Connecting faint-end slopes of the Lyman $\alpha$ emitter and Lyman-break galaxy luminosity functions

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ABSTRACT

We predict Lyman $\alpha$ (Ly$\alpha$) luminosity functions (LFs) of Ly$\alpha$-selected galaxies (Ly$\alpha$ emitters, or LAEs) at $z = 3$–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 Ly$\alpha$ line strengths as a function of UV-luminosity and redshift. Our analysis shows that 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. Motivated by this result, we predict Schechter function parameters at $z = 3$–6. Our analysis further shows that (i) 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 $z \gtrsim 4$), and (ii) a turnover in the Ly$\alpha$ LF of LAEs at 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 $-12 > M_{UV} > -14$. 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

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

with a normalization parameter $\phi^*$, an exponential cutoff at $L \gtrsim L^*$ and a power law with faint-end slope $\alpha$ 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 $\alpha$ (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; Hibon 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 Ly$\alpha$ lines are referred to as ‘Ly$\alpha$ emitters’ (or LAEs). LAEs are useful because they are selected on having a strong 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 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 Ly$\alpha$ luminosities at high-$z$ typically extends only over $\sim$1–1.5 orders of magnitude, the shape of the Ly$\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 $\alpha_{Ly\alpha}$ is essentially unconstrained: for example, Henry et al. (2012) used a sample of six (three) LAEs

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to find $\alpha_{\text{Ly}\alpha} = -1.70^{+0.77}_{-0.57}$ ($\alpha_{\text{Ly}\alpha} = -1.45^{+0.97}_{-0.70}$) 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$\alpha$ 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$\alpha$ line in their sample of $\sim 800$ $z \sim 3$ 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$\alpha$ fraction, which quantifies the fraction of LBGs for which the Ly$\alpha$ EW exceeds a certain value. The Ly$\alpha$ fractions – which represent integrated versions of the full EW-PDF – increase with EW and UV-luminosity density $\alpha_{\text{Ly}\alpha}$ exceeds a certain value. The Ly$\alpha$ line from UV-bright to UV-faint galaxies (Stark et al. 2010; Cassata et al. 2012; 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 $z \sim 6$ ($z \sim 4$).

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 $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, $h = 0.7$, $\sigma_8 = 0.9$.

2 METHOD

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

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

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 $(\alpha_{\text{UV}}, M_{\text{UV}}^*, \phi_{\text{LAE}}).$

The term $P(L_{\alpha} | M_{\text{UV}})$ is the conditional probability that a galaxy has a Ly$\alpha$ luminosity $L_{\alpha}$ given an absolute UV magnitude $M_{\text{UV}}$. This conditional probability can be recast in terms of the equivalent width (EW) probability density function $P(\text{EW} | M_{\text{UV}})$ as

$$P(L_{\alpha} | M_{\text{UV}}) = P(\text{EW} | M_{\text{UV}}) \frac{d\text{EW}}{dL_{\alpha}} \text{if } \text{EW} > \text{EW}_{\text{LAE}},$$

where $L_{\alpha}$ and EW are related as $L_{\alpha} = \text{EW} L_{\alpha} = \text{EW} [\nu L_{\alpha} / \lambda]$. Here, the luminosity/flux densities, frequency and wavelength are evaluated just longwards of the Ly$\alpha$ resonance at $\lambda = (1216 + \epsilon) \, \text{Å}$. We can extrapolate these flux/luminosities to their values where the UV-continuum measurements are usually made (see e.g. Dijkstra & Westra 2010). Furthermore, EW_{LAE} denotes the EW threshold that determines whether a galaxy would make it into an LAE sample. We adopt that EW_{LAE} = 0 Å, but note that some surveys adopt colour criteria for selecting LAEs as large as EW_{LAE} = 64 Å (see Dijkstra & Wyithe 2012). If EW \leq EW_{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$\alpha$ emitting galaxies in spectroscopic surveys – 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.

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), 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

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

with $\text{EW}_e = \text{EW}_{e,0} + \mu_{\text{EW}}(M_{\text{UV}} + M_{\text{UV},0}) + \mu_z (z + z_0)$, where $\mu_{\text{EW}}, \mu_z, M_{\text{UV},0}$ and $\text{EW}_{e,0}$ 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, $N$ 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 $\text{EW}_e$.

3 RESULTS

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

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1 We use the relation $L_{\alpha} = C_1 L_{\text{UV}} L_{\alpha}^0$, where $L_{\text{UV}} \propto \nu^{-\beta - 2}$ is the UV luminosity density $L_{\text{UV}}$, and $C_1 \equiv \nu_{\alpha} \alpha L_{\alpha}^0 (\lambda_{\alpha} / 1216)^{-\beta - 2}$ converts the flux density at $\lambda = (1216 + \epsilon) \, \text{Å}$ to that at $\lambda_{\alpha} = 1600 \, \text{Å}$, which is the wavelength where $L_{\text{UV}}$ 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 EW_{LAE} \sim 20 Å (Leung et al. 2015).

3 We have verified that varying EW_{LAE} in the range [0, 50] Å 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 $F \sim 0.5$. 

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model in Section 3.2 in which the mean Lyα 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 Lyα 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 = const.

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

$$\phi(L_d)dL_d \propto \int_0^\infty L_{UV,1}^{\alpha-1} \exp \left[- \frac{L_{\text{UV},N}}{L_{\text{UV}}} - \frac{L_d}{\lambda L_{\text{UV},p}} \right] dL_{\text{UV},p}, \quad (4)$$

$$\propto L_{\text{UV},1}^{\alpha/2}K_{\alpha-\nu}(2\sqrt{\frac{L_d}{\lambda L_{\text{UV}}}}) dL_d, \quad (5)$$

where $K_\nu(x)$ is the modified Bessel function of the second kind and $L_{\text{UV},1}$ is the luminosity corresponding to $M_{UV}$.

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

$$\alpha_{Ly} = \frac{d\log \phi(L_d)}{d\log L_d} = \frac{\sqrt{\gamma}K_{\alpha-\nu}(2\sqrt{\gamma})}{K_{\alpha-\nu}(2\sqrt{\gamma})} \quad (6)$$

with $\gamma \equiv L_d/(L_{\text{UV},1})$. For $L_d \ll L_{\text{UV},1}$, we have $\gamma \ll 1$, and we obtain to leading order $\alpha_{Ly} \approx -\Gamma(1-\alpha_{UV})/\Gamma(-\alpha_{Ly}) = \alpha_{UV}$. Thus, having a constant EW, corresponds to an unchanged faint-end slope, $\alpha_{Ly} = \alpha_{UV}$.

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

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

$$P(\text{EW}|L_{UV}) \propto \delta(\text{EW} - \text{EW}_d), \quad (7)$$

where $\text{EW}_d(L_{UV}) \equiv \text{EW}_{d,0}(L_{UV}/L_{UV,0})^\gamma$. The parameter $\text{EW}_d$ can be interpreted as the mean of the full PDF. This $\delta$-function PDF leads to

$$\phi(L_d)dL_d \propto dL_d \times L_{d,UV}^{\alpha/(\gamma+1)} \times \exp \left[- \left(\frac{L_d}{C_1 \text{EW}_{d,0}L_{UV}}\right)^{1/(\gamma+1)} \right]. \quad (8)$$

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

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

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

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

Specifically, the model parameters related to EW are given by (EW$_{d,0}$, $P_{\text{MW}}$, $\alpha_t$, $M_{UV,0}$, $z_0$, $F$) $= (23$, $7$, $6$, $5$, $15$, $21.9$, $-4$, $0$, $0.53$). The EW-PDF covers the range $[\text{EW}_{\text{min}}, \text{EW}_{\text{max}}]$. Here, the lower limit

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

Figure 1. Upper panel: the predicted number of LAEs in the range $\log_{10}(L_d/\text{erg s}^{-1}) \pm \Delta \log_{10}(L_d/\text{erg s}^{-1})$ using the UV-LF evolution from Bouwens et al. (2014a) at $z = 5.7$ (black solid line). The grey dashed line marks the faint-end slope ($\alpha_{Ly} = -1.90$) 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 $\log_{10}(L_d/\text{erg s}^{-1}) = [42, 43.5]$ (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 $P(\text{EW})$, 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 Lyα LFs, and discuss the impact of varying $M_{\text{max}}$ 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 $M_{UV} = -20.89 + 0.12 \times (\phi_{UV} = 0.48 \times 10^{-20} \text{cMpc}^{-3}$ and $\alpha_{UV} = -1.85 - 0.09 (z = 6)$. Following these analyses, we use $\lambda_{UV} = 1600$ Å as rest-frame wavelength in which the UV continuum was measured and assume a UV spectral slope $\beta = -1.7$. This choice for $\beta$ 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 $\log_{10}(L_d/\text{erg s}^{-1}) \pm \Delta \log_{10}(L_d/\text{erg s}^{-1})$, i.e. $\psi(L_d)\Delta \log_{10}(L_d)$, as a function of $L_d$. This quantity is related to $\phi(L_d)$ as $\psi(L_d) = \phi(L_d)L_d\log 10 \log$ denotes the natural logarithm. We compare these predictions to the data from Ouchi et al. (2008). In addition, we show the MUSE detection limits$^7$ for its medium deep field (MDF, limiting flux $F > 1.1 \times 10^{-18} \text{erg s}^{-1}\text{cm}^{-2}$, integration time $T_{\text{int}} = 10$ h), and, deep field (DF, $F > 3.9 \times 10^{-19} \text{erg s}^{-1}\text{cm}^{-2}, T_{\text{int}} = 80$ h) surveys as well as an exemplary JWST$^8$ limit ($F > 10^{-18} \text{erg s}^{-1}\text{cm}^{-2}, T_{\text{int}} = 10^4$ s).

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


The minimum luminosity that we can account for in our models is $L_{\alpha}$ min, which expects that the LF flattens or turns over below some luminosity. The integral over redshift evolution in the characteristic UV-luminosity which drops where $EW_{\text{min}}$ right-hand panel shows the predicted redshift evolution in the Lyα 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 $\alpha$ and the right-hand panel, the overall normalization $\phi^*$. Predictions at $z > 6$ (within the shaded grey area) do not account for reionization. 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. $EW_L(z > 6) = EW_L(z = 6)$ (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 Lyα 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 $\sim 2$ 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 Lyα EW-PDF, which in turn was inferred from the observed redshift-evolution of Lyα ‘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 Lyα 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 $\alpha_{\text{UV}}$. Finally, the right-hand panel shows the predicted redshift evolution in $\phi^*$.

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

$$L_{\alpha, \text{min}} = EW_{\text{min}}(M_{\text{UV, max}}) C_1 L_{\text{UV, min}},$$

where $EW_{\text{min}} = -a_i = 17.5$ Å (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 $L_{\alpha, \text{min}} = 10^{39}$ erg s$^{-1}$ for $M_{\text{UV, max}} = -12$. At this luminosity we expect the predicted Lyα 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 Fig. 3, for four different values of $L_\alpha$. This figure illustrates for example that Lyα observations that probe a flux corresponding to $L_\alpha = 10^{39}$ erg s$^{-1}$ – a level that can be reached in MUSE ultradeep 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 $z \sim 6$ which corresponds to $T_{\text{int, reionization}} \sim 10^9$ s integration time.

Fig. 4 shows the predicted 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 $\sim 2$ 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 Lyα EW-PDF, which in turn was inferred from the observed redshift-evolution of Lyα ‘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 Lyα 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 $\alpha_{\text{UV}}$. Finally, the right-hand panel shows the predicted redshift evolution in $\phi^*$.

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In Fig. 4, we make these points more explicit, and show the predicted faint-end of the LAE LF for four values of $M_{\text{UV, max}}$ (calculated with the UV-LF parameters at $z = 3.1$). For each curve we marked $L_{\alpha, \text{min}}$ with dotted lines. For example, a potential UV turnover at $M_{\text{UV}} \sim -12$ leads to deviations of the Lyα LF at $L_\alpha \sim 10^{39}$ erg s$^{-1}$ and a cutoff at $L_\alpha \sim 10^{39}$ erg s$^{-1}$. Fig. 4 also contains data points taken from Rauch et al. (2008). Rauch et al. (2008) performed an ultradeep (92 h) exposure with VLTs FORS2 low-resolution spectrograph. The goal of these observations was to detect fluorescent Lyα 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 Lyα), they detected

$$L_{\alpha, \text{dev}} = C_1 L_{\text{Ly}\alpha}(x) \phi(L_\alpha)$$

with $x = M_{\text{UV, max}} - M_{\text{UV}}$. Here, $\Delta M_{\text{UV}}$ describes the half-width of $p(M_{\text{UV}}|L_\alpha)$ at a chosen probability threshold.
numerous ultrafaint Lyα 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 Lyα 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 Lyα 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 Lyα photons. The fact that Lyα LFs are likely steeper than the UV-LFs implies that the Lyα 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 Lyα 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 Lyα 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 Lyα LFs of LAEs in the absence of reionization. Comparison to observed LFs at these redshifts highlights the impact of reionization.

### 5 CONCLUSIONS

We predicted Lyα LFs of Lyα-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 Lyα 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 Lyα 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 Lyα 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 Lyα luminosities \( 10^{40} \text{ erg s}^{-1} \lesssim L_\alpha \lesssim 10^{42} \text{ erg s}^{-1} \) 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 Lyα 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 \( P(EW) \) 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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REFERENCES


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.
Accordingly, our mapping can be written as
\[ \beta = \beta_0 + \mu_{\beta}^{(\beta)}(M_{UV} + 19) + \mu_{z}^{(\beta)}(z - 7), \]

where \( \mu_{\beta}^{(\beta)} = \Delta \beta / \Delta M_{UV} \) and \( \mu_{z}^{(\beta)} = \Delta \beta / \Delta z \).

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

A4 Non-constant UV spectral slope

The spectral slope \(\beta\) is not a constant, but depends on UV magnitude and redshift (as discussed above). This introduces some additional dispersion in the predicted Ly\(\alpha\) flux at a fixed \(M_{UV}\). However, varying \(\beta\) within \([-2.0, -1.5]\) changes the Ly\(\alpha\) flux only by \(1 - (A_{UV}/A_{Ly\alpha})^{1.5 - 2.0} \sim 13\) per cent. This dispersion is smaller than that introduced by the EW-PDF. If we replace the constant \(\beta\) with the empirical fit described in Section A2, then our predicted 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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