashikawa et al. 2006; Gronwall et al. 2007; Murayama et al. 2007; Ouchi et al. 2008; Nilsson et al. 2009; Guaita et al. 2010). Blank field spectroscopy has been used blindly to search for Lyα emitters in deep HST-ACS slitless spectroscopic observations (Malhotra et al. 2005) or slit spectroscopy (van Breukelen, Jarvis & Venemans 2005; Martin et al. 2008; Rauch et al. 2008; Sawicki et al. 2008), with Rauch et al. (2008) exploring the faintest emitters.

The general consensus today is that the apparent luminosity function of Lyα galaxies, that is the non-IGM corrected luminosity function, does not evolve at $z \sim 3 - 6$ (Rhoads & Malhotra 2001; Ouchi et al. 2003; van Breukelen, Jarvis & Venemans 2005; Shimasaku et al. 2006; Murayama et al. 2007; Gronwall et al. 2007; Ouchi et al. 2008; Groé et al. 2009). However, this conclusion is drawn from small samples, as the narrow band imaging techniques sample only thin slices in redshift (typically $\Delta z = 0.1$) and needs to be spectroscopically confirmed. Extensive spectroscopic follow-ups of narrow band Lyα candidates have been carried out in recent years, gathering hundreds of spectroscopic confirmations between $z \sim 2$ and $z \sim 7$. However, the spectroscopic coverage rarely reaches $30 \pm 50\%$ of the photometric sample (Murayama et al. 2007; Gronwall et al. 2007; Ouchi et al. 2008), but usually is much lower (Kashikawa et al. 2006; Nilsson et al. 2007; Matsuda et al. 2005). Moreover, current blind spectroscopic surveys sample only small areas to relatively shallow fluxes. It is likely that the apparent lack of evolution is a coincidence of the evolving intrinsic Lyα LF combined with an evolution of the intergalactic medium absorption with redshift (e.g. Ouchi et al. 2008). Firm conclusions about the possible evolution of the luminosity function have not yet been secured. Moreover, existing spectroscopic and narrow band samples are not sufficiently deep to constrain, even at intermediate redshift ($z \sim 3$), the slope of the luminosity function.

Measuring the luminosity function in turn enables to compute the luminosity density and star formation rate density evolution under a set of well constrained hypotheses. The contribution of Lyα to the total star formation rate is yet not robustly measured mainly because the faint end slope of the luminosity function remains poorly constrained.

In this paper, we present the results from a very deep blind spectroscopic survey search of Lyα emitters over an unprecedented large sky area. We looked for the serendipitous detection of Lyα emission in the slits of the VIMOS VLT Deep Survey, concentrating on the VVDS–Deep and VVDS–Ultra-Deep surveys reaching up to 18h of integration on the VLT-VIMOS. We describe the spectroscopic and photometric data and the associated selection function in Section 2. The search for Lyα emitters and the final sample are presented in Section 3, and we discuss its properties in Section 4. The luminosity function calculation is discussed in Section 5, and the star formation rate density is derived. We discuss these results and give a summary in Section 6.

Throughout the paper, we use and AB magnitudes and a standard Cosmology with $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$ and $h = 0.7$.

2. Search for serendipitous emission lines in the VVDS Deep and Ultra-Deep spectroscopic surveys

The Vimos-VLT Deep Survey (VVDS) exploited the high multiplex capabilities of the VIMOS instrument on the ESO-VLT (Le Fèvre et al., 2003) to collect more than 45000 spectra of galaxies between $z \sim 0$ and $z \sim 5$ (Le Fèvre et al., 2005; Garilli et al. 2008). In the VVDS-Deep 0216-04 field, more than $10^4$ spectra have been collected for galaxies with $i_{AB} \leq 24$, observed with the LR-Red grism across the wavelength range $5500 < \lambda < 9350 \AA$, with integration times of 16000 seconds. In addition, the VVDS Ultra-Deep (Le Fèvre et al. 2010, in preparation) collected $\sim 1200$ spectra for galaxies with $i_{AB} \leq 24.75$, obtained with LR-blue and LR-red grisms, with integration times of 65000 seconds for each grism. This produces spectra with a wavelength range $3600 < \lambda < 9350 \AA$. For both the Deep and Ultra-Deep surveys, the slits have been designed to be 1" in width, providing a good sampling of the 1" typical seeing of Paranal, and between $4^\prime$ and $15^\prime$ in length, allowing good sky determination on both sides of the main target. The resulting spectral resolution is $R = 230 \pm 250$ for both the LR-blue and LR-red grisms. The observations of the VVDS-Deep and Ultra-Deep have been taken in different observing runs split typically between 3 to 5 nights respectively. Given the Paranal seeing variations, the seeing quality of the final observations spans from 0.5" to 1.2" FWHM.

In this work, we take advantage of the fact that the VIMOS spectrograph produces a spectrum for the whole piece of sky covered by each slit. If a Lyα emitting galaxy with a redshift compatible with our wavelength range serendipitously falls in the slit, the Lyα line will appear in the 2-d spectrum. Obviously other line emitting galaxies at redshifts such that one or more of their emission line spectrum falls in the observed wavelength range will also be detected.

During the processing of the 2-d spectra of the VVDS main targets we identified that a population of serendipitous emission line objects was present. We therefore subsequently performed a systematic search for serendipitous emission line galaxies in the $\sim 8000$ Deep and $\sim 1200$ Ultra-Deep spectra. This was then followed by unambiguous redshift identification of all the line emitting galaxies as described in Section 3.2. A significant number of VVDS primary targets are also Lyα emitting galaxies (Le
Fèvre et al., 2010, in preparation), we added them to build a more complete LAE sample.

2.1. The dataset

The dataset consists of three sets of VIMOS pointings: the Deep, the Ultra-Deep blue, and the Ultra-Deep red. Each pointing consists of 4 separate quadrants, each containing approximately 100 slits. We summarize each dataset below:

- Deep dataset: it consists of 20 pointings, for a total of 80 quadrants and about 8000 slits; the main VVDS targets have been selected from an area of 0.62 deg$^2$ to have 17.5 $< I_{AB} <$ 24. The spectra have been obtained with the LR-Red grism, providing a wavelength range 5500 $< \lambda <$ 9350Å. The exposure times are about 16000 seconds, allowing to reach fluxes as low as $5 \times 10^{-18}$ erg/cm$^2$/s (see details below). The total sky area serendipitously covered is 22 arcmin$^2$.

- Ultra-Deep dataset: it consists of 3 pointings, for a total of 12 quadrants and about 1200 slits; the main targets have been selected to have $23 \leq I_{AB} \leq 24.75$ from an area of 0.16 deg$^2$. Each slit placed on a primary VVDS target has been observed twice, once with the LR-Blue grism, and once with the LR-Red. For the blue spectra, the spectral range is 3600 $< \lambda <$ 6800Å, and for the red ones it is 5500 $< \lambda <$ 9350Å. Thus, for each of the 1200 slits, the Ultra-Deep blue and red spectra overlap for about 1300Å. We did not try to combine spectra in the overlapping regions, because blue and red spectra have been observed under different sky background and atmospheric seeing conditions. As we will show in the next Sections, 13 Ly$\alpha$ emissions have been found in the overlapping regions. As we handled the blue and red spectra separately this allows us to compare a posteriori the detection rate, as well as redshifts and fluxes. This is described in the next sections, respectively referring to the two samples as ’Ultra-Deep blue’ and ’Ultra-Deep red’. For each of the blue and red spectra the exposure time is 65000 seconds, allowing to reach a flux limit of $\sim 1.5 \times 10^{-18}$ erg/cm$^2$/s (details below). The total sky area serendipitously covered is 3.3 arcmin$^2$.

The noise of VIMOS spectra varies as a function of wavelength, as a result of a combination of different effects. First, the combination of the efficiency of VIMOS optics and the CCD quantum efficiency depends on the wavelength of the incident light. Second, the OH airglow sky emission lines are in a suite of bands which are dominating the background for $\lambda > 7500$Å, and are not easy to subtract from the combined object+sky spectra in low to medium resolution spectra. As a result, spectra are noisier at the wavelengths of the OH bands. An added uncertainty on the flux level is also sometimes present at the position of serendipitous Ly$\alpha$ emission because the background subtraction performed by the VIMOS data processing pipeline VIPGI (Scodeggio et al., 2005) is optimized using the a-priori knowledge of the position of the VVDS primary target. As the serendipitous target is offset from the main target, the low order polynomial fit used to remove the background is made using some background points including the emission line, therefore artificially lowering the line flux. Third, the thin E2V detectors on VIMOS produce fringing which strongly affects the part of the spectra at $\lambda > 8000$Å. As the VVDS has been using a low resolution $R \sim 230$ to maximize the number of objects in the survey, this produces a blend of the OH sky emission features, globally increasing the background noise at the position of the OH bands. As a result of these effects, the flux limit varies as a function of wavelength, hence of redshift. We determined the theoretical flux limit, separately for ’Ultra-Deep blue’, ’Ultra-Deep red’ and Deep, by measuring the typical rms at different wavelengths in the 2 $-$ d spectra. Empirically, we decided to set the limit to $3\sigma$ in at least 5 contiguous pixels. The limits for the three subsamples are shown as a function of wavelength in Figure 1. It can be noted that the background, even for each of the three subset, is changing as a function of the wavelength and redshift. As a result of the bright OH skylines at $\lambda > 7500$Å, a large part of the redshift range at $z > 5.5$ is in practice inaccessible. However, there are at least two very clean windows around $z=5.7$ and $z=6.5$, with a very low background corresponding to the absence of OH emission. The faintest flux limits can be observed in the range 4200 $< \lambda <$ 7600Å, reaching down to very faint flux levels of $\sim 1.5 \times 10^{-18}$ erg/cm$^2$/s at $3\sigma$. The combination of sky area covered, wavelength range, and depth is unprecedented.

2.2. Photometry

The VVDS 0216-04 field benefits from extensive deep photometry. The field was first observed with the CFH12K camera in BVRI bands (Le Fèvre et al., 2004; McCracken et al., 2003), in the $U$ band (Radovich et al. 2004) and $K$ band (Iovino et al. 2005). More recent and significantly deeper observations have been obtained as part of the CFHT Legacy Survey in $ugriz$ (Goranova et al. 2009; Coupon et al. 2009), and as part of the WIRDS survey in $J$, $H$ and $K$ bands. The CFHTLS observations reach $5\sigma$ point source limiting magnitudes in $i$ band of $i_{SB} = 28$ while the WIRDS observations reach a $3\sigma$ point source limit of $K_{SB} = 23.5$ (McCracken et al., in preparation).
3. The Lyα sample

3.1. Serendipitous emission lines identification

The final database consists of ~1200 2-d spectra observed with both red and blue grism (Ultra-Deep dataset), and ~8000 2-d spectra observed with the red grism. For each of the 92 quadrants observed, the reduction code (VIPGI, Scodeggio et al. 2005) produces a frame in which the ~100 2-d spectra are arranged one above the other, with the spectral direction along the x-axis. With the purpose of identifying serendipitous lines, we built a data processing procedure that automatically masked out all the continua and the bad features (bright residuals and OH skylines). The unmasked area is then used to search for emission lines, and to compute the effective area covered by each slit on the sky. An object falling serendipitously in a slit will produce a spectrum with a combination of continuum and emission lines. For faint objects with strong lines, the continuum is not detected, and we are left with emission lines with a line profile as produced by the spectrograph. For point source objects, VIMOS produces a line profile along the slit (in the spatial direction) which is almost identical to the seeing profile (FWHM ~ 1′′ or about 5 pixels). This is the projected equivalent slit size resulting from the object size convolved with the seeing profile and the slit profile on the spectral dispersion direction for a maximum of about 5 pixels corresponding to the 1 arcsecond slit width projection (or about 30Å spectrally). The 2D line profiles produced are thus similar to point source images. For compact objects smaller than the atmospheric seeing disc, and if the seeing is smaller than the 1 arcsec slit width, the observed line profile in the spectral dimension will be dominated by the projected seeing profile. For extended objects the line profile becomes wider in the spatial direction leading to oval shaped emission lines. As these spectroscopic line images are similar to those of stars or galaxies on deep images, we blindly run SExtractor on the masked 2D area then used to search for emission lines. We show a random pick of 8 serendipitous lines in Figure 2 and 3.1. For each line, we show both the 2-d and 1-d spectra. We obtain a total sample of 133 serendipitous emission line emitters, 105 found in the Ultra-Deep survey and 28 in the Deep. Most of these galaxies have no evident continuum appearing in the spectra. We show a random pick of 8 serendipitous lines in Figure 2 and 3.1. For each line, we show both the 2-d and 1-d spectra.

3.2. Lyα identification

Once the fiducial emission line catalog is built, we have to unambiguously assign a rest-frame wavelength to any given emission line. If one emission line is identified in a contiguous spectrum covering 3600 to 9350 Å, there are several possibilities for the line identification assuming a star-forming galaxy spectrum: below 3727 Å the line is most probably Lyα, above 3727 Å the emission line can be Lyα, [OII]3727 Å, Hβ, [OIII]5007 Å (assuming [OIII]4959 Å is not detected, [OII]5007 Å, [OIII]4959 Å = 3), or Hα. In the spectrum of normal star forming galaxies, [OII], Hβ and [OIII] are most often present. Therefore, as a first approach we assumed that the emission lines could be [OII] at 3727 Å, Hβ at 4861 Å, [OIII] at 5007 Å, Hα at 6563 Å, and we checked for other expected emission lines at different wavelengths in our spectral window. Using the typical line ratios for star-forming galaxies of average metallicity we estimate the flux of the other expected lines, and check whether they could be detected above our flux limit. However, the line flux ratios strongly depend on the galaxy metallicity. For example, typical ranges of line ratios are: [OII]/[OIII] = 0.1 ± 0.5, Hα/[OII] = 0.3 ± 5 and Hβ/Hα = 0.1 ± 0.8 (Lamareille et al. 2006; Maier et al. 2006; Tresse et al. 2007; Cowie&Barger 2008, Kewley&Ellison 2008). So, we decided to use the following line ratios, typical of galaxies with average metallicity: [OIII]/[OII] = 0.35, Hα/[OII] = 1 and Hβ/Hα = 0.35. Cases of extreme metallicity are discussed below.

Narrow-line type-II AGN with classical line ratios would be straightforward to identify given the broad wavelength range of our spectra. If we were to assign the single emissions lines to lines like CIV-1549, CIII-1909, or MgII-2800 we would expect to see other emission lines in our observed range either towards the UV (Lyα, CIV, CIII) or towards the red (MgII, [OII], [NeIII]). Broad line type-I AGN are also relatively easy to identify at our spectral resolution. We have not found any type-I or type-II AGN in our data, consistent with expected AGN counts in the area sampled (e.g. Bongiorno et al., 2007; Lamareille et al., 2009).

As the spectral window spans from 3600 Å to 9350 Å for the Ultra-Deep subsample and from 5500 Å to 9350 Å for the deep subsample, we analyze these samples separately.

- Ultra-Deep: 2 single lines in the Ultra-Deep are at λ < 3727 Å, and then can likely be identified as Lyα, while 103 are at λ > 3727 Å. Among the latter, 93 lines are at λ < 6920 Å. If they were [OII], we would have [OIII] and Hβ in our spectral window. We estimate, using the line ratios reported above, that 75 of these 93 lines should be accompanied by either detectable [OIII] or detectable Hβ or both, but as they are not detected they are therefore most probably to be identified with Lyα. For the 10 emission lines at λ > 6920 Å, this argument cannot be used, because the possible [OIII] and Hα emission would lie out from our spectral window. Using similar arguments, we can infer that none of the Ultra-Deep lines are Hβ, [OIII] or Hα, because they would be always accompanied by at least one other line in our spectral window with a flux brighter than the flux limit.

- Deep: The deep subsample contains 28 serendipitous lines. Again, all of them can be in principle interpreted as both Lyα or [OII]. Since for the Deep the spectral window is smaller than for the Ultra-Deep, the same argument as for the ultra-deep tells us that only 7 of these lines are not [OII]. For the other 21, either a possible [OIII] emission is outside the spectral range, or it would be too faint to be detected. However, we can conclude also that the bulk of them are not Hα, [OIII] or Hβ, because at least one other detectable line would be detected in our spectra.

From this first analysis, we can conclude that basically none of the serendipitous lines in the sample are Hα, Hβ or [OIII],
Fig. 2. Random selection of LAE candidates from the Ultra-deep blue dataset, ordered by increasing redshift. For each of them we show the full 2-d (top) and 1-d (bottom) spectra. The position of Lyα is indicated by an arrow on both the 2-d and 1-d spectra, and by a label reporting the redshift on the 1-d spectrum. The observed wavelength scale at the bottom of the 1-d spectrum is transformed into the redshift of Lyα at each wavelength on the top.
Fig. 3. Same as figure 2, for objects detected in the Ultra-deep red and in the Deep datasets.
that 84 among the 133 bona fide serendipitous lines are not [OII], and that most of the line identification uncertainty for the other 49 emission lines is between [OII] and Lyα. We note that these findings will not change too much if we had used much lower values for the metallicity. Assuming, for example, [OIII]/[OII] \sim 10, if the serendipitous line was assigned to [OII], we should always have detected [OIII] for all lines with \lambda < 6920.

We can perform a further check in order to evaluate the contribution of Lyα and [OII] emission to the observed population. In particular, we measured the observed equivalent width of the lines to produce the distribution of the rest-frame EW for each of the two cases, as presented in Figure 4, for all the 217 lines as well as for the 49 ambiguous lines. While the distribution of the rest-frame EW for the lines if they are Lyα is mostly below 150Å, we find that if the lines were assigned to [OII], \sim 70% of the distribution would be with EW[OII] > 100Å. Among the 49 galaxies that cannot be unambiguously classified as either Lyα or [OII], 37 would have EW[OII] > 100Å. We compare this distribution to the distribution of EW[OII] observed for galaxies with MB \approx -18 in the VVDS-Deep (Vergani et al. 2008) in the same redshift range 0.86 < z < 1.5, and we note that 90% of the normal galaxy population has EW[OII] < 100Å. At z \approx 1, galaxies with EW[OII] > 100Å have only rarely been observed in deep spectroscopy surveys, and none with EW > 150Å (Hammer et al., 1997; Vergani et al., 2008). Since we expect to have just 5 lines with EW[OII] > 100Å (10% of 49), we can conclude that for about 32 (37-5) the identification is very likely to be Lyα. So, at the most we can identify the line as [OII] for 17 galaxies (49-32). We therefore conclude that

about 10% of the single emission lines could be assigned to either [OII] or Lyα, while more 90% of them are most likely Lyα.

Another check on the line identification with Lyα is to look at the line profile. Lyα line profiles are most often asymmetric, with a truncation towards the blue because of absorption by the
intergalactic medium, and an extended red wing because of complex velocity fields (Shapley et al., 2003; Ouchi et al., 2008). On individual objects, the line detection is not always of sufficient S/N to detect a line asymmetry, instead we produced the average normalized Ly\(\alpha\) line profiles for LAE in different redshift ranges up to \(z \sim 6\), as shown in Figure 5 (the description of the combination technique and a more detailed analysis of the combined spectra are presented in Section 4.3). The asymmetry of the profile is clearly seen at all redshifts, even in the lower redshift bins. For each combined spectrum we measured also the skewness of the line in the range 1201 < \(\lambda\) < 1231Å, that measures the degree of asymmetry of a given distribution. If the line profile would be perfectly described by a gaussian, that is by definition symmetric, the skewness would be zero. On the other hand, a positive value for the skewness indicates a distribution skewed towards red wavelengths. As Figure 5 shows, in each redshift bin between 2 < \(z\) < 5.9 the skewness is positive and is increasing with redshift as expected from IGM absorption, reinforcing the primary identification with Ly\(\alpha\).

There are 6 galaxies with a single emission line in the atmospheric windows 8450 < \(\lambda\) < 8620 and 9000 < \(\lambda\) < 9300 clean of OH sky emission lines, and they observed equivalent widths 540 < \(E\lambda\) < 1250Å. If these lines were [OII]3727 or H\(\alpha\), the rest \(E\lambda\) would be 220 < \(E\lambda\) < 510 or 400 < \(E\lambda\) < 880Å with a mean \(E\lambda\)=315 or 550Å respectively, clearly outside the range of EW for [OII] or H\(\alpha\) emitting galaxies at \(z \sim 1\). No sign of the broad component of an AGN which could produce high H\(\alpha\) EW has been observed. We also produced the line profile of the 6 galaxies in this redshift range, reported in Figure 6. The resulting profile is clearly asymmetric, as confirmed by the positive value for the skewness. As other single emission line candidates with strong observed EW are even more unlikely than [OII]3727 or H\(\alpha\) and should show other emission lines in our observed wavelength domain, we argue that the most likely possibility is that these emission lines are Ly\(\alpha\) with 5.96 < \(z\) < 6.62, making them some of the most distant galaxies found to date.

In summary, among the 133 emission lines identified serendipitously in the 2D spectra, we conclude that 124 are most likely Ly\(\alpha\), while a low fraction of 14 (10%) can be either Ly\(\alpha\) or [OII]. In the following, we assume that all galaxies with ambiguous line assignment are Ly\(\alpha\).

3.3. Final sample

We completed the LAE sample by adding the primary VVDS spectroscopic targets that unambiguously have Ly\(\alpha\) in emission. We found 70 Ly\(\alpha\) emitters among the \(\sim 1200\) Ultra-Deep primary targets, all at redshift \(z < 3.5\), and 14 among the \(\sim 8000\) Deep targets. The Deep survey is actually limited to \(\lambda > 5500\)Å, hence it could not see Ly\(\alpha\) at \(z < 3.5\). All these galaxies have a high quality flag (larger than or equal to 2; Le Fèvre et al., 2010, in prep.) for the redshift, since they have other spectral features that allow to unambiguously identify the redshift and therefore classify them as Ly\(\alpha\) emitters. They show in fact OI at 1303Å, CII at 1335Å, SiIV at 1397Å, CIV at 1549Å, and sometimes CIII at 1909Å. The final sample is therefore made of 217 LAE, including 133 serendipitous LAE, and 84 LAE from the primary VVDS targets. The sample is summarized in Table 1.

For each emission line, we carefully measured the position of the line (and thus the redshift), the total flux in the line and the continuum. The continuum, in units of \(F_{\lambda}\), is measured as close as possible to the red wing of the Ly\(\alpha\) line, by averaging the counts between 1230 and 1250Å. From these fundamental quantities, the observed and rest-frame equivalent widths and the luminosities are derived:

\[
L = 4\pi F d(z)^2 \quad \text{EW}_{\text{rest}} = F/C \frac{1}{1+z}
\]

where \(L\) and \(F\) are respectively the luminosity and the flux in the line, \(z\) is the redshift of the line, \(d(z)\) is the luminosity distance at the redshift of the line, \(\text{EW}_{\text{rest}}\) is the rest-frame Equivalent Width and C is the continuum around the line. Obviously, when the continuum is not detected, the derived equivalent widths are just a lower limit, and we used 1 sigma of the background as the continuum value.

Moreover, each luminosity can be converted to a star formation rate (SFR) combining the classical prescription to derive the SFR from H\(\alpha\) Luminosity by Kennicutt (1998) and the expected ratio between Ly\(\alpha\) and H\(\alpha\) flux. In particular:

\[
SFR(M_{\odot} yr^{-1}) = L_{\text{H}\alpha}(\text{ergs s}^{-1})/(1.26 \times 10^{41}),
\]

with H\(\alpha\) flux corrected for internal extinction and valid for a Salpeter IMF. The conversion between H\(\alpha\) and Ly\(\alpha\) luminosity has been theoretically derived by Brocklehurst 1971 (assuming case B recombination):

\[
L_{\text{Ly}\alpha} = 8.7 L_{\text{H}\alpha}.
\]

and it does not account for dust and escape fraction corrections. Combining the two gives:

\[
SFR(M_{\odot} yr^{-1}) = L_{\text{Ly}\alpha}(\text{ergs s}^{-1})/(1.1 \times 10^{42}).
\]

In Figure 7 we report the flux and the position (both wavelength and redshift if the lines are identified as Ly\(\alpha\)) for the three surveys separately. It can be noted that the Ultra-Deep blue is providing the biggest sample with 164 emission lines galaxies (94 serendipitous lines and 70 targets of the spectroscopy), while the Ultra-Deep red and the Deep contribute with respectively 24 and 42 emission lines galaxies. Note also that in a few instances we measure line fluxes that are weaker than the nominal flux limit at that wavelength: this is because the background, at each wavelength, is measured as the average of the backgrounds in the different quadrants and pointings. For some pointings, the background is lower than the average, and thus fainter lines can be detected.

3.4. Completeness simulations

As we saw in Fig. 1, the background of our spectra has a complicated structure, as there are strong variations with wavelength. To perform a statistical analysis of the number density evolution of Ly\(\alpha\) galaxies, it is important to carefully determine, for each wavelength (and thus for each redshift), what is our capability to recover a line with a given luminosity.
For each sub-dataset, we show the flux versus redshift together with the flux limit as a function of the redshift and wavelength (solid lines). The flux limit is empirically measured on the 2-d spectra. Filled and open circles represent respectively serendipitous Lyα galaxies and targets with Lyα emission.

We performed a Monte Carlo simulation, building a catalog of 1000 fake lines for each dataset, for a total of 3000. Each line has a known flux, randomly extracted from a flat distribution between \( F_{\text{Ly} \alpha}) = 1 \times 10^{-18} \) and \( F_{\text{Ly} \alpha}) = 1 \times 10^{-16} \). The redshift is randomly extracted from a flat distribution between \( z=2 \) and \( z=4.7 \) (for blue spectra) and between \( z=3.7 \) and \( z=6.7 \) (for red spectra). The fake lines are then added at the wavelength corresponding to the known redshift, in a randomly extracted slit. Since emission lines in our sample are not or barely resolved either in the spatial or in the spectral directions (see next sections), we chose to use simple gaussian profiles with FWHM of 1″×30Å.

We attempted to recover these simulated lines, without a-priori knowledge of redshifts and fluxes, by applying the same procedure used on the real 2-d spectra, described in Section 3.1. The results are reported in Figure 8 presenting the completeness as a function of the line luminosity and of the redshift, for the three subsamples. We can see that Ultra-Deep blue & red and Deep are 50% complete respectively at \( F_{\text{Ly} \alpha} \sim 2 \times 10^{-18} \) and \( \sim 8 \times 10^{-18} \).

3.5. Slit flux loss

Since the slits used have sizes comparable to the seeing of the images, part of the line flux cannot be recovered and will be always lost. The flux loss depends on the offset between the galaxy and the slit center positions, on the size of the galaxy with respect to the slit width and on the atmospheric seeing. For an object perfectly centered in the slit, the flux loss will be minimal, but not zero. If the position of the object in the slit is known, as in the case of the objects with an optical counterpart, it is relatively easy to compute the flux loss. However, a significant number of galaxies in our sample do not have an optical counterpart within ±0.5″ from the expected position of the object along the slit and within ±2″ off axis in the direction perpendicular to the slit (see Section 4.2).

As we do not know for these galaxies their positions inside the slits, we cannot compute object by object the actual flux loss. This problem is common to all surveys of serendipitous Lyα emitters (e.g. Rauch et al. 2008; Lemaux et al. 2009), and is usually solved with a statistical approach for the objects with no detected counterpart. In this Section, we derive the slit flux loss as a function of the position of the object in the slit, so that we can correct the line flux for those objects with an optical counterpart, and then we estimate a statistical correction for the objects without any optical counterpart.

We start from the consideration that the bulk of our Lyα galaxies are unresolved in the spatial direction (see Section 4.2),
having sizes comparable with the seeing of the observations. The FWHM distribution in the spatial direction of the lines in our sample spans from 0.5 to 1.2 arcseconds, with 90% of them having FWHM = 0.7 ± 1.2 arcsec (see Figure 11). This implies that we can model them as gaussians, with fixed FWHM. We built a simulation in which an emission line object with a given FWHM is placed in a 1 arcsec slit at different positions with respect to the center of the slit until it is completely outside of the slit width. The small inset in Figure 9 shows the fraction of recovered flux as a function of the offset between the objects and the slit, for three seeing conditions FWHM = 0.7, 0.9 and 1.2 arcsec (corresponding to σ ∼ 0.3, 0.38 and 0.5 arcsec). If the galaxy was perfectly centered in the slit, only ∼ 70, 80 and 90% of the flux would be recovered, respectively for the 1.2, 0.9 and 0.7 arcsec FWHM lines; on the other hand, if the galaxy would be placed at 2σ = 0.8 arcsec outside the slit, only 20% of the light would be retrieved.

Thus, we can estimate that the slit flux loss for the 84 primary spectroscopic targets, that are perfectly centered in the slits, is around 15%, with a typical range between 10% and 30% depending on the seeing. For the serendipitous object with an optical counterpart, whose offset with respect to the center of the slit is known, we estimated the flux loss assuming they are compact under the average seeing conditions of a pointing. We show their distribution of the recovered flux in Figure 9.

In order to check if the percentage of recovered flux that we find for the serendipitous sample is reasonable, we use a Monte Carlo simulation. In particular, we generate 3000 2-dimensional gaussian profiles with FWHM randomly extracted between 0.7 and 1 arcsec, applying an offset between the position of the peak and the center of the slit randomly extracted between ±1 arcsec. The distribution of the recovered flux for the 3000 lines is shown in Figure 9. We note that the choice of ±1′′ as maximum offset introduces an artificial cut-off at ~10% of the recovered flux. This choice however is justified by the fact that an hypothetical object placed offset from the slit by more than ±1′′ should have a true Lyα flux > 10× stronger than the one measured in the slit spectroscopy, hence its optical counterpart should be visible in photometry. There is an overall agreement from the result of this simulation and the flux loss estimated for the serendipitous lines with optical counterpart. For ~40% of the cases, the recovered flux is higher than 70%. The median of both histograms is ≃ 55%; we will use this value to correct the measured fluxes for the serendipitous lines with no optical detection in our sample.

4. Sample properties

4.1. Redshift distribution

In Figure 10 we show the redshift distribution for our sample. The distribution extends from z = 2 to z = 6.7, with a median < z > = 3. We have 5 detections at z ~ 6.5 and 9 at z ~ 5.7. The main VVDS targets with Lyα come mainly from the Ultra-Deep survey, and interestingly, they show a different redshift distribution: even though the peak for the two subsample is around z = 2.2 ± 2.5, the serendipitous show a broader tail at z > 4, while 85% of the targets have z < 4. A simple Kolmogorov-Smirnov test rules out with more than 99% confidence that the two distribution are statistically equivalent. This reflects the different selection for the 2 subsamples: magnitude selected for the former, flux selected for the latter.

4.2. Optical counterparts and size distribution

We searched the deep CFHTLS ugriz images, including the combined ugriz stack, for optical counterparts of the 133 serendipitous LAE. In order to account for possible positional uncertainties, we required the counterpart to be within ±0.5′′ from the position of the spectrum along the slit. Moreover, since even bright off-slit objects can show a detectable spectrum (see Sect. 3.5), we search for counterparts within ±2′′ of axis. We found faint
Fig. 11. Full width half maximum (FWHM) distribution as measured from the CFHTLS images (top panel) and from the Lyα 2-d spectra (bottom panel). Targets are shown with a solid line, serendipitous objects with and without photometric counterparts are shown with a dotted and dashed line, respectively. The CFHTLS image used has being built stacking the 25% best seeing exposures, and has a final PSF FWHM of about 0.5". In the top panel, we just show serendipitous objects with photometric counterpart.

counterparts for 53 (50%) and 13 (46%) LAE respectively in the ultradeep and in the deep sample, with magnitudes \(i_{AB}\) ranging from 23.5 to 27.5. These counterparts are always \(\pm 1''\) off axis at the most. For the remaining 67 objects we did not find an optical counterpart down to a magnitude \(AB \sim 28\).

In Figure 11 we compare the Full Width at Half Maximum (FWHM) for the serendipitous Lyα emitters and the spectroscopic targets, as measured on the deep CFHTLS images and directly on the 2-d spectra of the Lyα line.

In particular, we used CFHTLS-D1 (VVDS-02h field) D-25 stack in the \(z\)-band, that has been built stacking the 25% best seeing images together resulting in a PSF FWHM of about 0.5 arcsec (see Table 26 of Goranova et al. 2009). Thanks to the better angular resolution, these images are very useful to check whether or not our galaxies are resolved in the spatial direction. On the other side, we are also interested in measuring the size for our sample also on the 2-d spectra, to check the assumption we made in Sect. 3.5, where we estimated the slit flux loss.

The FWHM of the serendipitous and main VVDS magnitude selected populations with optical counterparts measured in the D-25 stack are compared in the top panel of Figure 11. The distribution for both populations peaks at around 0.5 arcsec with a gaussian distribution width. This is expected from the measurement errors on these faint objects if they are unresolved under the seeing of the D-25 stack. The width of the Lyα line measured on the 2-d spectra (bottom panel of Figure 11) indicates that the Lyα line is emitted from a compact region, as the size distribution is comparable to the seeing distribution of the spectroscopic observations. This is therefore indicating that most of the LAE are compact, both on the continuum and line emission.

From these measurements it is clear that the faint LAE population is compact in size. Interestingly, there is a clear lack of large objects (FWHM > 1–1.5 arcsec) in our sample. Faint LAE clearly have different sizes than the large Lyα blobs identified in the bright LAE population (Steidel et al. 2000; Matsuda et al. 2004; Ouchi et al., 2008). The weak continuum and Lyα sizes are in agreement with Venemans et al. (2005), Taniguchi et al. (2009), and the HST-based study of Bond et al. (2010). Our results support a picture where Lyα emission from faint LAE is compact and originates from the same area as the UV continuum as found by Bond et al. (2010), and we do not confirm the trend reported by Nilsson et al. (2009) of more extended sizes in the narrow band Lyα images than in the broadband images. While extended Lyα emission like observed in Lyα blobs and Lyα halos is expected if Lyα is produced from resonant scattering on diffuse gas surrounding the galaxy, our data may indicate that the gas reservoir of faint LAEs is rather compact or that, if extended, it is only scattering a small fraction of the Lyα photons. We will explore the evolution with redshift of these properties in a forthcoming paper.

We show the size distribution measured directly on the 2-d spectra in the bottom panel of Fig. 11: due to the poorer seeing of these observations with respect to the CFHTLS ones, this distribution is peaked at 0.9 arcsec. Hence, this justifies our choice to simulate lines as gaussians with an average FWHM of 0.9 arcsec to estimate the slit flux loss in Section 3.5.

4.3. Spectral properties of the LAE

We produced combined spectra for all the Lyα in our sample, including primary VVDS targets as well as sources identified serendipitously. In order to preserve line shapes and to avoid averaging out faint features, we used accurate redshift measurements from a half-gaussian fit to the red wing of the Lyα lines, that has been used to determine the central wavelength of Lyα, hence the redshift. Each spectrum has then been de-redshifted to rest-frame, normalized using the continuum flux in 1400–1800 Å up to \(z = 4.6, 1400–1800 Å\) for \(4.6 \leq z \leq 5.9\), and the Lyα line itself for \(5.9 < z \leq 6.7\), then averaged using a sigma-clipping algorithm. The results in several redshift ranges are shown in Figure 12 and Figure 13, for serendipitous and target objects, respectively. A number of spectral features can be readily identified at all \(z\), including of course Lyα, but also prominent CIV in absorption as well as HeII in emission well detected in the two lowest redshift bins.

Bluer than Lyα we can see that the continuum is more absorbed as redshift increases, with a ratio \((f[1250−1350Å]/f[1100−1180Å])\) for serendipitous LAE of 1.34, 1.47, 2.0, 9.3 for redshifts \(z \sim 2.3, 3, 4, 5.3\) respectively, and for target LAE a ratio of 1.41 and 1.51 for redshifts \(z \sim 2.3, 3\) respectively. For our highest redshift objects \(5.9 < z < 6.7\), uncertainties on the continuum blueward of Lyα only enables to state that this ratio is higher than 5. These measurements are comparable to the expected average extinction by the intergalactic medium, as Madau et al. (1995) predict ratios of 1.3, 1.5, 2.5 and 8.2 for
is clearly indicating that a younger stellar population is present. The horizontal dashed lines indicate the level of zero flux.

\begin{align*}
\alpha &\sim 2.3, 3, 4, 5.3, \text{ respectively. This strengthens our identification of these emission line objects as LAE.} \\
\text{Ly}\beta \sim 1026\AA \text{ is readily observed, and the Lyman-break at 912\AA is well detected for redshifts } z > 2.9 \text{ placing this feature in our observed wavelength range, as expected.} \\
\text{To check for a difference between the targeted magnitude limited sample and the serendipitous LAE, we produced the combined spectra for all target LAE in the redshift domains } 2 \leq z \leq 2.7 \text{ and } 2.7 < z \leq 3.5 \text{ as shown in Figure 13, while above } z = 3.5 \text{ the serendipitous LAE dominate and their combined spectra are quasi identical to the spectra shown in Figure 12. Many spectral features are clearly detected in absorption: Ly}\beta – 1026\AA, \text{OII} – 1303\AA, \text{SiIV} – 1397\AA. \text{ Besides Ly}\alpha, \text{CIV} – 1549\AA, \text{HeII} – 1640\AA \text{ and CIII} – 1909\AA \text{ are all detected in emission.} \\
\text{The Ly}\alpha \text{ rest-EW increases from } 38 \pm 1\AA \text{ at } z \approx 2.3 \text{ to } 370 \pm 150 \text{ at } z \approx 6.3. \text{ This trend is probably the result of two effects: a general trend of increasing star formation at higher redshifts, and a difference between the observed galaxy populations, with less (more) luminous galaxies observed at lower (higher) redshifts. The mean EW of HeII–1640 for the full sample is } \text{EW} = 1.4 \pm 0.2\AA, 2.0 \pm 0.1\AA, \text{and } 4.0 \pm 2.0\AA \text{ at } z = 2.3, z = 3.1, \text{ and } z = 4 \text{ respectively, indicating the presence of a young stellar population a few } 10^7 \text{ years old (Schaerer 2002). Considering only the serendipitous } \text{Ly}\alpha, \text{the EW(HeII) is rising from } 3.9 \pm 0.4 \text{ at } z \approx 2.3 \text{ to } 14.5 \pm 1.5 \text{ at } z \approx 3.1. \text{ This is clearly indicating that a younger stellar population is present at the higher redshift. The difference of EW between the full Ly}\alpha \text{ sample and the serendipitous Ly}\alpha \text{ at } z \approx 3.1 \text{ is significant, } 4.0 \pm 2.0 \text{ versus } 14.5 \pm 1.5, \text{ possibly again a consequence of the different populations observed, Ly}\alpha \text{ in the serendipitous sample corresponding to fainter objects with stronger star formation or less extinction of the Ly}\alpha \text{ emitted photons. This difference at the same redshift could therefore indicate that continuum–faint Ly}\alpha \text{ contain younger stellar populations than continuum–bright Ly}\alpha. \text{ This will be the subject of further studies.} \\
\text{The Ly}\alpha \text{ line in the combined spectra has an asymmetric profile with the blue wing truncated and an extended red wing, as shown in Figure 5. This is expected as gas outflow and intergalactic absorption impose a sharp blue cutoff and a broad red wing. This Ly}\alpha \text{ shape and the clear detection of other expected emission and absorption features in the combined spectra provides further supporting evidence that the bulk of the lines in our sample are Ly}\alpha \text{ rather than [OII].} \\
\end{equation}

**4.4. Properties of the 6 galaxies with } 5.96 \leq z \leq 6.62**

The combined spectrum of the 6 galaxies identified with } 5.96 < z < 6.62 \text{ is shown in Figure 6. The continuum below Ly}\alpha \text{ is barely detected in this redshift range, consistent with a strong absorption by the intergalactic medium, while we detect a continuum at the } 2\sigma \text{ level above 1215}\AA. \text{ The line profile shown in Figure 6 is also asymmetric in this redshift range, reinforcing the identification of the emission lines with Ly}\alpha. \\
\text{The distribution of rest EW(Ly}\alpha\text{) in the range } 70 < EW < 500, \text{ with a mean } EW=310\AA \text{ and a dispersion of 150}\AA. \text{ Malhotra&Rhoads 2002 suggested that } EW>300\text{may indicate a top heavy IMF. However, our measurements are just around this limit, and moreover very uncertain, so we cannot draw any conclusions on this issue. Moreover, using Eq. 4 to convert luminosities to SFR for these 6 galaxies we obtain SFR in the range } 4 < SFR < 22M_{\odot}\text{yr}^{-1}, \text{ values that are not so extreme as to require a top-heavy IMF.}
None of these galaxies are photometrically detected, neither in the single bands reaching as faint as $i_{AB} = 28$ (1σ), nor in the combined ugirz image, reaching an equivalent magnitude of $AB \approx 29$.

4.5. Photometric properties

In Figures 14 and 15 we show the ugr and gri diagrams for all galaxies in our sample (serendipitous and targets) at $2.6 < z < 4.2$. In fact, young star forming galaxies usually display very red colors around the 912Å Lyman limit: the flux below 912Å is virtually set to zero by the IGM absorption, while the star formation activity produces strong emission beyond Lyα line, producing a very pronounced and high S/N feature. This peculiarity is extensively used to look for high redshift ($z > 2$) galaxies (e.g. Steidel et al. 1999; Giavalisco 2002; Bouwens et al. 2007; 2009; 2010). We determined the part of the color-color plots in which high-z “dropouts” are expected to be convolving synthetic spectral energy distributions for star-forming galaxies with the SDSS photometric system filters.

In Fig. 14, about 80% of the galaxies with $2.6 < z < 3.6$ fall in the expected u-band dropout region. Similarly, in Figure 15, about 50% of the galaxies at $3.6 < z < 4.2$ fall in the expected g-band dropout region. The fact that a significant fraction of objects with secure spectroscopic redshifts falls out of the predicted color selection boxes has already been noted by Le Fèvre et al. (2005b), also for LAE as Gronwall et al. (2007) find a significant fraction of their sample outside of a UVR LBG box, and is mainly the result of the photometric measurement process (Le Fèvre et al., 2010, in prep.).

5. Luminosity functions

5.1. Formalism

We aim to combine the serendipitous and target Lyα emitters in the U-DEEP and DEEP surveys to produce luminosity functions at different redshifts. Since the targets and serendipitous objects have very different selection criteria, for the luminosity function

\[ L(\lambda_{L_{\alpha}}) \propto \frac{sfr}{sfr(z)} \]
Fig. 16. Equivalent Width of the Lyα line as a function of the absolute magnitude at 1600Å, for the objects with photometric counterpart, in three different redshift bins. Objects with detected continuum are shown as filled dots. Objects without a detected continuum, for which the equivalent width is only a lower limit, are shown as upward arrows. The dotted line shows $M_{UV} = -21.5$: objects brighter than this limit show a deficit of large equivalent widths ($EW_0 > 20$).

Fig. 17. Luminosity versus equivalent width for the galaxies in our sample (red points); filled and open circles indicate respectively galaxies with and without a detected continuum. For the latter, the measure of the EW is just a lower limit. Black diamonds, triangles, crosses and squares show respectively the samples of Ouchi et al. (2008), Dawson et al. (2007), Murayama et al. (2007) and Saito et al. (2008).

calculation we treated them independently. So, each galaxy from the target sample has a weight calculated with respect to the photometric selection, and each galaxy from the serendipitous sample has a weight calculated with respect to the spectroscopic selection.

Each of the two sample, however, is the combination of subsamples having different magnitude or Lyα flux limits and covering different areas: serendipitous LAE have been identified because their line flux exceeds the spectroscopic flux limit; those coming from the Ultra-Deep have a flux limit $\sim 1.5 \times 10^{-18} \text{erg/cm}^2/\text{s}$, while those coming from the Deep survey have a flux limit of $\sim 5 \times 10^{-18} \text{erg/cm}^2/\text{s}$. The VVDS primary spectroscopic targets are selected according to their magnitude in the I-band; those coming from the Ultra-Deep are selected to have $m_I < 24.75$, and those coming from the Deep to have $m_I < 24$.

To combine together subsamples reaching different flux (or magnitude) limits in different areas, we used the extended version of the $1/V_{max}$ formalism developed by Avni & Bahcall (1980). For each object we computed two effective volumes $V_{max}(j)$, one for the ultra-deep limit and the other for the deep one (if the object is a target, the limit is the magnitude limit, if the object is a serendipitous one, the limit is the Lyα flux limit). So, for an object with redshift $z$ assigned to the redshift bin $z_1 < z < z_2$:

$$V_{max}(j) = \theta(j) \int_{z_1}^{z_{sup}(j)} \frac{dV}{dz} \, dz$$

where $z_{sup}$ is the minimum between $z_2$ and the redshift at which the object could have been observed within the limits of the $j$th selection, $\theta$ is the solid angle covered by the $j$th survey, and $dV/dz$ is the comoving volume element. For each object, $V_{max}$ is defined as:

$$V_{max} = \sum_j V_{max}(j).$$

This basically means that the brightest objects, that are visible in both the ultradeep and deep surveys, are weighted according to the effective volume accessible to them in both surveys, while the faintest one, that are visible just in the ultradeep survey are weighted just with respect to this latter. The target sampling rate and the success rate have been taken into account in computing the volumes for the targets. They are $\sim 0.1$ and $\sim 0.3$ for Ultradeep and Deep surveys, respectively.

The Lyα luminosities have been here corrected for the flux slit loss, as explained in Sect. 3.5: for the targets, the expected slit loss is 15%, and for the serendipitous sample is $\sim 45\%$. We verified that the choice of an average value for such correction do not affect our main results: in particular, the Schechter best-fit values presented in Section 5.2 do not change, within the errors, if the slit flux loss correction are randomly extracted for each object from the distribution shown in Fig. 9. Finally, we combined
the two $V_{\text{max}}$ for them using Equation 6. Moreover, a completeness correction has been applied to each object according to its flux and redshift, both for targets and for serendipitous emitters.

Once we have $V_{\text{max}}$ for both the targets and serendipitous objects, we compute the galaxy number density for each $\Delta \log(L)$ and $\Delta z$ bin as:

$$\phi(L, z) = \frac{1}{\Delta \log(L)} \sum_n \frac{1}{V_{\text{max}}}$$

where $n$ is the number of objects in that bin.

### 5.2. Evolution of the luminosity functions

We estimated the luminosity functions for 3 redshift bins: $z = 1.95 - 3$, $z = 3 - 4.55$, $z = 4.55 - 6$ in order to keep enough galaxies per redshift bin for a reliable estimate of the LF. The results are shown in Figure 18.

When comparing our datapoints in these different redshift intervals, we can see that the observed apparent luminosity function (i.e. the non-IGM corrected LF) does not evolve in the redshift range $z = 2.5$ to $z = 6$ within our error bars. Although our data cover a slightly wider redshift interval they are in agreement with the literature data, within the error bars. This is quantified below.

The unprecedented depth of our survey enables to extend the luminosity function at $z = 2 - 3$, down to $\log(L_{\text{Ly}C}) = 41.3$, about one order of magnitude deeper than literature data at similar redshifts. This allows us to strongly constrain the slope of the luminosity function at $z \sim 2.5$. This parameter is extremely important, because a small change of this slope can produce a large change in the luminosity density.

We assumed here that the luminosity function of Ly$\alpha$ emitters is well represented by a Schechter law (Schechter 1976):

$$\Phi(L) dL = \Phi^* (L/L^*)^\alpha \exp(-L/L^*) d(L/L^*)$$

We obtained the best-fit functions for the 3 redshift bins using this Schechter function. As a first try, we fitted the luminosity functions in the 3 redshift intervals allowing all the 3 parameters describing the Schechter function to vary. However, by doing this, the typical luminosity $L^*$ in the first two bins and the slope $\alpha$ in the high redshift bin are poorly constrained. Indeed, in the first two bins we do not have Ly$\alpha$ galaxies brighter than $10^{43}\text{erg/cm}^2/\text{s}$, and in the last one we do not observe emission lines fainter than $10^{42}\text{erg/cm}^2/\text{s}$. So, we decided to use other datapoints in the literature to constrain $L^*$ in the first two bins. In particular, we averaged the $L^*$ values obtained by Ouchi et al. (2008) and Gronwall et al. (2007) at $z = 3.1$, obtaining $\log(L^*) = 42.7$. So, in our fit procedure we fixed $\log(L_{\text{Ly}C}) = 42.7$ in the first two bins. We verified that this approach is equivalent to including Ouchi et al. (2008) and Gronwall et al. (2007) datapoints with $\log(L_{\text{Ly}C}) \geq 43$ to ours and performing the fit. Moreover, we constrained $\alpha$ in the last bin to the average of the value in the first two bins. The best-fit parameters are reported in Table 5.2.

Importantly, we note that the luminosity functions reported above are not corrected for absorption by the intergalactic medium. The Ly$\alpha$ flux from high-$z$ sources is generally absorbed by neutral hydrogen present in the IGM, that absorbs the blue wing of the Ly$\alpha$ line, producing an asymmetric line profile (Hu et al. 2004; Shimasaku et al. 2006). We therefore measure IGM absorbed Ly$\alpha$ fluxes, and not intrinsic Ly$\alpha$ fluxes. Moreover, the amount of absorption is not the same at different redshifts: at high $z$ the amount of intervening intergalactic medium is larger. As a consequence, if the observed i.e apparent luminosity functions do not evolve from $z = 2.5$ to $z = 6$, the intrinsic one positively evolves. The IGM optical depths have been estimated in various studies (i.e. Madau 1995, Fan et al. 2006 and Meiksin 2006): all the authors agree that the amount of absorption increases from $\sim 15\%$ at $z \sim 3$ to $\sim 50\%$ at $z \sim 6$ (at this redshift, basically all the blue side of the line is absorbed). Using the standard radiative transfer prescription by Fan et al. (2006) for the IGM optical depths, we can obtain the intrinsic luminosities $L_{\text{int}}$ from the observed $L_{\text{obs}}$. At $z \sim 2.5$, 4.2 and 6 the ratio $L_{\text{obs}}/L_{\text{int}}$ is respectively 0.91, 0.73 and 0.52.

In Figure 19 we show instead the intrinsic luminosity functions, corrected for the IGM absorption according to the prescription of Fan et al. (2006), together with our Schechter fits to the data.

The first main result from this analysis is that there does not seem to be a strong evolution of the apparent luminosity function between $z \sim 6$ and $z \sim 2.5$, within our error bars. In fact, looking at Figure 18 we see that within our $1\sigma$ errors, the luminosity functions in the different redshift bins overlap: moreover, looking at the Schechter best fit parameters in Table 5.2, we can see again that within $1\sigma$ the Schechter parameters do not evolve. On the other hand, by looking at the intrinsic luminosity functions in Figure 19, we do see an evolution between $z \sim 6$ and $z \sim 4$, while no sizeable evolution is observed between $z \sim 4$ and $z \sim 2$. The observed evolution can be parametrized with the evolution
in $L^\star$, that is at $z \sim 6$ about 1.8 times higher than in the first bin. However, its significance level is only 1.5$\sigma$.

The second interesting result comes from our ability to constrain the faint end of the luminosity function. We find slopes \( \alpha = -1.6_{-0.12}^{+0.12} \) at \( z \sim 2.5 \) and \( -1.78_{-0.12}^{+0.10} \) at and \( z \sim 4 \). Our data formally exclude a flat slope \( \alpha \sim -1 \) at 5 and 6.5$\sigma$, at these two redshifts. Our slope values are significantly better constrained than the best value of 1.36 and the marginalized value of \( -1.49_{-0.45}^{+0.48} \) found at \( z \sim 3.1 \) by Gronwall et al. (2007), a consequence of the 10 times fainter flux limit of our sample. Note that other authors, who again do not have deep enough data, do not try to fit $\alpha$, but they rather fix it to some plausible value (-1, -1.5 and -2) for Ouchi et al. 2008; -1.6 for Dawson et al. 2007; -1.2 and -1.6 for Lemaux et al. 2009). Our analysis therefore establishes the first reliable estimate of the faint end slope of the luminosity function of Ly\(\alpha\) galaxies at $z < 5$.

It is also important to state that the possible “non-Ly\(\alpha\)” emitters in our sample, described in Sect. 3.2, do not strongly affect these results. First of all, the luminosity distribution of the “ambiguous” lines (the 49 lines that cannot be unambiguously identified as Ly\(\alpha\) based on the line ratios) is similar to that of the global sample, and thus it is not expected to affect the slope determination. However, it is possible that in the 4.55 < $z$ < 6.6 redshift bin the contamination is higher than in the others. In fact, for all the lines at $\lambda > 6920$ (corresponding to $\alpha$(Ly\(\alpha\)) $\geq 4.7$), we cannot check for other lines in the spectra, if the line is identified as [OII] (see Sect. 3.2). However, we showed that the contamination is not expected to be higher than 10%, based on the EW distribution. Thus, assuming that all the 17 lines that can be identified as [OII] are at $z > 4.7$ would decrease the luminosity function in the last bin of a factor of 50% at the most. This would imply a weaker evolution of the luminosity function from $z = 6$ to $z = 4$.

5.3. Evolution of the star formation rate density

With these new constraints on the evolution of the Ly\(\alpha\) luminosity function at these redshifts, it is interesting to estimate the contribution of the Ly\(\alpha\) emitters to the global star formation rate density of the Universe. This is not trivial, as Ly\(\alpha\) emission produced not only by star formation activity, but also by other processes like cooling radiation, AGN activity or shock winds. Moreover, Ly\(\alpha\) emission is attenuated by IGM and dust.

We are computing here the SFRD using only the intrinsic Ly\(\alpha\) luminosity functions. In order to estimate the contribution of the galaxies in our sample, we integrated the luminosity function from $L_{Ly\alpha} = 0.04 \times L_\star$ to log[$L_{Ly\alpha}$]=44 (roughly the interval covered by our data). We then converted these Ly\(\alpha\) luminosity densities in star formation rate densities by using Equation 4.

The derived star formation rates are shown in Figure 20, together with the most recent estimates of the SFRD at redshift between $z=0$ and $z=6$. Ouchi et al. (2008) and Gronwall et al. (2007) use a sample of narrow band selected Ly\(\alpha\) emitters, while the other estimates are based on the UV galaxy luminosity function.

We can see that our measurements show a slight evolution of the Ly\(\alpha\) SFRD between $z \sim 2.5$ and $z \sim 4$, and a much more significant evolution from $z \sim 4$ and $z \sim 6$. Our values are compatible within the errors to those obtained by Ouchi et al. (2008).

When comparing our estimates of the Ly\(\alpha\) SFRD with the UV-derived ones, we see that the total contribution of Ly\(\alpha\) galaxies to the global star formation density at $z \sim 2-6$ is important, increasing from ~ 20% at $z \sim 2.5$ to ~ 100% at $z \sim 6$. This implies that the Ly\(\alpha\) emission is a good tracer of the star formation, this statistically implies that, while at redshift $z \sim 2$ only a small fraction of the galaxies contributing to the star formation history of the universe also show a Ly\(\alpha\) emission, all the galaxies at $z \sim 6$ do show Ly\(\alpha\) in emission. In other words, the so called escape fraction, that is the fraction of Ly\(\alpha\) emission produced by the star formation that actually escapes the star formation regions changes a lot with the cosmic epoch, from 20% at $z = 2.5$, reaching up to 100% at $z \sim 6$. This seems to indicate that the mechanism which is absorbing the Ly\(\alpha\) photons in most of the galaxies at $z = 2$ is not effective at $z \sim 6$, as is expected in a very low dust medium. However, dust estimates at $z \sim 5-6$ show that the dust content should be sufficient to produce significant Ly\(\alpha\) photons absorption (e.g. Bouwens et al. 2009).
This produces a survey volume of 

\(10^4\) \(Mpc^3\) down to a flux of \(1.4 \times 10^{-17} \text{erg/cm}^2/\text{s}\); Martin et al. (2008) sampled \(4.5 \times 10^4 \text{Mpc}^3\) down to similar fluxes in a narrow redshift range. Narrow band imaging surveys sampled bigger volumes than ours, but to a shallower flux: Ouchi et al. (2008) covered a volume of \(\sim 10^4 \text{Mpc}^3\), down to fluxes \(\sim 2 \times 10^{-17} \text{erg/cm}^2/\text{s}\). Serendipitous surveys have been presenting low number of objects (Sawicki et al., 2008), even if somewhat deeper (Malhotra et al., 2005; Rauch et al., 2008). We are therefore sampling deeper into the LAE luminosity function as we discussed in section 5.2.

From an observational point of view, we demonstrate the efficiency of blind LAE searches with efficient multi-slit spectrographs. The success of our approach is the result of combining a broad wavelength coverage to a large effective sky area, with long integration times, made possible by the high multiplex of the VIMOS instrument. The broad wavelength coverage has been essential to secure the spectroscopic redshifts from one single observation, without the need for follow-up to confirm the Ly\(\alpha\) nature of the emission lines detected. This observing efficiency compares favorably with the time needed to perform narrow band imaging searches followed by multi-slit spectroscopy, and comparing the wide range in redshift covered by the former versus a narrow range for the latter. When the density of faint LAE is high, of the order several LAE/arcmin\(^2\), multi-slit spectrographs become more efficient to secure a large number of confirmed sources than narrow band imaging searches, while at bright fluxes covering a wide field is essential to find rarer sources and narrow band imaging is more efficient. The two approaches will therefore remain complementary. Our main findings are the following:

1. We found a total of 217 LAE with confirmed spectroscopic redshifts in the range \(2 \leq z \leq 6.62\), 133 coming from the serendipitous discovery in the multi-object spectrograph slits of the VVDS (105 from the Ultra-Deep and 28 from the Deep), and 84 coming from targeted VVDS observations of galaxies with \(17.5 \leq i_{AB} \leq 24.75\) (Le Fèvre et al., 2010, in prep.). About 50% of the Ultra-Deep and 40% of the Deep serendipitous targets have a detected optical counterpart down to magnitude \(AB \sim 28\) in deep CFHTLS images.

2. The observed projected density of LAE with a Ly\(\alpha\) emission brighter than \(F_{\text{Ly}\alpha} \sim 1.5 \times 10^{-18} \text{erg/s/cm}^2\) in the range \(2 \leq z \leq 6.6\) is \(33\) LAE per arcmin\(^2\), with \(25\) LAE per arcmin\(^2\) with \(2 \leq z \leq 4.5\) and \(8\) LAE per arcmin\(^2\) with \(4.5 < z \leq 6.6\). The corresponding volume density of faint LAE with \(L(\text{Ly}\alpha) \gtrsim 10^{41} \text{ergs/s} \sim 4 \times 10^{-2} \text{Mpc}^{-3}\), a high density not yet observed at these redshifts.

3. The mean rest-frame EW(Ly\(\alpha\)) of LAE in our sample range from \(40\) \(\AA\) at \(z = 2\) to \(300 \sim 400\) \(\AA\) at \(z = 5\) and 6, and the star formation rate covers a wide range \(0.1 \sim 20\) \(M_\odot\) yr\(^{-1}\), assuming no ISM or IGK extinction and a Salpeter IMF. The HeII-1640\(\AA\) emission has EW \(\sim 4 \sim 14\) at \(z = 2\) indicating the presence of young stars of a few Myr. We therefore detected vigorously star forming galaxies as well as galaxies with star formation comparable to dwarfs located at low redshifts.

4. The Ly\(\alpha\) apparent luminosity function does not evolve between \(z=2\) and \(z=6\), within the error bars of our survey. Taking into account the average differential evolution in the IGM absorption with redshift therefore translates into a positive evolution of the intrinsic Ly\(\alpha\) LF of about 0.5 magnitude from \(z = 2\) to \(z = 5\) and 6.

5. We obtain a robust estimate of the faint end slope of the LAE luminosity function from a large sample of spectroscopically confirmed LAE. It is very steep: we find \(\alpha = -1.6\) at \(z \sim 2.5\) and \(1.8\) at \(z \sim 4\).

6. The SFRD contributed by Ly\(\alpha\) galaxies is increasing from \(5 \times 10^{-3} \text{M}_\odot\) yr\(^{-1}\) Mpc\(^{-1}\) at \(z = 2.5\) to \(2 \times 10^{-2} \text{M}_\odot\) yr\(^{-1}\) Mpc\(^{-1}\) at \(z = 6\). The contribution of the Ly\(\alpha\) galaxies to the total SFRD of the universe as inferred by UV luminosity functions reported in the literature increases from \(\sim 20\%\) at \(z=2.5\)
to $\sim 100\%$ at $z=6$. This seems to imply that all the galaxies that are forming stars at $z = 6$ must show Ly$\alpha$ emission, therefore are in a very low dust medium. At $z = 2.5$ 80\% of the star forming galaxies must have the Ly$\alpha$ emission produced by star formation blocked by some mechanism so that only 20\% of the star forming galaxies show Ly$\alpha$ emission. A direct consequence would be that the Ly$\alpha$ escape fraction varies from 0.2 at $z = 2.5$ to about 1 at $z = 6$. This result would remain robust only if the total SFRD estimates based on UV luminosity functions using Lyman break galaxies identifications are complete.

The new VVDS measurements reported here bring a new important constraint to the LAE LF with a steep faint end slope observed at $2 < z < 4.5$. This implies that LAE with star formation rates of a few $10^{-11}$M$_\odot$yr$^{-1}$ comparable to that of low redshift dwarf star forming galaxies are dominating the LAE SFRD at these redshifts. While it remains to be proven that the faint end slope of the LF stays steep going to still higher redshifts, assuming the slope $\alpha \simeq 1.7$ as implied by our measurements at $2 < z < 4.5$ would imply that the LAE population is becoming the dominant source of star formation producing ionizing photons in the early universe $z \rightarrow 5 - 6$, becoming equivalent to that derived from Lyman Break Galaxies searches. The steep faint end slope further implies that during reionisation sub-L$^*$ galaxies may have played an important role in keeping the universe ionized.

These results further demonstrate that efforts dedicated to constraining the evolution of the luminosity function of high redshift LAE will remain an important tool to probe into the reionisation period.

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References

Ando, M., Ohta, K., Iwata, L., et al., 2006, ApJ, 645, L9
Avni, Y., and Bahcall, J. N., 1980, ApJ, 235, 694
Beckwith, S. V. W., Stiavelli, M., Koekemoer, A. M., et al., 2006, AJ, 132, 1729
Bond, N. A., Feldmeier, J. J., Matkovic, A., et al., 2010, ApJ, 716, 200
Bongiorno, A., Zamorani, G., Gavignaud, I., et al., 2007, A&A, 472, 443
Bouwens, R.J., Illingworth, G.D., Franx, M., and Ford, H., 2007, ApJ, 660, 928
Bouwens, R.J., Illingworth, G.D., Franx, M., et al., 2009, ApJ, 705, 936
Bouwens, R.J., Illingworth, G.D., Oesch, P.A., et al., 2010, ApJ, 709, 133
Brocklehurst, M., 1971, MNARS, 153, 471
Coupon, J., Ilbert, O., Kilbinger, M. et al., 2009, A&A, 500, 981
Cowie, L. L., and Hu, M. H., 1998, AJ, 115, 1319
Cowie, L. L., & Berger, A. J., 2008, ApJ, 686, 72
Cuby, J.G., Le Fèvre, O., McCracken, H., et al., 2003, A&A, 405, 19
Dawson, S., Rhoads, J. E., Malhotra, S., et al., 2007, ApJ, 671, 1227
Deharveng, J-M., Small, T., Barlow, T.A., et al., 2008, ApJ, 680, 1072
Djorgovski, S., Spinrad, H., McCarthy, P., and Strauss, M.A., 1985, ApJ, 299, L1
Finkelstein, S. L., Rhoads, J. E., Malhotra, S., and Grogin, N., 2009, ApJ, 691, 465
Fan, X., Strauss, M. A., Becker, R. H., et al., 2006, AJ, 132, 117
Garilli, B., Le Fèvre, O., Guzzo, L., et al., 2008, A&A, 486, 683
Gawiser, E., van Dokkum, P. G.; Gronwall, C., et al., 2006, ApJ, 642, 13
Gawiser, E., Francke, H., Lai, K., et al., 2007, ApJ, 671, 278
Giavalisco, M., Koratkar, A., Calzetti, D., 1996, A&A, 466, 831
Giavalisco, M., 2002, ARA&A, 40, 579
Goranova, Y., Huelot, P., Magnard, F., et al., 2009, The CFHTLS T0006 Release, http://terapix.iap.fr/plt/table_synth006.html
Grove, L. F., Fynbo, J. P. U., Ledoux, C., et al., 2009, A&A, 497, 689
Gronwall, C., Ciardullo, R., Hickey, T., et al., 2007, ApJ, 677, 79
Guaita, L., Gawiser, E., Padilla, N., et al., 2010, ApJ, 714, 235
Hammer, F., Flores, H., Lilly, S. J., et al., 1997, ApJ, 481, 49
Hu, E. M., et al., 2004, AJ, 127, 563
Iovino, A., McCracken, H. J., Garilli, B., et al., 2005, A&A, 442, 423
Kashikawa, N., et al., 2006, ApJ, 648, 7
Kennicutt, R. C., 1998, ApJ, 498, 541
Kewley, L. J., & Ellison, S. L., 2008, ApJ, 681, 1183
Kunth, D., Mas-Hesse, J. M., Terlevich, E., et al., 1998, A&A, 334, 11
Lamareille, F., Contini, T., Brinchmann, J., et al., 2006, A&A, 448, 907
Lamareille, F., Brinchmann, J., Contini, T., et al., 2009, A&A, 495, 53
Lemaux, B. C., Lubin, L. M., Sawicki, M., et al., 2009, ApJ, 700, 20
Le Fevre, O., Saisse, M., Mancini, D., et al., 2003, SPIE, 4841, 1670
Le Fevre, O., Vettolani, G., Garilli, B., et al., 2005, A&A, 439, 845
Le Fevre, O., Paltani, S., Arnouts, S., et al., 2005b, Nature, 437, 519
Mais, P., Cassata et al.: SFRD from Ly$\alpha$ emitters in VVDS

18