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Connecting faint-end slopes of the Lyman α emitter and Lyman-break galaxy luminosity functions

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ABSTRACT

We predict Lyman α ($\text{Ly}\alpha$) luminosity functions (LFs) of $\text{Ly}\alpha$ -selected galaxies ($\text{Ly}\alpha$ emitters, or LAEs) at $z = 3\text{--}6$ using the phenomenological model. This model combines observed UV-LFs of Lyman-break galaxies (LBGs, or drop-out galaxies), with constraints on their distribution of $\text{Ly}\alpha$ line strengths as a function of UV-luminosity and redshift. Our analysis shows that while $\text{Ly}\alpha$ LFs of LAEs are generally not Schechter functions, these provide a good description over the luminosity range of $\log_{10}(L_{\alpha}/\text{erg s}^{-1}) = 41\text{--}44$. Motivated by this result, we predict Schechter function parameters at $z = 3\text{--}6$. Our analysis further shows that (i) the faint-end slope of the $\text{Ly}\alpha$ LF is steeper than that of the UV-LF of LBGs, (with a median $\alpha_{\text{Ly}\alpha} < -2.0$ at $z \gtrsim 4$), and (ii) a turnover in the $\text{Ly}\alpha$ LF of LAEs at $\text{Ly}\alpha$ luminosities $10^{40} \lesssim L_{\alpha} \lesssim 10^{41} \text{ erg s}^{-1}$ may signal a flattening of UV-LF of LBGs at $-12 > M_{\text{UV}} > -14$. We discuss the implications of these results – which can be tested directly with upcoming surveys – for the Epoch of Reionization.

Key words: galaxies: high-redshift – galaxies: luminosity function, mass function – dark ages, reionization, first stars – ultraviolet: galaxies.

1 INTRODUCTION

The luminosity function (LF) of galaxies provides one of the most basic statistical descriptions of a population of galaxies. It describes the number density of galaxies in a given luminosity interval. Generally, the LF is well described by a Schechter (1976) function

$$\phi(L)dL = \phi^* \left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right) d\left(\frac{L}{L^*}\right) \quad (1)$$

with a normalization parameter ϕ^* , an exponential cutoff at $L \gtrsim L^*$ and a power law with faint-end slope α for $L \ll L^*$. The parameters depend on wavelength considered, galaxy type (e.g. passive versus star forming) and cosmic time.

At high redshift, galaxies are typically identified either through their broad-band colours, for example using the drop-out or Lyman-break technique (Steidel et al. 1996), or through narrow-band searches aimed at detecting emission lines (Partridge & Peebles 1967; Djorgovski et al. 1985). In particular, young star-forming galaxies emit a significant fraction of their radiation as Lyman α ($\text{Ly}\alpha$) emission, and this method has been proved to be very efficient in finding samples out to $z \sim 7$ (e.g. Rhoads et al. 2000,

2012; Rhoads & Malhotra 2001; Ouchi et al. 2008; Bond et al. 2009, 2010; Guaita et al. 2010; Kashikawa et al. 2011; Hiben et al. 2012; Ono et al. 2012; Ota & Iye 2012; Shibuya et al. 2012; Finkelstein et al. 2013; Konno et al. 2014).

Galaxies that have been selected (found) on the basis of their $\text{Ly}\alpha$ lines are referred to as ‘ $\text{Ly}\alpha$ emitters’ (or LAEs). LAEs are useful because they are selected on having a strong $\text{Ly}\alpha$ line flux irrespective of their associated UV-continuum emission. Therefore, LAEs can be fainter in the continuum compared to Lyman-break galaxies (LBGs), and complement galaxy samples obtained via broad-band searches which have been extensively carried out with the *Hubble Space Telescope* out to $z \sim 10$ (e.g. Yan & Windhorst 2004; Beckwith et al. 2006; Bouwens et al. 2006, 2014a; Wilkins et al. 2010; Trenti et al. 2011; Finkelstein et al. 2012, 2014; Grazian et al. 2012; Oesch et al. 2014; Schmidt et al. 2014). Moreover, the sensitivity of the observed $\text{Ly}\alpha$ flux to intervening neutral hydrogen gas makes LAEs an excellent probe of the Epoch of Reionization (see e.g. Dijkstra 2014, for a review).

Since the range of observed $\text{Ly}\alpha$ luminosities at high- z typically extends only over $\sim 1\text{--}1.5$ orders of magnitude, the shape of the $\text{Ly}\alpha$ LF is not strongly constrained and a fit with a Schechter function leads to significant degeneracy in the parameters. In particular, the faint-end slope $\alpha_{\text{Ly}\alpha}$ is essentially unconstrained: for example, Henry et al. (2012) used a sample of six (three) LAEs

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to find $\alpha_{\text{Ly}\alpha} = -1.70_{-0.57}^{+0.73}$ ($\alpha_{\text{Ly}\alpha} = -1.45_{-0.70}^{+0.92}$) at $z = 5.7$. Other approaches include assuming a fixed value for $\alpha_{\text{Ly}\alpha}$ and resorting to the data to constrain the other parameters (van Breukelen, Jarvis & Venemans 2005; Dawson et al. 2007; Ouchi et al. 2008; Hu et al. 2010; Kashikawa et al. 2011; Ciardullo et al. 2012; Zheng et al. 2013). In contrast, the ultraviolet (UV) LF of LBGs is much better constrained due to available data stretching over several orders of magnitude in luminosity (McLure et al. 2010; Bouwens et al. 2011; Yan et al. 2011, 2012; Bradley et al. 2012; Oesch et al. 2012; Lorenzoni et al. 2013; Schenker et al. 2013). For the faint-end slope, the most recent by Bouwens et al. (2014a) finds $\alpha_{\text{UV}} = -1.91 \pm 0.09$ ($\alpha_{\text{UV}} = -1.64 \pm 0.04$) at $z \sim 6$ ($z \sim 4$).

There exists a clear opportunity to connect LAEs and LBGs via the Ly α line emission properties of LBGs. Shapley et al. (2003) provided a probability distribution function (PDF) of the rest-frame equivalent-width (EW) of the Ly α line in their sample of ~ 800 $z \sim 3$ LBGs. Dijkstra & Wyithe (2012) showed that this observed PDF was well described by an exponential function, and that the characteristic scalelength of this function *increased* towards fainter UV-luminosities. While there do not exist equally well-measured PDFs at higher redshifts and/or fainter UV-luminosities, recent studies have constrained both the redshift and UV-luminosity dependence of the so-called Ly α fraction, which quantifies the fraction of LBGs for which the Ly α EW exceeds a certain value. The Ly α fractions – which represent integrated versions of the full EW-PDF – increase from $z = 2$ to $z = 6$ at fixed M_{UV} (Stark et al. 2010; Cassata et al. 2015) and from UV-bright to UV-faint galaxies (Stark et al. 2010; Pentericci et al. 2011; Stark, Ellis & Ouchi 2011; Ono et al. 2012; Schenker et al. 2012).

There have been several attempts to link the redshift evolution of LBGs and their Ly α fractions to LAE LFs (Dijkstra & Wyithe 2012; Faisst et al. 2014; Schenker et al. 2014). In this paper, we follow the work of Dijkstra & Wyithe (2012) and combine the most recent constraints on UV-LFs and Ly α fractions to make predictions for Ly α LFs. Dijkstra & Wyithe (2012) showed that this phenomenological model reproduces observed Ly α LFs and their redshift evolution remarkably well. Here, we focus specifically on the faint-end slope of the Ly α LF of LAEs, because (i) we can make robust predictions for this faint-end slope, (ii) as we will show later, this faint-end slope can be highly relevant for understanding the Epoch of Reionization.

This paper is structured as follows. In Section 2, we lay out our method. We present our results in Section 3 and discuss them in Section 4. Finally, we conclude in Section 5. The cosmological parameters we adopt are $\Omega_{\text{m}} = 0.3$, $\Omega_{\Lambda} = 0.7$, $h = 0.7$, $\sigma_8 = 0.9$.

2 METHOD

The number density of LAEs with luminosities in the interval $[L_{\alpha} \pm dL_{\alpha}/2]$ is given by

$$\phi_{\text{LAE}}(L_{\alpha})dL_{\alpha} = dL_{\alpha} \int_{M_{\text{UV},\text{min}}}^{M_{\text{UV},\text{max}}} dM_{\text{UV}} \phi(M_{\text{UV}})P(L_{\alpha}|M_{\text{UV}}). \quad (2)$$

Here, $\phi(M_{\text{UV}})dM_{\text{UV}}$ denotes the number density of LBGs as a function of in the range $M_{\text{UV}} \pm dM_{\text{UV}}/2$. This function can be represented by the Schechter function with parameters $(\alpha_{\text{UV}}, M_{\text{UV}}^*, \phi_{\text{UV}}^*)$.

The term $P(L_{\alpha}|M_{\text{UV}})dL_{\alpha}$ is the conditional probability that a galaxy has a Ly α luminosity L_{α} given an absolute UV magnitude M_{UV} . This conditional probability can be recast in terms of the equivalent width (EW) probability density function $P(\text{EW}|M_{\text{UV}})$ as $P(L_{\alpha}|M_{\text{UV}}) = P(\text{EW}|M_{\text{UV}}) \frac{\partial \text{EW}}{\partial L_{\alpha}}$ if $\text{EW} > \text{EW}_{\text{LAE}}$, where L_{α} and EW are related as $L_{\alpha} = \text{EW}L_{\nu} = \text{EW}[\nu L_{\nu}/\lambda]$. Here, the lumi-

nosity/flux densities, frequency and wavelength are evaluated just longwards of the Ly α resonance at $\lambda = (1216 + \epsilon) \text{ \AA}$. We can extrapolate these flux/luminosities to their values where the UV-continuum measurements are usually made (see e.g. Dijkstra & Westra 2010).¹ Furthermore, EW_{LAE} denotes the EW threshold that determines whether a galaxy would make it into an LAE sample. We adopt that $\text{EW}_{\text{LAE}} = 0 \text{ \AA}$, but note that some surveys adopt colour criteria for selecting LAEs as large as $\text{EW}_{\text{LAE}} = 64 \text{ \AA}$ (see Dijkstra & Wyithe 2012). If $\text{EW} \leq \text{EW}_{\text{LAE}}$, then $P(L_{\alpha}|M_{\text{UV}}) = 0$ since in this case the galaxy does not qualify as an LAE. This threshold more closely represents detection threshold for Ly α emitting galaxies in spectroscopic surveys² – e.g. with *MUSE* (Bacon et al. 2010), *HETDEX* (Hill et al. 2008) and/or *VIMOS* (Cassata et al. 2011, 2015). We have verified that our main results do not depend on this choice.³

The preceding factor F in equation (2) is merely a normalization constant to fit the data and, hence, can be thought of as the ratio of predicted versus the total number of LAEs. This factor should ideally be $F = 1$. However, Dijkstra & Wyithe (2012) required that $F \sim 0.5$. The origin of this number is not known (see Dijkstra & Wyithe 2012, for an extensive discussion),⁴ but we stress it only affects the predicted normalization linearly and not the predicted faint-end slopes.

Hence, the key function in our analysis is $P(\text{EW}|M_{\text{UV}})$. Several functional forms have been explored in the literature. Schenker et al. (2014) compared the maximum likelihood values for several EW distributions to their Keck MOSFIRE (McLean et al. 2012) data, and concluded that the exponential distribution introduced by Dijkstra & Wyithe (2012) provides an adequate fit. This functional form is

$$P(\text{EW}|M_{\text{UV}}, z) = \mathcal{N} \exp \left[-\frac{\text{EW}}{\text{EW}_c(M_{\text{UV}}, z)} \right] \quad (3)$$

with $\text{EW}_c = \text{EW}_{c,0} + \mu_{M_{\text{UV}}}(M_{\text{UV}} + M_{\text{UV},0}) + \mu_z(z + z_0)$, where $\mu_{M_{\text{UV}}}$, μ_z , $M_{\text{UV},0}$, z_0 and $\text{EW}_{c,0}$ are model parameters. These parameters were chosen to match the observations of Shapley et al. (2003) and Stark et al. (2010, 2011) as closely as possible. Furthermore, \mathcal{N} is a normalization constant which is forced to be zero outside of $[\text{EW}_{\text{min}}, \text{EW}_{\text{max}}]$. Our choice of values for the model parameters is described in Section 3.3, where we present the numerical results. In Appendix A, we show explicitly that the main results in this paper are insensitive to both the functional form of $P(\text{EW})$ and the parametrization of EW_c .

3 RESULTS

We first present results in which $\text{EW}_c = \text{constant}$ (in Section 3.1). This allows us to demonstrate that for models in which the Ly α fraction does not evolve with M_{UV} , the faint-end slope of the LF of LAEs approaches that of LBGs. We then present a simplified

¹ We use the relation $L_{\alpha} = C_1 \text{EW}L_{\text{UV},\nu}$ where $L_{\text{UV},\nu} \propto \nu^{-\beta-2}$ is the UV luminosity density $L_{\text{UV},\nu}$ and $C_1 \equiv \nu_{\alpha}/\lambda_{\alpha}(\lambda_{\text{UV}}/\lambda_{\alpha})^{-\beta-2}$ converts the flux density at $\lambda = (1216 + \epsilon) \text{ \AA}$ to that at $\lambda_{\text{UV}} = 1600 \text{ \AA}$, which is the wavelength where $L_{\text{UV},\nu}$ was measured (Dijkstra & Westra 2010).

² Note that in practice an EW cut is likely still needed to distinguish between LAEs and lower z interlopers, such as [O II] emitters. This EW cut can nevertheless be lower than $\text{EW}_{\text{LAE}} \sim 20 \text{ \AA}$ (Leung et al. 2015).

³ We have verified that varying EW_{LAE} in the range $[0, 50] \text{ \AA}$ changes $\alpha_{\text{Ly}\alpha}$ by ~ 0.02 .

⁴ The value of F depends weakly on the adopted UV Schechter function parameters. For example, Bowler et al. (2014) reported slightly different best-fitting values, which drive F up to $F \sim 0.7$ – 0.8 . The Finkelstein et al. (2014) parameters, on the other hand, also suggest $F \sim 0.5$.

model in Section 3.2 in which the *mean* Ly α EW-PDF increases towards fainter UV-LF. This model demonstrates quantitatively that the faint-end slope of the LF of LAEs is steeper than that of LBGs if the Ly α fraction increases towards fainter UV-luminosities. In Section 3.3, we present the results that we obtained from the EW-PDF given in equation (3).

3.1 Exemplary case with $EW_c = \text{const.}$

We consider the case $P(EW|M_{UV}) = P(EW)$, i.e. $EW_c = \text{const.} \equiv \lambda/C_1$. Furthermore, we set $\mathcal{N} = 0$ for $EW < EW_{LAE}$. Under these assumptions, we find

$$\phi(L_\alpha)dL_\alpha \propto \int_0^\infty L_{UV,v}^{\alpha-1} \exp\left[-\frac{L_{UV,v}}{L_{UV}^*} - \frac{L_\alpha}{\lambda L_{UV,v}}\right] dL_{UV,v} \quad (4)$$

$$\propto L_\alpha^{\alpha_{UV}/2} K_{-\alpha_{UV}}\left(2\sqrt{\frac{L_\alpha}{\lambda L_{UV}^*}}\right) dL_\alpha, \quad (5)$$

where $K_n(x)$ is the modified Bessel function of the second kind and L_{UV}^* is the luminosity corresponding to M_{UV}^* .

Equation (5) shows that the Ly α LF generally does not take-on a Schechter form. The slope of the LF is given by

$$\alpha_{Ly\alpha} \equiv \frac{d \log \phi(L_\alpha)}{d \log L_\alpha} = -\frac{\sqrt{y} K_{\alpha_{UV}-1}(2\sqrt{y})}{K_{\alpha_{UV}}(2\sqrt{y})} \quad (6)$$

with $y \equiv L_\alpha/(L_{UV}^*\lambda)$. For $L_\alpha \ll L_{UV}^*\lambda$, we have $y \ll 1$, and we obtain to leading order $\alpha_{Ly\alpha} \approx -\Gamma(1 - \alpha_{UV})/\Gamma(-\alpha_{UV}) = \alpha_{UV}$. Thus, having a constant EW_c corresponds to an unchanged faint-end slope, $\alpha_{Ly\alpha} = \alpha_{UV}$.

3.2 Exemplary case where $P(EW|M_{UV})$ evolves with M_{UV}

If EW_c depends on M_{UV} , a general analytic solution for $\phi(L_\alpha)$ does not exist. For illustration purposes, we first consider a case in which we replace equation (3) with a Dirac- δ distribution,

$$p(EW|L_{UV}) \propto \delta(EW - EW_d), \quad (7)$$

where $EW_d(L_{UV}) \equiv EW_{d,0} (L_{UV}/L_{UV}^*)^\gamma$. The parameter EW_d can be interpreted as the mean of the full PDF. This δ -function PDF leads⁵ to

$$\phi(L_\alpha)dL_\alpha \propto dL_\alpha \times L_\alpha^{\alpha_{UV}/(\gamma+1)} \times \exp\left[-\left(\frac{L_\alpha}{C_1 EW_{d,0} L_{UV}^*}\right)^{1/(\gamma+1)}\right]. \quad (8)$$

Here, the faint-end slope is $\alpha_{Ly\alpha} = \alpha_{UV}/(\gamma + 1)$. The Ly α LF thus has a *steeper* faint-end slope than the LBG LF, if $\gamma < 0$ (i.e. if EW_d decreases towards fainter L_{UV} , as has been observed). Also note that we again obtain $\alpha_{Ly\alpha} = \alpha_{UV}$ if EW_d does not evolve with M_{UV} .

3.3 Realistic case with $P(EW|M_{UV})$ inferred from observations

For the model parameters of $P(EW|M_{UV})$ in equation (3), we adopt the values from Dijkstra & Wyithe (2012).⁶ Example EW-PDFs

⁵ For simplicity, we set the minimum and maximum UV luminosity to zero and infinity, respectively.

⁶ Specifically, the model parameters related to EW_c are given by $(EW_{c,0}, \mu_{M_{UV}}, \mu_z, M_{UV,0}, z_0, F) = (23 \text{ \AA}, 7 \text{ \AA}, 6 \text{ \AA}, 21.9, -4.0, 0.53)$. The EW-PDF covers the range $[EW_{\min}, EW_{\max}]$. Here, the lower limit

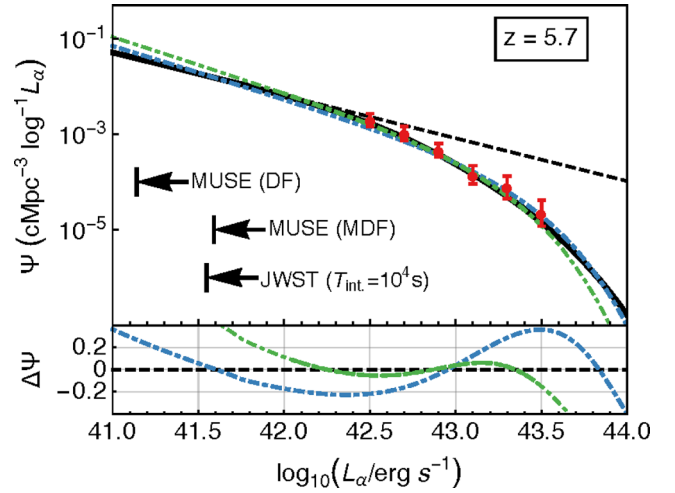


Figure 1. Upper panel: the predicted number of LAEs in the range $\log_{10}(L_\alpha/\text{erg s}^{-1}) \pm d\log_{10}(L_\alpha/\text{erg s}^{-1})$ using the UV-LF evolution from Bouwens et al. (2014a) taken at $z = 5.7$ (black solid line). The grey dashed line marks the faint-end slope ($\alpha_{Ly\alpha} = -1.90$) and the dash-dotted lines show Schechter fits to our numerical findings. Once the fit was carried out over the whole shown luminosity range (blue) and once only in $\log_{10}(L/\text{erg s}^{-1}) = [42, 43.5]$ (green). The red discs are the $z = 5.7$ observations by Ouchi et al. (2008) and the black arrows denote the *MUSE* DF and MDF as well as the *JWST* limits at that redshift (see the text for details). Lower panel: relative deviation of the fits to the numerical results.

are shown in Appendix A1. For a more detailed motivation of this $P(EW)$, we refer the reader to Dijkstra & Wyithe (2012). We integrate the UV-LF over the range $M_{UV,(\text{min,max})} = (-30, -12)$ when predicting Ly α LFs, and discuss the impact of varying M_{\max} in Section 4.

The redshift evolution of the best-fitting Schechter parameters of the UV-LF is taken from Bouwens et al. (2014a) and given as $M_{UV}^* = -20.89 + 0.12z$, $\phi_{UV}^* = 0.48 \times 10^{-0.19(z-6)} 10^{-3} \text{ cMpc}^{-3}$ and $\alpha_{UV} = -1.85 - 0.09(z - 6)$. Following these analyses, we use $\lambda_{UV} = 1600 \text{ \AA}$ as rest-frame wavelength in which the UV continuum was measured and assume a UV spectral slope $\beta = -1.7$. This choice for β does not affect our results (see Appendix A4 for detailed discussion).

The upper panel of Fig. 1 shows the resulting number density of LAEs at $z = 5.7$ in the luminosity range $\log_{10}L_\alpha \pm d\log_{10}L_\alpha/2$, i.e. $\psi(L_\alpha)d\log_{10}L_\alpha$, as a function of L_α . This quantity is related to $\phi(L_\alpha)$ as $\psi(L_\alpha) = \phi(L_\alpha)L_\alpha \log 10$ ('log' denotes the natural logarithm). We compare these predictions to the data from Ouchi et al. (2008). In addition, we show the *MUSE* detection limits⁷ for its medium deep field (MDF, limiting flux $F > 1.1 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$, integration time $T_{\text{int.}} = 10 \text{ h}$), and, deep field (DF, $F > 3.9 \times 10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2}$, $T_{\text{int.}} = 80 \text{ h}$) surveys as well as an exemplary *JWST*⁸ limit ($F \gtrsim 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$, $T_{\text{int.}} = 10^4 \text{ s}$).

$EW_{\min} \equiv -a_1$, where $a_1(M_{UV})$ follows the form $a_1 = 20 \text{ \AA}$ for $M_{UV} < -21.5$, $a_1 = (20 - 6(M_{UV} + 21.5)^2) \text{ \AA}$ for $-21.5 \leq M_{UV} \leq -19.0$ and $a_1 = -17.5 \text{ \AA}$, otherwise (see Dijkstra & Wyithe 2012). We used $EW_{\max} = 1000 \text{ \AA}$ but we verified that this choice does not affect our results quantitatively.

⁷ *MUSE* survey limits taken from http://muse.univ-lyon1.fr/IMG/pdf/science_case_gal_formation.pdf.

⁸ *JWST* survey limits obtained from <http://www.stsci.edu/jwst/science/sensitivity/>.

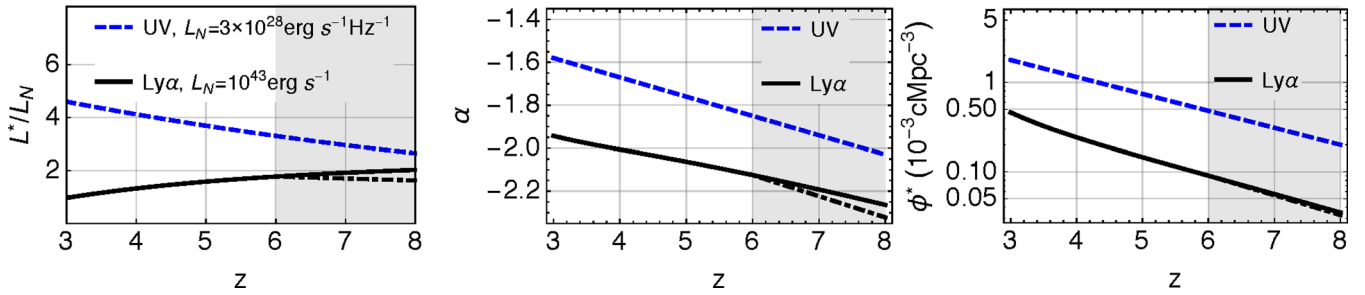


Figure 2. Evolution of the Schechter parameters of the UV-LF from Bouwens et al. (2014a, as blue dashed lines) and the parameters of the computed Ly α LF (black lines). In particular, the left-hand panel shows the characteristic luminosity L^* (note the different normalization constants), the central panel the faint-end slope α and the right-hand panel, the overall normalization ϕ^* . Predictions at $z > 6$ (within the shaded grey area) do not account for reionization (see Section 4.3). In this region, the black solid lines correspond to models with an uninterrupted EW evolution, whereas the dash-dotted lines represent a model in which we freeze the EW evolution, i.e. $\text{EW}_c(z > 6) = \text{EW}_c(z = 6)$ (this assumption has been adopted in previous works).

Fig. 1 also shows two Schechter function approximations to our numerical findings fitted over the full luminosity-range shown (in blue) and over $\log_{10}(L_\alpha / \text{erg s}^{-1}) = [40.5, 42]$ (in green). Although we do not expect the resulting Ly α LF to be a Schechter function (as shown in Section 3.2), it provides a reasonable fit over the displayed luminosity range. This can also be seen in the lower panel of Fig. 1, where we display the relative deviation of the fits to the LF.

Fig. 2 shows the redshift evolution of the Schechter best-fitting parameters (as black lines). Predictions for $z > 6$ do not account for reionization effects and are calculated with an unaltered EW evolution (solid line) as well as an EW-PDF which does not evolve after $z = 6$ (dash-dotted line). We discuss this result separately in Section 4.3. For comparison, we plot the corresponding redshift parametrization of the UV-LF by Bouwens et al. (2014a, as blue dashed lines). The left-hand panel shows that L^* increases by a factor ~ 2 over the redshift range $z = 3$ –6, which differs from the redshift evolution in the characteristic UV-luminosity which drops by 20 per cent. This difference is driven by the redshift evolution in the Ly α EW-PDF, which in turn was inferred from the observed redshift-evolution of Ly α ‘fractions’ over this redshift range. The central panel shows that $\alpha_{\text{Ly}\alpha} < \alpha_{\text{UV}}$. This is again a consequence of inferred redshift evolution of the Ly α EW-PDF (see Section 3.2). This figure also illustrates the close-to-linear $\alpha_{\text{Ly}\alpha}$ – z relation. This evolution is mostly driven by the redshift evolution of α_{UV} . Finally, the right-hand panel shows the predicted redshift evolution in ϕ^* .

4 DISCUSSION

4.1 Low- L turnover

The integral over $\phi(L_\alpha)dL_\alpha$ diverges for $\alpha < -2$. We therefore expect that the LF flattens or turns over below some luminosity. The minimum luminosity that we can account for in our models is

$$L_{\alpha, \min} = \text{EW}_{\min}(M_{\text{UV}, \max}) C_1 L_{\text{UV}, \min}, \quad (9)$$

where $\text{EW}_{\min} = -a_1 = 17.5 \text{ \AA}$ (see footnote 6 in Section 3.3) denotes the minimum EW in our EW-PDF at the maximum absolute UV-magnitude (i.e. the lowest UV-luminosity). For example, we obtain $L_{\alpha, \min} \sim 10^{39} \text{ erg s}^{-1}$ for $M_{\text{UV}, \max} = -12$. At this luminosity we expect the predicted Ly α luminosity to go to zero, as is shown in Fig. 4.

An estimate for where we may start to see departures from a power-law slope can be obtained by considering the conditional probability $p(M_{\text{UV}}|L_\alpha)$. Bayes’ theorem states that $p(M_{\text{UV}}|L_\alpha) \propto \phi(L_\alpha|M_{\text{UV}})\phi(M_{\text{UV}})$, of which we show examples in

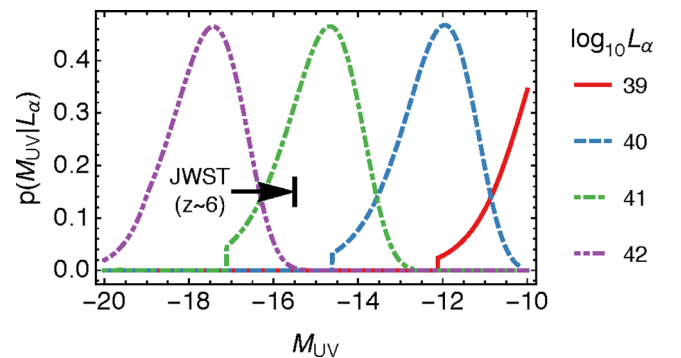


Figure 3. $p(M_{\text{UV}}|L_\alpha) \propto p(L_\alpha|M_{\text{UV}})\phi(M_{\text{UV}})$ versus M_{UV} for some exemplary values of L_α . The black arrow shows the *JWST* photometric limit quoted by Windhorst et al. (2006) for $z \sim 6$ which corresponds to $T_{\text{int.}} \sim 10^6$ s integration time.

Fig. 3 for four different values of L_α . This figure illustrates for example that Ly α observations that probe a flux corresponding to $L_\alpha = 10^{40} \text{ erg s}^{-1}$ – a level that can be reached in *MUSE* ultra-deep fields (UDFs) – effectively probe galaxies with $-14 < M_{\text{UV}} < -11$, which are fainter than can be probed directly even with the *JWST*. The *JWST* detection limit shown in Fig. 3 is taken from Windhorst et al. (2006). Fig. 3 further shows that if the UV-LF flattens off at – say $-M_{\text{UV}} \gtrsim -12$ that then the effects should become noticeable in the predicted Ly α LF around $L_\alpha = 10^{40} \text{ erg s}^{-1}$, as here galaxies with $M_{\text{UV}} \sim -12$ dominate the contribution to the Ly α LF.

In Fig. 4, we make these points more explicit, and show the predicted faint end of the LAELF for four values of $M_{\text{UV}, \max}$ (calculated with the UV-LF parameters at $z = 3.1$). For each curve we marked $L_{\alpha, \min}$ with dotted lines. For example, a potential UV turnover at $M_{\text{UV}} \sim -12$ leads to deviations⁹ of the Ly α LF at $L_\alpha \sim 10^{40} \text{ erg s}^{-1}$ and a cutoff at $L_\alpha \sim 10^{39} \text{ erg s}^{-1}$. Fig. 4 also contains data points taken from Rauch et al. (2008). Rauch et al. (2008) performed an ultra-deep (92 h) exposure with VLTs FORS2 low-resolution spectrograph. The goal of these observations was to detect fluorescent Ly α emission from optically thick clouds powered by the ionizing background. While their sensitivity turned out not to be good enough to detect this fluorescent emission (revised estimates of the ionizing background and the conversion efficiency into Ly α), they detected

⁹ The first deviations in the Ly α LF can be found at $L_{\alpha, \text{dev.}} = C_1 L_{\text{UV}}(x) \text{EW}_c(x)$ with $x \equiv M_{\text{UV}, \max} - \Delta M_{\text{UV}}$. Here, ΔM_{UV} describes the half-width of $p(M_{\text{UV}}|L_\alpha)$ at a chosen probability threshold.

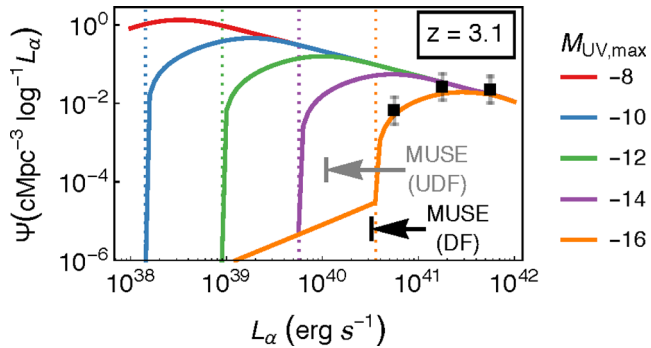


Figure 4. $\psi(L_\alpha)dL_\alpha$ versus L_α at $z = 3.1$ for different values of $M_{UV,max}$ illustrating the cutoff at low $Ly\alpha$ luminosities. The dashed and dotted lines show the ‘cutoff’ and ‘deviation’ points for each $M_{UV,max}$ discussed in Section 4. Data points are from Rauch et al. (2008) taken at that redshift (see the text for a discussion on the error bars). And the black (grey) arrow denotes planned future *MUSE* (ultra) DF limits.

numerous ultrafaint $Ly\alpha$ emitting sources characterizing their LF down to $L_\alpha \sim 6 \times 10^{40} \text{ erg s}^{-1}$. We computed the uncertainties with the cosmic variance calculator of Trenti & Stiavelli (2008). These data points fall on the predicted LF for $M_{UV,max} = -16$. However, we caution that the turnover occurs at the lowest luminosity data point only, which might suffer from incompleteness (although it lies above the detection threshold). In the same figure, we provide the estimated *MUSE* limits for the DF and the gravitationally lensed UDF surveys.

4.2 Implications for the Epoch of reionization

Low-luminosity galaxies are expected to play a major role in driving the reionization of the Universe (e.g. Robertson et al. 2010; Trenti et al. 2010; Kuhlen & Faucher-Giguère 2012; Boylan-Kolchin, Bullock & Garrison-Kimmel 2014). Determining the faint end of the LF such as its slope and a turnover luminosity is essential for constraining the volume emissivity of ionizing photons. However, even future experiments will have difficulties detecting these galaxies directly via their UV continuum flux. Current constraints rely, therefore, on extrapolation of local properties to higher redshifts (Weisz, Johnson & Conroy 2014), (relatively few) gravitationally lensed objects (Alavi et al. 2014; Atek et al. 2014) or inferences from gamma-ray burst observations (Trenti et al. 2012). In this work, we have shown that the $Ly\alpha$ LF can provide an independent probe of the faint end of the UV-LF, and that for example the *MUSE* DF survey could already detect (or rule out) a turnover at $M_{UV} \lesssim -15$.

Recent studies have shown that $Ly\alpha$ escape may be correlated with the escape of ionizing photons (Behrens, Dijkstra & Niemeyer 2014; Verhamme et al. 2014), as the escape of ionizing photons requires low H I-column density ($N_{HI} < 10^{17} \text{ cm}^{-2}$) channels, which can also provide escape routes for $Ly\alpha$ photons. The fact that $Ly\alpha$ LFs are likely steeper than the UV-LFs implies that the $Ly\alpha$ volume emissivity – and therefore possibly the ionizing emissivity – are weighted more strongly towards low-luminosity galaxies. This is consistent with the expectation that ionizing photons escape more easily from lower mass – and hence lower luminosity – galaxies. A steep faint-end slope of the $Ly\alpha$ LF may therefore provide observational support for this scenario.

4.3 Predictions for redshifts $z = 6-8$

We extrapolated our predictions for the best-fitting Schechter parameters of the LAE LF to $z > 6$ in two ways (shown in Fig. 2):

(i) in the first, we assume that the EW-PDF continues to evolve as inferred from the observations at $z = 3-6$. This model is represented by the *solid lines*, and, (ii) in the second, we ‘freeze’ the EW distribution for $z > 6$ at the value it had at $z = 6$ (*dashed lines*). This latter assumption has been common in previous works (see e.g. Dijkstra, Mesinger & Wyithe 2011; Bolton & Haehnelt 2013; Jensen et al. 2013; Choudhury et al. 2014; Mesinger et al. 2015). We show results for these two models to get a sense for the uncertainties on our predictions. We stress that we have purposefully *not* modelled the impact of reionization on the EW-PDF. Reionization is likely responsible for the observed ‘drop’ in the observed $Ly\alpha$ fractions at $z > 6$ (e.g. Pentericci et al. 2011; Ono et al. 2012; Schenker et al. 2012; Treu et al. 2013; Caruana et al. 2014; Tilvi et al. 2014). Understanding this drop has been the main focus of previous works, and is outside the scope of this paper. Our predictions for $z = 6-8$ are useful in a different way, as they provide predictions for the $Ly\alpha$ LFs of LAEs in the absence of reionization. Comparison to observed LFs at these redshifts highlights the impact of reionization.

5 CONCLUSIONS

We predicted $Ly\alpha$ LFs of $Ly\alpha$ -selected galaxies (LAEs) at $z = 3-6$ using the phenomenological model of Dijkstra & Wyithe (2012). This model combines observed UV-LFs of LBGs, with observational constraints on the $Ly\alpha$ EW-PDF of these LBGs, as a function of M_{UV} and redshift. The results from our analysis can be summarized as follows.

(i) While $Ly\alpha$ LFs of LAEs are generally not Schechter functions, these provide a good description over the luminosity range of $\log_{10}(L_\alpha / \text{erg s}^{-1}) = 41-44$ (see Fig. 1).

(ii) We predict Schechter function parameters at $z = 3-6$ (shown in Fig. 2). The faint-end slope of the $Ly\alpha$ LF is steeper than that of the UV-LF of LBGs, with a median $\alpha_{Ly\alpha} < -2.0$ at $z \gtrsim 4$ (see the *central panel* in Fig. 2). While the current work was in the advanced stage of completion, Dressler et al. (2014) posted a preprint in which they observationally infer a very steep faint-end slope at $z \sim 5.7$ ($-2.35 < \alpha < -1.95$, also see Dressler et al. 2011). The central value $\alpha = -2.15$ is in excellent agreement with the value $\alpha \sim -2.1$ predicted in our framework.

(iii) The faint end of the LAE LF provides independent constraints on the very faint end of the UV-LF of LBGs. For example, the predicted LAE LF at $Ly\alpha$ luminosities $10^{40} \text{ erg s}^{-1} \lesssim L_\alpha \lesssim 10^{41} \text{ erg s}^{-1}$ is sensitive to the UV-LF of LBGs in the range $-11 > M_{UV} > -15$ (see Figs 3 and 4). These LBGs are too faint to be detected directly (even with *JWST*). A turnover in the $Ly\alpha$ LF of LAEs may signal a flattening of UV-LF of LBGs. We discuss implications of these results for the Epoch of Reionization in Section 4.2.

We have verified that these results are insensitive to our assumed functional form of $P(\text{EW})$ and how we parametrized its dependence on z and M_{UV} . Our predictions can be tested directly with various upcoming surveys.

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APPENDIX A: VARYING THE EW DISTRIBUTION

In this appendix, we demonstrated that our main results and conclusions do not depend on our assumed EW-PDF.

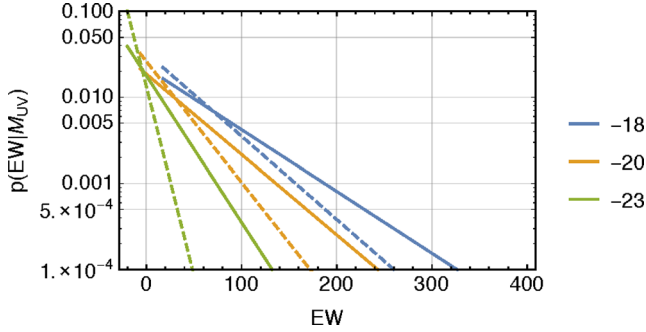


Figure A1. The PDF $P(\text{EW}|M_{\text{UV},z})$ as described in equation (3) for three different values of M_{UV} . The solid (dashed) lines shows the EW distribution for $z = 5.7$ ($z = 3.1$). Negative EWs corresponds to having $\text{Ly}\alpha$ in absorption. Note that for about half of $z \sim 3$ LBGs, $\text{Ly}\alpha$ is seen in absorption (Shapley et al. 2003). Our formalism incorporates this measurement (see Dijkstra & Wyithe 2012).

A1 Fiducial $P(\text{EW})$

Our default EW distribution is given by equation (3). We plot the PDF for three UV magnitudes and two redshifts in Fig. A1.

A2 Schenker et al. (2014) parametrization

As mentioned in Section 2, Schenker et al. (2014) suggest an alternative parametrization of the EW-PDF, namely

$$P(\text{EW}|\beta) = \frac{A_{\text{em}}}{\sqrt{2\pi}\sigma\text{EW}} \exp\left[-\frac{(\log \text{EW} - \mu(\beta))^2}{2\sigma^2}\right]. \quad (\text{A1})$$

This lognormal PDF possesses the parameters A_{em} , σ and μ . The latter is given by

$$\mu(\beta) = \mu_\alpha + \mu_s(\beta - 2.0), \quad (\text{A2})$$

where β is the UV continuum slope. Schenker et al. (2014) found their EW distribution to depend more strongly on β than on (M_{UV}, z) , and therefore constrained $P(\text{EW}|\beta)$. We can include this parametrization into our formalism if we map $P(\text{EW}|\beta)$ on to $P(\text{EW}|M_{\text{UV}}, z)$.

This mapping is based on three results from Bouwens et al. (2014b).

(i) We use their empirical linear correlation between β and M_{UV} at $z \sim 7$. This relation constrains $\beta(M_{\text{UV}} = -19.5) = -2.05 \pm 0.09 \pm 0.13$.

(ii) Furthermore, we apply their measured change per unit redshift $\Delta\beta/\Delta z = -0.1 \pm 0.05$.

(iii) Finally, we use their measurement that $\Delta\beta/\Delta M_{\text{UV}} = -0.2$ (-0.08) for $M_{\text{UV}} \leq -19$ (> -19).

Accordingly, our mapping can be written as

$$\beta = \beta_0 + \mu_{M_{\text{UV}}}^{(\beta)}(M_{\text{UV}} + 19) + \mu_z^{(\beta)}(z - 7), \quad (\text{A3})$$

where $\mu_{M_{\text{UV}}}^{(\beta)} \equiv \Delta\beta/\Delta M_{\text{UV}}$ and $\mu_z^{(\beta)} \equiv \Delta\beta/\Delta z$.

In equation (A1), we used the best parameters by Schenker et al. (2014), i.e. $(A_{\text{em}}, \sigma, \mu_\alpha, \mu_s) = (1.0, 1.3, 2.875, -1.125)$. In addition, since A_{em} is degenerate with F , we set $F = 1$. The orange dashed line in Fig. A2 shows the resulting $\text{Ly}\alpha$ LF at $z = 5.7$. The agreement in the faint end between the two procedures is remarkable. For greater

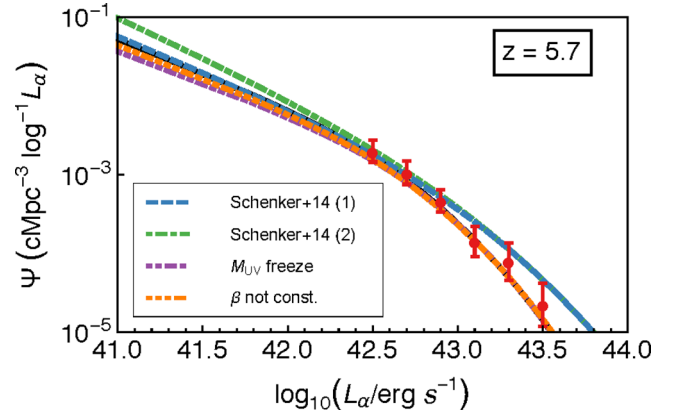


Figure A2. The $\text{Ly}\alpha$ LF at $z = 5.7$ for different EW distributions. The solid black line and Ouchi et al. (2008) data points are the same as shown in Fig. 1. As comparison we show the $\text{Ly}\alpha$ LF computed using the Schenker et al. (2014) parametrization of the EW-PDF once with the full β - M_{UV} relation as given in Section A2 (blue dashed line) and once with a constant $\mu_{M_{\text{UV}}}^{(\beta)} = -0.2$ over all M_{UV} (green dash-dotted line). Also shown are our results when freezing the EW-PDF at $M_{\text{UV}} = -19$ (purple) and when using the β - M_{UV} relation instead of a constant β (orange).

luminosities, however, the Schenker et al. (2014) parametrization leads to a (much) higher number density of LAEs. While there are significant uncertainties in the above procedure, the agreement we get at the faint-end slope is especially encouraging. Future surveys can be extremely useful in further connecting the LAE and LBG populations by constraining the bright end of the LAE LF.

A3 ‘Freezing’ the EW-PDF for faint galaxies

Since the evolution in the EW-PDF for fainter sources involves a (modest) extrapolation of observationally inferred $P(\text{EW})$, we have also tested an alternative PDF where we ‘froze’ the evolution at $M_{\text{UV}} = -19$. That is, we also conservatively assume that the EW-PDF stops evolving at $M_{\text{UV}} > -19$ (even though observations hint that this is not the case, see fig. 13 of Stark et al. (2010)). Fig. A2 shows the resulting $\text{Ly}\alpha$ LF (purple line). It is clear that our results are only affected slightly, i.e. the faint-end slope $\alpha_{\text{Ly}\alpha}$ is reduced by ~ 0.05 . We also tested this over a variety of redshifts.

A4 Non-constant UV spectral slope

The spectral slope β is not a constant, but depends on UV magnitude and redshift (as discussed above). This introduces some additional dispersion in the predicted $\text{Ly}\alpha$ flux at a fixed M_{UV} . However, varying β within $[-2.0, -1.5]$ changes the $\text{Ly}\alpha$ flux only by $1 - (\lambda_{\text{UV}}/\lambda_{\text{Ly}\alpha})^{1.5-2.0} \sim 13$ per cent. This dispersion is smaller than that introduced by the EW-PDF. If we replace the constant β with the empirical fit described in Section A2, then our predicted $\text{Ly}\alpha$ LF (represented by the orange line in Fig. A2) is barely any different from our fiducial model that used $\beta = -1.7$ (represented by the black solid line).

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