Seeing through the trough: outflows and the detectability of Lyα emission from the first galaxies

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ABSTRACT

The next generation of telescopes aim to directly observe the first generation of galaxies that initiated the reionization process in our Universe. The Lyα emission line is robustly predicted to be the most prominent intrinsic spectral feature of these galaxies, making it an ideal target to search for and study high-redshift galaxies. Unfortunately, the large Gunn–Peterson optical depth of the surrounding neutral intergalactic medium (IGM) is thought to render this line extremely difficult to detect prior to reionization. In this paper, we demonstrate that the radiative transfer effects in the interstellar medium (ISM), which cause Lyα flux to emerge from galaxies at frequencies where the Gunn–Peterson optical depth is reduced, can substantially enhance the prospects for the detection of the Lyα line at high redshift. In particular, scattering off outflows of interstellar H I gas can modify the Lyα spectral line shape such that ≳5 per cent of the emitted Lyα radiation is transmitted directly to the observer, even through a fully neutral IGM. It may therefore be possible to directly observe ‘strong’ Lyα emission lines (EW ≳ 50 Å rest frame) from the highest redshift galaxies that reside in the smallest H II ‘bubbles’ early in the reionization era with James Webb Space Telescope (JWST). In addition, we show that outflows can boost the fraction of Lyα radiation that is transmitted through the IGM during the later stages of reionization, and even post-reionization. Coupled with the fact that the first generation of galaxies are thought to have very large intrinsic equivalent Lyα equivalent widths, our results suggest that the search for galaxies in their redshifted Lyα emission line can be competitive with the drop-out technique out to the highest redshifts that can be probed in the JWST era.

Key words: line: profiles – radiative transfer – scattering – ISM: kinematics and dynamics – galaxies: high-redshift – intergalactic medium.

1 INTRODUCTION

One of the main science drivers of the next generation of telescopes is to detect the first generation of galaxies1 that formed in our Universe. These galaxies contained hotter and more compact stars (e.g. Tumlinson & Shull 2000; Bromm, Kudritzki & Loeb 2001), whose initial mass function (IMF) was likely top-heavy (Larson 1998; Bromm, Coppi & Larson 2002). Both the top-heavy IMF and low (or zero) gas metallicity enhanced the number of ionizing photons that the first galaxies emitted compared to that of local galaxies, at a fixed star formation rate (Tumlinson & Shull 2000; Bromm et al. 2001; Schaerer 2002, 2003). This enhancement in ionizing luminosity results in larger H II regions in the interstellar medium (ISM) of these galaxies. As a result, one of the key predicted properties of the first galaxies are prominent nebular emission lines, dominated in flux by hydrogen Lyα (λ = 1216 Å; see e.g. Johnson et al. 2009; Johnson 2010). The first generation of galaxies are therefore likely to have been strong Lyα emitters, with equivalent widths (EW) possibly as high as EW ∼ 1500 Å (Schaerer 2002, 2003; Johnson et al. 2009, also see Partridge & Peebles 1967; Meier 1976).

In this paper, we investigate the prospects for detecting this Lyα emission. The first galaxies were surrounded by a mostly neutral intergalactic medium (IGM), which is extremely optically thick

1 The definition of ‘the first generation of galaxies’ is somewhat arbitrary. We take it to mean any star-forming galaxy during the earliest stages of reionization that might be detected (in either their continuum or their lines) by the next generation of telescopes. Although the analysis presented in this paper also applies to the first stars that likely formed one by one in minihaloes, the overall fluxes from these sources are much too faint to be detected in the near future (regardless of radiative transfer effects that may boost the detectability of Lyα emission from such sources).

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to Lyα radiation. Loeb & Rybicki (1999) showed that scattering of Lyα photons through a neutral IGM causes galaxies to be surrounded by diffuse Lyα haloes (also see Kobayashi & Kamaya 2004; Kobayashi, Kamaya & Yoneda 2006). While the total flux in these haloes can be substantial, their large angular size results in surface brightness levels that are beyond reach of ever future telescopes such as the James Webb Space Telescope (JWST; see Section 2.1).

If Lyα radiation from the first galaxies is to be detected, it will therefore be via Lyα photons that were transmitted directly to the observer. In a neutral IGM, there are two mechanisms by which this can be achieved.

(i) The first mechanism is due to ionizing radiation that escapes from the galaxy, which creates a surrounding H II ‘bubble’, that can strongly boost the detectability of Lyα emission (e.g. Cen & Haiman 2000; Haiman 2002; Cen, Haiman & Mesinger 2005). This is because Hubble expansion redshifts Lyα photons while they propagate freely through the ionized gas. As a result, a fraction of photons enter the neutral IGM on the red side of the line centre, where the IGM optical depth can be smaller by orders of magnitude. For example, the Gunn–Peterson optical depth at redshift \( z \) is given by (e.g. Barkana & Loeb 2001)

\[
\tau_{GP} \approx 7.3 \times 10^2 s_H \left( \frac{1 + z}{10} \right)^{3/2},
\]

where \( s_H \) denotes the neutral volume fraction of hydrogen in the IGM. The Gunn–Peterson optical depth (equation 1) reduces to (Miralda-Escude 1998; Dijkstra & Wyithe 2006)

\[
\tau_{GP}(\Delta v) \approx \frac{2.3}{600 \text{ km s}^{-1}} \left( \frac{1 + z}{10} \right)^{3/2} \Delta v^{-1},
\]

for photons that enter the neutral IGM with a redshift of \( \Delta v \) from line centre. Equation (2) illustrates that photons that enter the neutral IGM significantly redwards of the Lyα resonance only ‘see’ a small fraction of the full Gunn–Peterson optical depth. However, given the high density of the surrounding IGM, it is generally assumed that the first galaxies would not have had large enough H II ‘bubbles’ to prevent complete damping of the line.

(ii) The second mechanism for enhancing the transmission of Lyα photons from high-redshift galaxies is due to radiative transfer effects within the ISM of galaxies (in particular outflows of interstellar H I gas), which can shift Lyα photons to the red side of the line before it reaches the IGM (Santos 2004). Observed interstellar metal absorption lines (Si ii, O i, C ii, Fe ii and Al ii) in Lyman Break Galaxies (LBGs) are typically strongly redshifted relative to the galaxies’ systemic velocity (median offset is \( \sim -160 \text{ km s}^{-1} \)), while the Lyα emission line is strongly redshifted (median offset is \( \sim +450 \text{ km s}^{-1} \)); Steidel et al. 2010, also see Shapley et al. 2003). This suggests that large-scale outflows are ubiquitous in LBGs (Shapley et al. 2003; Steidel et al. 2010). Furthermore, scattering of Lyα photons by H I in outflows can successfully explain observed Lyα line shapes in Lyα emitting galaxies at \( z = 3–6 \) (Verhamme, Schaerer & Maselli 2006; Verhamme et al. 2008; Vanzella et al. 2010).

2 The fact that the reionization process likely affects the observed number and distribution of high-redshift Lyα emitting galaxies is exactly the reason why Lyα emitting galaxies are thought to probe this epoch (Haiman & Spaans 1999; Malhotra & Rhoads 2004; Furlanetto, Zaldarriaga & Hernquist 2006; Kashikawa et al. 2006; Malhotra & Rhoads 2006; Dijkstra, Wyithe & Haiman 2007a; McQuinn et al. 2007; Iliev et al. 2008; Mesinger & Furlanetto 2008; Dayal, Maselli & Ferrara 2010).

In this paper, we explore the outflow mechanism in more detail. We will show that these ‘local’ (i.e. inherent to the galaxy itself) processes in the ISM can cause as much as \( \gtrsim 5 \) per cent of the emitted Lyα radiation to be directly transmitted to the observer even through a fully neutral IGM. This result is important for the study of high-redshift galaxies, because it suggests that detecting the Lyα emission line of the first generation of galaxies may well be within reach of the next generation of telescopes including JWST.

The outline of this paper is as follows. We describe our models and present our results in Section 2. We discuss our models and the implications of this work in Section 3, before we conclude in Section 4. The cosmological parameter values used throughout our discussion are \( (\Omega_m, \Omega_{\Lambda}, \Omega_b, h) = (0.27, 0.73, 0.046, 0.70) \) (Komatsu et al. 2009).

## 2 MODELLING OF Lyα FROM HIGH-REDSHIFT GALAXIES

We divide our study into modelling of three phenomena which are important in the apparent brightness of Lyα emitters at high redshift. First, in Section 2.1 we compute the integrated (over the sky) flux density, and integrated (over frequency) surface brightness profiles of the Loeb–Rybicki (LR) haloes that surround the first generation of galaxies. This calculation illustrates the difficulty of directly detecting these Lyα haloes. Then, in Section 2.2 we show how radiative transfer through a static ISM causes the predicted LR haloes to be accompanied by Lyα point sources, which are more easily detectable. Finally, in Section 2.3 we show that this result is strengthened further when the ISM of galaxies contains outflows of H I. In all our calculations we assume that the intrinsic, i.e. the emitted, luminosity of the galaxy is \( L_{\alpha} = 10^{43} \text{ erg s}^{-1} \), which corresponds to a star formation rate of SFR \( \lesssim 2 M_{\odot} \text{ yr}^{-1} \) for \( Z \leq 10^{-3} Z_{\odot} \) (Schaefer 2003, for a Salpeter IMF from 1 to 100 M_{\odot}).

For comparison, the brightest observed Lyα sources at \( z = 6.5–6.6 \) have ‘observed’ luminosities (i.e. the observed flux times \( 4\pi d_L^2(z) \)), where \( d_L(z) \) denotes the luminosity distance to redshift \( z \) of a few times \( 10^{43} \text{ erg s}^{-1} \) (Kashikawa et al. 2006; Ouchi et al. 2010). Depending on what fraction of the emitted Lyα flux we detect, their intrinsic luminosities can be significantly higher. Our results scale linearly with \( L_{\alpha} \).

Throughout this paper, we denote photon frequency with the dimensionless parameter \( x = (v - v_\text{rest})/\Delta v_p \), in which \( v_\text{rest} = 2.47 \times 10^{15} \text{ Hz} \) denotes the Lyα rest-frame frequency; \( \Delta v_p = v_{\text{HII}}/c \), \( v_{\text{HII}} = \sqrt{2k_B T_{\text{ISM}}/m_p} = 12.9(T_{\text{ISM}}/10^4 \text{ K})^{1/2} \text{ km s}^{-1} \), where \( T_{\text{ISM}} \) denotes the gas temperature in the ISM. Here, \( c, k_B \) and \( m_p \) denote the speed of light, Boltzmann constant and the proton mass, respectively. In all our calculations we assume that the gas temperature in the ISM is \( T_{\text{ISM}} = 10^4 \text{ K} \), but we have explicitly verified that our final results do not depend on this assumption. Furthermore, the Gunn–Peterson optical depth for photons that enter the IGM while in the red wing of the Lyα line is independent of temperature (see equation 2), and the assumed IGM temperature of \( T_{\text{ISM}} = 300 \text{ K} \) (appropriate for neutral intergalactic gas; see e.g. Pritchard & Loeb 2008) is irrelevant.

### 2.1 Loeb–Rybicki haloes

Fig. 1 shows the observed properties of Lyα haloes that surround galaxies embedded within a fully neutral comoving IGM. The histogram in the left-hand panel shows the integrated (over the entire area on the sky) emerging spectrum computed with the Monte Carlo Lyα radiative transfer code McHammer (Dijkstra, Haiman
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Figure 1. The observed properties of Lyα halos (a.k.a. LR halos) that surround galaxies embedded within a fully neutral comoving IGM. The ‘noisy’ features in these plots are due to the finite (here N_{phot} = 10^5) number of photons used in our Monte Carlo calculations. Left-hand panel: the histogram shows the integrated (over the entire area on the sky) emerging spectrum, under the assumption that all Lyα photons were emitted at line centre, and assuming an emitted Lyα luminosity of L_α = 10^{43} erg s^{-1}. The lower horizontal axis shows the dimensionless frequency parameter x, while the upper horizontal axis shows the frequency parameter that was employed by Loeb & Rybicki (1999). The peak flux density occurs at x_{IGM} \sim 300 which in our model corresponds to a redshift of \sim 660 km s^{-1}. The FWHM of the spectrum is \sim 1500 km s^{-1}. The vertical axes are expressed in arbitrary units on the left, and physical units on the right. The peak-integrated flux density reaches 30 nJy. For comparison NIRSpec aboard JWST is expected to reach a sensitivity of \sim hundreds of nJy in 10^5 s (S/N = 10) for R = 2700, or line fluxes of \gtrsim 10^{-19} erg s^{-1} cm^{-2}. Right-hand panel: the integrated (over frequency) surface brightness S as a function of impact parameter (θ) from the galaxy. We find that S \sim 10^{-21} erg s^{-1} cm^{-2} arcsec^{-2} at all θ. This plot illustrates that it will be extremely difficult to directly detect these Lyα haloes (see text).

&w Spaans 2006; with modifications described in Dijkstra & Loeb 2008a). Following the previous work, we assumed in this calculation that the Lyα photons were emitted at line centre, i.e. x = 0. The lower horizontal axis shows the dimensionless frequency parameter x, while the upper horizontal axis shows the frequency parameter that was employed by Loeb & Rybicki (1999). All Lyα photons emerge with a systemic redshift (i.e. x ≪ 0). The peak flux density occurs at x_{IGM} \sim 300 which corresponds to a redshift of \sim 660 km s^{-1}. We stress that for this plot alone we have adopted T_{IGM} in the definition of the dimensionless frequency parameter x (which we refer to as x_{IGM} to clearly distinguish it from the ‘x’ that is used in other plots), because in this model all photons scatter solely through the IGM. The full width at half-maximum (FWHM) of the spectrum is \sim 1500 km s^{-1}. The vertical axes contain arbitrary units on the left, and physical units on the right. The peak-integrated flux density is \sim 30 nJy.

The right-hand panel shows the integrated (over frequency) surface brightness S (in erg s^{-1} cm^{-2} arcsec^{-2}) as a function of impact parameter (θ), angular separation) from the galaxy in arcsec. The surface brightness contains a core out to θ \sim 20 arcsec after which it drops steadily. We find that S \sim 10^{-21} erg s^{-1} cm^{-2} arcsec^{-2} at all θ. For comparison, Rauch et al. (2008) reached a 1 − σ surface brightness limit of S_{lim} = 8 \times 10^{-20} erg s^{-1} cm^{-2} arcsec^{-2} in a 92 h long exposure with the European Southern Observatory (ESO) VLT-FORS2 instrument, which represents the deepest observations to date. This, when combined with JWST’s proposed sensitivity limit2 to point sources of \gtrsim 10^{-19} erg s^{-1} cm^{-2} implies that it is and will remain extremely difficult to detect these Lyα haloes, even with the next generation of telescopes.

2.2 Static ISM

In the previous calculation, we assumed that all Lyα escaped from the galaxy at the line centre. In reality complex, radiative transfer effects occur inside the ISM of a galaxy. H I observations show that local galaxies contain H I column densities of N_{HI} \sim 10^{19}−10^{21} cm^{-2}. Such large columns of H I gas can affect the spectrum of Lyα photons as they emerge from the galaxy. Furthermore, we expect column densities of gas in high-redshift galaxies to increase as \propto (1 + z)^2 (see the end of this section for a more quantitative discussion). It is therefore plausible that Lyα photons need to traverse a substantial, i.e. N_{HI} > 10^{20} cm^{-2}, column of H I gas before escaping from the galaxy. To estimate the impact of large H I column densities on the detectability of Lyα emission, we turn to analytic solutions for the spectrum of Lyα photons emerging from static, homogeneous, extremely optically thick media. Following the analyses of Harrington (1973) and Neufeld (1990), Dijkstra et al. (2006) computed the Lyα spectrum emerging from a sphere to be

\[ J(x) = \frac{\pi^{0.5}}{\sqrt{2d_{\alpha}x_{0}}} \left( \frac{x^2}{1 + \cosh \sqrt{\frac{2x^2}{\pi \sigma_m}}} \right), \] (3)

assuming a source of photons in the centre of the sphere. Here, \tau_0 = 5.9 \times 10^5(N_{HI}/10^{20} cm^{-2})T_{ISM}/10^5 K^{-1/2} denotes the line centre optical depth from the centre to the edge of the sphere, and \alpha = 4.7 \times 10^{-4}(T_{ISM}/10^4 K)^{-1/2} denotes the Voigt parameter. The function J(x) is normalized to (2\pi)^{-1}, and its maximum occurs at x_0 = \pm 0.9(\alpha_0 x_0)^{1/3} \sim \pm 13(N_{HI}/10^{20} cm^{-2})^{1/3}(T_{ISM}/10^4 K)^{-1/3}. This dimensionless frequency shift translates to Δν = \pm 160(N_{HI}/10^{20} cm^{-2})^{1/3}(T_{ISM}/10^4 K)^{1/6} km s^{-1}. The weak temperature dependence (\propto T_{ISM}^{1/6}) explains the weak dependence of our results on the assumed ISM temperature. The Lyα spectrum emerging from a semi-infinite slab with the same line centre optical depth is broader by a factor of 1.1, but is otherwise very similar.

We compute how the predicted properties of the observed Lyα radiation change when we inject photons into a neutral IGM following the distribution given by equation (3), rather than in the line centre (as in Section 2.1). The most important difference is that a non-zero fraction of the photons are transmitted directly to the
observer without scattering. The solid histogram in Fig. 2 shows the spectrum of Lyα photons that were not scattered at all. These unscattered photons would be observed as a point source. The grey line shows the intrinsic flux density of the source, \(J_{\rm int}(x)\), which corresponds to the observed Lyα spectrum if we were able to detect all Lyα radiation (equation 3). Overplotted as the black solid line shows the analytic calculation of the observed spectrum \(J_{\rm point}(x)\) given by \(J_{\rm point}(x) = J(x) \exp(-\tau_{\rm GM}(x))\). The inset shows the fraction of directly transmitted Lyα flux, \(f_{\text{trans}}\), as a function of \(N_{\text{H}}\) column density. The transmitted fraction increases from \(\sim 1\) per cent at \(N_{\text{H}} = 10^{21}\) cm\(^{-2}\) to \(\geq 5\) per cent at \(N_{\text{H}} \geq 7 \times 10^{25}\) cm\(^{-2}\). A transmission \(f_{\text{trans}}\) of only a few per cent is important: if the intrinsic Lyα EW of the first generation of galaxies was as high as 1500 Å, then the observed rest-frame EW is \(\text{EW} \sim 50(f_{\text{trans}}/0.03)\) Å (see text).

### Figure 2.

The solid histogram in figure shows the spectrum of Lyα photons that were not scattered at all. These unscattered photons would be observed as a point source. The grey line shows the intrinsic flux density of the source, \(J_{\rm int}(x)\), which corresponds to the observed Lyα spectrum if we were able to detect all Lyα radiation (equation 3). Overplotted as the black solid line shows the analytic calculation of the observed spectrum \(J_{\rm point}(x)\) given by \(J_{\rm point}(x) = J(x) \exp(-\tau_{\rm GM}(x))\). The inset shows the fraction of directly transmitted Lyα flux, \(f_{\text{trans}}\), as a function of \(N_{\text{H}}\) column density. The transmitted fraction increases from \(\sim 1\) per cent at \(N_{\text{H}} = 10^{21}\) cm\(^{-2}\) to \(\geq 5\) per cent at \(N_{\text{H}} \geq 7 \times 10^{25}\) cm\(^{-2}\). A transmission \(f_{\text{trans}}\) of only a few per cent is important: if the intrinsic Lyα EW of the first generation of galaxies was as high as 1500 Å, then the observed rest-frame EW is \(\text{EW} \sim 50(f_{\text{trans}}/0.03)\) Å (see text).

\[\text{EW} \sim 50(f_{\text{trans}}/0.03)\] Å

4 The scattered radiation is spread out in a halo that resembles the LR haloes. However, at small angular separations (\(\theta \lesssim 1\) arcsec) we find that the surface brightness profile is enhanced by a factor of \(\sim 10\) (see Appendix A for an example). This is still well below detection thresholds of existing and future facilities. Furthermore, this enhancement in the central surface brightness profile vanishes when we allow for the existence of an H\(\alpha\) region around the galaxy (see Fig. A1).

5 Here, \(\tau_{\text{GP,0}}\) denotes the Gunn–Peterson optical depth given by equation (1), \(\phi(x/T_{\text{GM}})\) denotes the Voigt function (Rybicki & Lightman 1979) in which we have emphasized that this function depends on temperature and \(\mathcal{M} = \sqrt{T_{\text{GM}}/T_{\text{IGM}}}\). This factor \(\mathcal{M}\) converts a dimensionless frequency offset \(x\) at ISM temperatures to a larger offset \(x_{\text{GM}} = \mathcal{M}x\) at IGM temperatures. When \(\mathcal{M}x \ll 3\), then \(\tau_{\text{GM}}(x)\) becomes independent of assumed IGM temperature (also see equation 2). Not surprisingly, the analytic calculation agrees well with the Monte Carlo calculation (which in the end should generate random realizations of this function). We point out that the predicted Lyα spectral line shape is not as asymmetric as is often observed in lower redshift galaxies. This is because the Lyα absorption cross-section varies weakly with frequency (as \(\Delta v^{-1}\); see equation 2) in its damping wing, and scattering in the IGM introduces no 'sharp' cut-off in the observed Lyα line shape.

6 The inset of Fig. 2 shows how the fraction of directly transmitted Lyα flux depends on \(N_{\text{H}}\) column density. As mentioned previously, \(f_{\text{trans}} \sim 10^{-2}\) at \(N_{\text{H}} = 10^{21}\) cm\(^{-2}\). The transmitted fraction increases to \(\geq 5\) per cent at \(N_{\text{H}} \geq 7 \times 10^{25}\) cm\(^{-2}\). For comparison, the central column density for a standard Mao & White exponential disc – when seen face on – is \(N_{\text{H}0} \sim 3 \times 10^{22}[(1+z)/11]^{3/2}(250/13\text{ km s}^{-1})\) cm\(^{-2}\), under standard assumptions that the spin parameter \(\lambda = 0.05\), and that \(f_d = m_d = 0.05\). This suggests that \(H_1\) column densities in excess of \(10^{21}\) cm\(^{-2}\) are expected at the redshifts of interest, and that therefore that \(f_{\text{trans}}\) can exceed a few per cent.

We stress that although small, a transmission \(f_{\text{trans}}\) of only a few per cent is important. The total observed flux in the Lyα point source at \(z = 10\) is \(f_{\text{obs}} = 3.7 \times 10^{-19}(f_{\text{trans}}/0.05) \sim 10^{-19}\) erg s\(^{-1}\) cm\(^{-2}\) which is within reach of JWST. For example, an \(R = 1000\) grating would yield a \(\pm 3\) detection in a \(10''\) exposure band\( I\). In addition to rendering the line emission from very high redshift galaxies detectable by JWST, this effect could lead to strong Lyα, since given an intrinsic Lyα EW for the first generation of galaxies of \(E_{\text{W,1}} = 1500\) Å, the observed rest-frame EW is \(E_{\text{W}} \sim 50(f_{\text{trans}}/0.03)\) Å. For comparison, only \(\gtrsim 4\) per cent of LBGs at \(z = 3\) have emission lines with \(E_{\text{W}} \gtrsim 50\) Å (Shapley et al. 2003). Indeed, for an observed rest frame EW \(\gtrsim 75f_{\text{trans}}/0.05\) Å, and a line flux of \(f_{\text{obs}} = 3.7 \times 10^{-19}(f_{\text{trans}}/0.05)\) erg s\(^{-1}\) cm\(^{-2}\), the corresponding continuum flux density is \(f_c \sim 2.7\) mJy, which would only yield a \(\pm 2 - \sigma\) detection in \(10''\) with NIRCAM on JWST. The Lyα line flux may therefore be (slightly) more easily detectable than the continuum emission, even when we only observe a few per cent of the emitted Lyα flux.
2.3 Outflowing ISM

Because outflows appear ubiquitous in galaxies, and because they appear to affect the Ly$\alpha$ radiative transfer through the ISM of galaxies (see Section 1 and also see Section 3.3), we repeat the exercise of Section 2.2 for a suite of outflow models. Following Verhamme et al. (2006, 2008), we model the outflow as a spherically symmetric thin shell of gas that contains an H$\text{I}$ column density $N_{\text{HI}}$ (also see Ahn, Lee & Lee 2003), and outflow velocity $v_{\text{sh}}$. We assume that the shell has a radius of 1 kpc and a thickness of 0.1 kpc, but stress that the precise physical scale of the outflow is not important for our results. Our assumed gas temperature in the outflowing H$\text{I}$ shell of $T_{\text{ISM}} = 10^4$ K corresponds to a $b$-parameter of $b \sim 13$ km s$^{-1}$ in the terminology of Verhamme et al. (2008). Our results do not depend on this choice for $b$, as the amount of flux at large $\Delta v$ depends very weakly on this parameter (see the right-hand panel of fig. 15 of Verhamme et al. 2006). We further assume the H$\text{I}$ shells to be dust-free (see Section 3.3). Verhamme et al. (2008) typically found that log $N_{\text{HI}} \sim 19$–22, and $v_{\text{sh}} \sim 0$–500 km s$^{-1}$, and this is the range of parameter space we explore. We compute Ly$\alpha$ spectra emerging from the outflows with the Monte Carlo transfer code (Dijkstra et al. 2006). In our calculations, the Ly$\alpha$ photons are emitted at line centre, i.e. $x = 0$. We verified that our results are insensitive to this assumption.\footnote{We repeated some calculations in which Ly$\alpha$ photons were emitted following a Gaussian distribution with a standard deviation of $\sigma = 100$ km s$^{-1}$. While the precise emerging line shapes changed, the overall transmitted fraction remained practically identical.} We compute the impact of the IGM on the directly observed fraction of Ly$\alpha$ by simply suppressing the intrinsic spectrum by $\exp(-\tau_{\text{IGM}}(x))$ (see Section 2.2).

The grey solid line in Fig. 3 shows an example of the intrinsic spectrum for a model in which we assumed that ($N_{\text{HI}}, v_{\text{sh}}$) = ($10^{20}$ cm$^{-2}$, 200 km s$^{-1}$). The intrinsic spectrum is highly asymmetric, with more flux coming out on the red side of the Ly$\alpha$ line centre. The spectrum peaks at about $\sim 2v_{\text{sh}}$, as expected for radiation that scatters back to the observer on the far side of the galaxy (see Verhamme et al. 2006; Ahn et al. 2003 for a detailed discussion on these features in the spectrum). However, a significant fraction of the radiation comes out at larger redshifts. This radiation can be transmitted directly to an observer through a neutral IGM, and would be observed as a point-source. The black solid line shows the spectrum of the point source (see Appendix A for a plot of the surface brightness profile of the scattered radiation). We find that the spectrum of the point source contains $f_{\text{trans}} \sim 4$ per cent of all emitted photons. Note that the FWHM of the observed spectrum of the galaxy, as well as the offset, arises purely from radiative transfer effects.

The directly transmitted fraction $f_{\text{trans}}$ depends on $N_{\text{HI}}, v_{\text{sh}}$ and $z$. In Fig. 4, we show $f_{\text{trans}}$ as a function of $v_{\text{sh}}$ for $N_{\text{HI}} = 10^{20}$ cm$^{-2}$ (red squares) and $N_{\text{HI}} = 10^{21}$ cm$^{-2}$ (blue squares) at $z = 10$. Having outflows as low as $\geq 50$ km s$^{-1}$ makes a significant difference in the predicted $f_{\text{trans}}$. For example, we find $f_{\text{trans}} \gtrsim 5$ per cent for $v_{\text{sh}} \gtrsim 200$ (50) km s$^{-1}$ for log $N_{\text{HI}} = 20$ (log $N_{\text{HI}} = 21$) at $z = 10$. Fig. 5 is the same as Fig. 4, but for $z = 15$. At higher redshifts, the overall transmitted fraction decreases because $\tau_{\text{GP,B}} \propto (1+z)^{-5}$ (see equation 1). Even at $z = 15$, we find $f_{\text{trans}} \gtrsim 5$ per cent for $v_{\text{sh}} \gtrsim 100$ km s$^{-1}$ and log $N_{\text{HI}} = 21$. We stress that the outflow parameters were chosen to lie at the range required to explain line shapes of observed LAEs at $z < 6$. If the dark matter haloes that host the highest redshift galaxies had lower masses (as expected in a hierarchical structure formation scenario), then outflows at higher redshift may have occurred at lower speeds, because of the observed (at lower redshifts) scaling of outflow velocity with circular velocity of the host dark matter halo (e.g. Martin 2005). On the other hand, higher redshift galaxies are expected to be more compact, and therefore we naively expect larger column densities of H$\text{I}$ gas at higher redshifts (see Section 2.2), in which case low outflow velocities can boost $f_{\text{trans}}$ tremendously. The outflow properties in the highest redshift galaxies and their impact on Ly$\alpha$ propagation are clearly the topics that need further investigation.

Figure 3. The black solid line shows the spectrum of Ly$\alpha$ photons that were transmitted directly to an observer through a fully neutral IGM. The grey solid line shows the intrinsic spectrum of this galaxy (see Ahn et al. 2003; Verhamme et al. 2006 for a detailed discussion on these features in the spectrum). The ISM of this galaxy was modelled as a thin, outflowing (with speed $v_{\text{sh}}$), spherically symmetric shell of H$\text{I}$ gas (with column density $N_{\text{HI}}$). This type of model successfully reproduces observed Ly$\alpha$ line shapes in known Ly$\alpha$ emitting galaxies. We assumed that ($N_{\text{HI}}, v_{\text{sh}}$) = ($10^{20}$ cm$^{-2}$, 200 km s$^{-1}$). Because a significant fraction of the radiation comes out of the galaxy with a large systematic redshift, $f_{\text{trans}} \sim 4$ per cent of all emitted photons is transmitted directly to the observer.

Figure 4. This figure shows the fraction of Ly$\alpha$ photons, $f_{\text{trans}}$, that is transmitted directly through a fully neutral IGM at $z = 10$, as a function of $v_{\text{sh}}$ for $N_{\text{HI}} = 10^{20}$ cm$^{-2}$ (red squares) and $N_{\text{HI}} = 10^{21}$ cm$^{-2}$ (blue squares). Outflows of $\geq 50$ km s$^{-1}$ can boost $f_{\text{trans}}$ tremendously to values as large as $f_{\text{trans}} \sim 10$–20 per cent (for $v_{\text{sh}} = 200$ km s$^{-1}$). That is, 10–20 per cent of all Ly$\alpha$ photons may be transmitted through a fully neutral IGM.
from the first galaxies

3 DISCUSSION

In this section, we discuss a range of issues arising from our model.

3.1 Detecting Lyα emission during and after the epoch of reionization

The results of the previous section focused on the first generation of galaxies that were surrounded by a neutral IGM. However, our work applies more broadly. For example, radiative transfer effects in the ISM can also boost the detectability of the Lyα line emitted by galaxies during the later stages, and even post-reionization (also see fig. 23 of Santos 2004). It is generally thought that ionized intergalactic gas is transparent to Lyα radiation. More specifically, residual H I that exists inside the ionized IGM is assumed to only affect radiation frequencies that lie bluewards of the Lyα resonance. However, in the standard cosmological model (ionized intergalactic gas in close proximity to galaxies is expected to be overdense (1 + δ ∼ 2–20; Barkana 2004). Furthermore, gravity causes this gas to flow towards galaxies. This inflowing, denser ionized gas is expected to scatter a significant fraction of the Lyα photons out of the line of sight. Even the ionized IGM therefore transmits on average as little as ∼10–30 per cent of the Lyα to an observer (Dijkstra et al. 2007b; Iliev et al. 2008; Zheng et al. 2010a; Dayal et al. 2010). It is therefore unclear whether H I regions during the reionization process actually transmit enough Lyα flux to an observer, to render it detectable.

However, in the presence of H I outflows, the transmitted fraction of Lyα radiation through ionized gas can increase dramatically. This is because the outflowing H I gas imparts a redshift to the Lyα photons that is well in excess of ∼ a few hundred km s⁻¹ (see Section 2.3 and Fig. 3). On the other hand, the influence of the ionized IGM only extends out to ∆v ≲ v_{\text{infal}} (Barkana 2004). Here, the inflow velocity, v_{\text{infal}} is of the order the circular velocity of the dark matter halo hosting the galaxy, v_{\text{circ}} = 80(M_{\text{halo}}/10^{10}M_\odot)^{1/3}((1+z)/11)^{1/2} km s⁻¹ (e.g. Barkana & Loeb 2001, where M_{\text{halo}} denotes the dark matter halo mass). The impact of the ionized IGM in close proximity to the galaxy is therefore significantly weaker when H I outflows are important in shaping the Lyα spectral line shape that emerges from galaxies.

This implies that winds can have important consequences when interpreting the observed sudden drop in the Lyα luminosity between z = 6.5 and z = 5.7 (Shimasaku et al. 2006; Kashikawa et al. 2006; Ota et al. 2008; also see Ouchi et al. in preparation). The most important aspect of this observation is that the rest-frame UV luminosity function of these same galaxies does not evolve between these redshifts (within the uncertainties; Kashikawa et al. 2006). Indeed, Dijkstra et al. (2007a) have shown that these two observations combined translate to a reduction in the number of detected Lyα photons from z = 6.5 by a factor of 1.1–1.8 (95 per cent CL) relative to z = 5.7. The simplest interpretation of this observation is that the IGM at z = 6.5 is more opaque to Lyα photons than at z = 5.7, because the IGM naturally only affects the observed Lyα flux. Dijkstra et al. (2007a) argued that this can be explained quite naturally by an evolution in the opacity of the ionized IGM. However, if winds reduce the impact of the ionized component, then this conclusion becomes uncertain, and the observed reduction in the Lyα luminosity function may be at least partly a reionization-induced signature.

In order to understand the evolution of the transmission in terms of the reionization history, it is therefore crucial to understand the properties of winds in high-redshift galaxies, and how they affect the transport of Lyα radiation.

3.2 Detecting other lines

In this paper, we have focused our attention on the Lyα emission line, because it is predicted to be the strongest spectral line of high-redshift galaxies. It may be possible to detect other spectral lines as well.

The most prominent alternative emission line is Hα (λ = 6536 Å), which is intrinsically weaker than Lyα in flux by a factor of ∼8, under the assumption of case-B recombination. However, only a fraction f_{\text{trans}} = 0.05 of the emitted Lyα radiation is transmitted, so that the observed Hα flux may be larger by a factor of ∼2.5(f_{\text{trans}}/0.05)⁻¹. On the other hand the Hα line lies deeper in the IR, λ = 7((1+z)/11) μm, where JWST’s Mid Infrared Instrument would yield a lower signal-to-noise ratio (S/N) detection of the Hα line for medium-resolution spectroscopy. This suggests that it may be more difficult to detect Hα than naively expected.

In addition, the Helium Balmer α (He II λ =1640 Å) line could contain a flux that is comparable to that of Hα (Oh, Haiman & Rees 2001; Johnson et al. 2009). However, the predicted strength of this line depends sensitively on the IMF, and it can be weaker than Hα by an order of magnitude for reasonable model assumptions (Johnson et al. 2009). On the other hand, the composite spectrum of observed z = 3 LBGs contains an He II λ = 1640 Å emission line (Shapley et al. 2003). The FWHM of this line is FWHM ~ 1500 km s⁻¹, which is broader than the FWHM of most other nebular emission lines. The origin of this line is not resolved. The line has been associated with Population III star formation (Jimenez & Haiman 2006) occurring in pockets of pristine gas that persisted down to low redshift, but may also originate in winds associated with massive Wolf–Rayet stars. In this latter case, the line is expected to vanish for low gas metallicities (Brinchmann, Pettini & Charlot 2008). Thus, it is not clear whether the detection of He II λ = 1640 Å in high-z LBGs implies that this line should be present in the higher redshift galaxies.

Finally, we expect numerous recombination lines associated with metals heavier than Helium (such as [O iii], [O ii], [S ii],…; e.g. Huchra 1977). Again, robust predictions of the strengths of these lines (which fall in the rest-frame optical) do not exist as it requires an accurate knowledge of the metallicity of H II regions in high-redshift galaxies. Furthermore, at gas metallicities Z ~ 10⁻³ Z_\odot we expect these lines to be significantly weaker.
3.3 Dust

Our calculations have ignored dust. To understand the impact of dust on the Lyα radiation field requires the understanding the Lyα transfer process through the ISM of galaxies. This is because the scattering process causes Lyα photons to traverse different paths through the ISM than rest-frame UV continuum photons (Charlot & Fall 1991; Neufeld 1991; Hansen & Oh 2006; Laursen, Sommer-Larsen & Andersen 2009). As a result dust has a different impact on Lyα line and UV continuum photons. Observations indicate the Lyα escape fraction decreases with the dust content of galaxies. More specifically, the mean Lyα equivalent width decreases with increasing observed reddening of LBG (Shapley et al. 2003). Verhamme et al. (2008) have used their models to quantify the actual escape fraction of Lyα photons from galaxies, $f_{\text{esc},\alpha}$, as a function of the observed dust reddening, and found that on average $f_{\text{esc},\alpha} \sim 10^{-7.5(E(B-V))}$. Bouwens et al. (2010) recently argued that candidate galaxies at $z = 7$ are considerably bluer than at lower redshifts (also see Stanway, McMahon & Bunker 2005). Their most luminous candidates are consistent with $E(B-V) \sim 0.05$, which translates to $f_{\text{esc},\alpha} \sim 0.4$ (which is significantly higher than Lyα escape fraction inferred for galaxies at $z \lesssim 2$; see e.g. Hayes et al. 2007, 2010). If we take this number literally, then our quoted Lyα fluxes are high by a factor of $\sim 2.5$ (which implies that dust is not the dominant uncertainty). Moreover, in hierarchical models of galaxy formation, we expect galaxies at higher redshifts, and lower luminosities, to be less evolved, and hence the impact of dust is likely to be weaker.

The relation derived by Verhamme et al. (2008) was obtained by averaging over a dozen galaxies, and there exists considerable scatter around their derived relation. For example, observations of low-redshift star-forming galaxies with the International Ultraviolet Explorer (IUE) and the Hubble Space Telescope (HST) revealed very weak Lyα emission (or even strong absorption) in metal-poor objects (Hartmann, Huchra & Geller 1984; Hartmann et al. 1988; Kuntz et al. 1994), while strong Lyα emission could be detected from some metal and dust-rich galaxies (e.g. Lequeux et al. 1995). This scatter is likely related to the precise geometry of the dust distribution (Scarlata et al. 2009), viewing angle towards the galaxies (Laursen et al. 2009) and outflows. When outflows are present in galaxies, the strength of Lyα emission appears to be independent of the dust content of the galaxy. In the absence of strong outflows, however, Lyα line strength appears to decrease with increasing dust content (Kuntz et al. 1998; Atek et al. 2008). Our work implies that in high-redshift galaxies, H I outflows further affect the subsequent impact of the IGM on the detectability of Lyα emitting galaxies.

3.4 Peculiar velocities

Following the announcement of the discovery of a $z = 10$ galaxy by Pelló et al. (2004) – which was later disputed (Bremer et al. 2004; Weatherley, Warren & Babbedge 2004) – Cen et al. (2005) argued that the line could be detected through a fully neutral IGM, if the Lyα emitting region in the galaxy was receding relative to the surrounding absorbing IGM with $v \gtrsim 35$ km s$^{-1}$. In this study, the galaxy ionized an H I region with a radius of $\sim 0.28$ kpc. While peculiar velocities of this magnitude do not play an important role in reducing the Gunn–Peterson damping wing optical depth (for which one needs $\Delta v \gtrsim 500$ km s$^{-1}$, equation 2), they can play a role in reducing the opacity of the ionized ‘local’ IGM (see Section 3.1), just like outflows. However, both mechanisms are expected to leave different signatures on the observed Lyα line shape: scattering off H I outflows is expected to result in asymmetric emission lines (see Fig. 3), while peculiar velocities may leave an intrinsically symmetric emission line (Cen et al. 2005). We caution that symmetric Lyα emission lines may be observed as a result of scattering through a static ISM (see Fig. 2), but point out that in the latter case the Lyα peak flux density is redshifted by $\sim 500$ km s$^{-1}$ relative to the galaxy’s systemic redshift. This shift is much larger than that expected for the model that uses peculiar velocities, which is $\sim 35–70$ km s$^{-1}$.

3.5 Comments on the model

The model used to generate Lyα line profiles in this paper assumes a single, thin, compact, spherical shell of H I gas surrounding the Lyα source (following Ahn et al. 2003; Verhamme et al. 2006, 2008; Vanzella et al. 2010). Recently, Steidel et al. (2010) described an alternative simple outflow model that folds in constraints from observed profiles of interstellar metal absorption lines. This model can also reproduce observed Lyα line shapes in LBGs. In this model, the outflow can extend out to $\sim 100$ kpc, and outflow velocity increases with radius. It is not clear whether the models are incompatible: one can imagine the outflow extends over a wide range of velocities and spatial scales, but that the outflow’s opacity to Lyα photons is dominated by gas closer to the galaxy that is restricted to a narrower range of velocities. As a result, it is possible to model the impact of the outflow on the Lyα radiation field as a single shell that has a low velocity dispersion. This is clearly an issue that needs further investigation. However, a more detailed investigation is beyond the scope of the present paper, especially because our main results are not likely sensitive to the precise model that one uses to describe the impact of the outflow on the Lyα radiation field.

In detail, the directly transmitted fraction of Lyα photons through the IGM at the highest redshifts (the ‘first’ galaxies at $z>10$) probably depends quantitatively on the precise outflow model that one uses, since different models may imply different predicted redshift evolution. For example, in the models of Verhamme et al. (2006, 2008) and Vanzella et al. (2010) the emission in the red wing of the line (at $\Delta v \gtrsim 500$ km s$^{-1}$) comes from Lyα photons that scatter back and forth repeatedly between the expanding H I outflow. In the model of Steidel et al. (2010), this frequency ‘diffusion’ does not occur, and the emission in the red wing of the line reflects the maximum velocity in the outflow. In this latter model, the flux in the red wing of the line is suppressed at $z \gtrsim 10$ if the outflow velocities are much lower at high redshift (see the end of Section 2.3). On the other hand, it is difficult to completely suppress frequency diffusion. Significant frequency diffusion occurs even in clumpy outflows with a covering factor of only $f_{\text{cov}} \approx 0.5$ (Hansen & Oh 2006, their fig. 19), which is less than the outflow covering factor inferred by Steidel et al. (2010) over a significant range of radii. We therefore expect that photons likely emerge at $\Delta v \gtrsim 500$ km s$^{-1}$ from the ‘first’ galaxies in both models, but that the fraction of the flux that emerges at these frequencies -- and therefore...
$f_{\text{trans}}$ – depends on the detailed properties of the H$_{\text{i}}$ in outflows in galaxies at these redshifts. This underlines one of our conclusions presented in Section 4 (also see Section 3.1) that it is crucial to understand the gas kinematics in the ISM (and/or circumgalactic medium) of high-redshift galaxies in order to infer the properties of the IGM from the observed Ly$\alpha$ flux.

Our main results regarding galaxies during the later stages of – and after – reionization ($z \lesssim 8$) require less (or no) extrapolation to higher redshifts, and practically do not depend at all on the precise underlying model of the Ly$\alpha$ line shape. Instead, these results rely only on the fact that the observed Ly$\alpha$ line shape can extend to frequencies that lie well beyond $\Delta v \sim 500$ km s$^{-1}$ out to $z = 5.5$ (Vanzella et al. 2010).

It has been argued that radiation pressure on dust grains – which in turn are coupled to the interstellar gas – provides an important source of pressure in the ISM of galaxies, and that the observed outflows in galaxies are driven predominantly by radiation pressure (see e.g. Murray, Quataert & Thompson 2005). Given that the highest redshift galaxies likely contained little dust (see Section 3.3), radiation pressure may be less important in these galaxies, and outflows could be weakened significantly. Interestingly, especially in these first galaxies, a significant fraction ($\sim 20$ per cent) of the total bolometric luminosity of the galaxy is Ly$\alpha$ line radiation. If this radiation is ‘trapped’ by a large column of H$_{\text{i}}$ gas, then the radiation pressure exerted by this Ly$\alpha$ radiation itself becomes important in driving the H$_{\text{i}}$ gas out (Dijkstra & Loeb 2008b), thereby enhancing the detectability of the Ly$\alpha$ emission.

### 4 CONCLUSIONS

The next generation of telescopes aim to directly observe the first generation of galaxies that initiated the reionization of our Universe. The Ly$\alpha$ emission line is robustly predicted to be the most prominent intrinsic spectral feature of these galaxies. In this paper we investigated the prospects for detecting this Ly$\alpha$ emission, taking account of radiative transfer effects that are likely to occur in the ISM of these galaxies.

Observed interstellar metal absorption lines (Si II, O I, C II, Fe II and Al II) in LBGs are typically strongly redshifted relative to the galaxies’ systemic velocity, while the Ly$\alpha$ emission line is strongly redshifted (Section 1). This suggests that large-scale outflows are ubiquitous in LBGs (Shapley et al. 2003; Steidel et al. 2010). Furthermore, scattering of Ly$\alpha$ photons by H$_{\text{i}}$ in outflows appears to facilitate the escape of Ly$\alpha$ photons from galaxies (Kunth et al. 1998; Atek et al. 2008; see Section 3.3), and has successfully explained the observed Ly$\alpha$ line shapes in Ly$\alpha$ emitting galaxies at $z = 3–6$ (e.g. Verhamme et al. 2006, 2008; Vanzella et al. 2010). Scattering off outflows of interstellar H$_{\text{i}}$ gas can shift Ly$\alpha$ photons to the red side of the line before it reaches the IGM (Fig. 3). At

![Figure 6](https://academic.oup.com/mnras/article-abstract/408/1/352/1057250)

**Figure 6.** Schematic explanation for why outflows promote the detectability of Ly$\alpha$ emission from galaxies surrounded by significant amounts of neutral intergalactic gas. In the top panel a galaxy is surrounded by a large bubble of ionized gas, which in turn is surrounded by neutral intergalactic gas. Ly$\alpha$ emission from this galaxy redshifts away from resonance as it propagates freely through the H II bubble (as indicated by the line colour). Once the Ly$\alpha$ photons reach the neutral IGM, they have redshifted far from resonance where the Gunn–Peterson optical depth is reduced tremendously (see equation 2). Because of the reduced GP optical depth, some fraction of the emitted Ly$\alpha$ is transmitted to the observer without scattering in the IGM. In this drawing, the thickness of the line represents the specific intensity of the Ly$\alpha$ radiation field. The bottom panel shows the outflows surrounding star-forming regions (represented by the expanding ring. The far side is receding from the observer and has a larger redshift, which is represented by the colour) can Doppler boost Ly$\alpha$ photons to frequencies redwards of the Ly$\alpha$ resonance. In this scenario, a non-negligible fraction of Ly$\alpha$ can propagate directly to the observer without the H II bubble. (See the online version of this article for the colour figure.)
these frequencies the Gunn–Peterson optical depth may be reduced to the order of unity as a result.

In this paper, we investigated the detectability of Ly\(\alpha\) radiation under the assumption that the outflows observed at low redshift also occur in the highest redshift galaxies. We found that outflows may cause as much as \(\gtrsim 5\) per cent of the emitted Ly\(\alpha\) radiation to be transmitted directly to the observer, even through a fully neutral IGM (Section 2.3). Since the intrinsic (rest-frame) equivalent width of the Ly\(\alpha\) line can be as high as \(\text{EW}_{\text{int}} = 1500\ \text{Å}\) for the first generation of galaxies, the observed \(\text{EW} = \text{EW}_{\text{int}}/\text{EW}_{\text{int}} = 75(f_{\text{trans}}/0.05)(\text{EW}_{\text{int}}/1500\ \text{Å})\). For comparison, only 4 per cent of the \(z = 3\) LBG population have larger EWs (Shapley et al. 2003). We showed that for \(f_{\text{trans}} \gtrsim 3\) per cent it may be easier to detect Ly\(\alpha\) line emission with NIRSPEC on the JWST, than continuum radiation with JWST's NIRCAM in the same integration time. We also note that the next generation of ground-based 30-m telescopes with diffraction limited AO are expected to be more (less) sensitive than JWST at \(\lambda \gtrsim 1.3\ \mu\text{m}\) for \(R \gg 100(R \lesssim 100)\) spectroscopy (see Mountain et al. 2009, their fig. 2). That is, ground-based high-resolution spectroscopic searches for high-redshift galaxies can detect fainter galaxies at a fixed integration time when \(f_{\text{trans}} \gtrsim 5\) per cent. Such searches can therefore be competitive with searches that employ the drop-out technique. Irrespective of the survey strategy that is used to search for the highest redshift galaxies, the prospect that Ly\(\alpha\) can provide galaxies with spectroscopic redshifts is promising, and important as no robust predictions exist for the detectability of other emission lines (Section 3.2).

This paper has focused on the first generation of galaxies that were surrounded by a neutral IGM, but our work also applies more broadly. For example we argued in Section 3.1 that H\(\text{I}\) outflows promote the detectability of the Ly\(\alpha\) emission line during later stages of reionization when much of the absorption is resonant absorption in a highly ionized H\(\text{II}\) region. As a result outflows can reduce the minimum H\(\text{II}\) bubble size that is required to render LAEs 'visible'. This is illustrated schematically in Fig. 6. Similarly, H\(\text{I}\) outflows also promote the detectability of the Ly\(\alpha\) emission line after reionization has been completed\(^9\) (Section 3.1).

In summary, radiative transfer effects in the ISM of high-redshift galaxies have been shown to broaden, and – in the case of outflows – redshift the emergent Ly\(\alpha\) flux to a level that allows 5 per cent or more of the photons to escape absorption by the neutral IGM. Coupled with the large intrinsic Ly\(\alpha\) line EW of the first generation of galaxies, we have shown that searches for galaxies in their redshifted Ly\(\alpha\) emission line can be competitive with the drop-out technique out to the highest redshifts that can be probed observationally in the JWST era.

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\(^9\) Recently, Zheng et al. (2010b) showed that scattering in the ‘local’ IGM immediately surrounding Ly\(\alpha\) sources can introduce a unique anisotropy in the two-point correlation function of LAEs at \(z = 5.7\). Zheng et al. (2010b) argued that this scattering-induced signature is reduced when the intrinsic (i.e. prior to scattering) Ly\(\alpha\) line width is enhanced. Winds are therefore also expected to reduce this clustering signature. That is, the clustering of LAEs post-reionization can provide constraints on the importance of winds in shaping the Ly\(\alpha\) line shape.

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APPENDIX A: LOEB–RYBICKI HALOES WITH OUTFLOWS

In the main body of this paper, we focused on Ly$\alpha$ radiation that was transmitted directly to the observer through a fully neutral IGM. This radiation is confined to an angular region that is set by the physical scale of the outflow (throughout the paper we referred to this as the ‘point source’), and is much more easily detectable than the scattered Ly$\alpha$ radiation that is in a diffuse halo. For completeness, we show how the surface brightness profile of the scattered radiation is modified because of the outflow in the galaxy.

In the left-and panel of Fig. A1, the black solid line shows the spectrum of unscattered radiation for the model with $(N_{\text{HI}}, v_{\text{sh}}) = (10^{20} \text{ cm}^{-2}, 200 \text{ km s}^{-1})$ (as in Fig. 3). The grey solid line is again the intrinsic spectrum that emerges from the galaxy. The red histogram shows the spectrum of the point source as extracted from the Monte Carlo code. The agreement between the Monte Carlo and analytic solution (given by equation 4) is again good.

In the right-hand panel, the black solid line shows the surface brightness profile of the standard LR halo (as in Fig. 1), while the red dashed line shows the surface brightness profile of the scattered radiation for the outflow model. Clearly, the surface brightness profile is boosted significantly at $\theta \lesssim 5$ arcsec. Radiation that escaped from the galaxy far in the red wing of the line (at $\Delta v \gtrsim 500 \text{ km s}^{-1}$) is modified because of the outflow in the galaxy. We point out that the maximum boost of a factor of $\sim 10$ is reached at $\theta \lesssim 1$ arcsec. In reality, we expect gas to be ionized at such short distances from the galaxy. Indeed, if we insert a small (radius $\sim 50$ pkpc) H II bubble around the galaxy, then we find that the boost disappears, and we almost recover the original surface brightness profile (as indicated by the blue dotted line). Larger H II regions only suppress the surface brightness profile of the central core. The main point of this calculation is to demonstrate that the radiative transfer processes that we invoked to boost the detectability of the ‘point source’ do not also boost the detectability of the Ly$\alpha$ haloes.