Measuring the properties of reionized bubbles with resolved Lyα spectra

Charlotte A. Mason and Max Gronke

ABSTRACT

Identifying and characterizing reionized bubbles enables us to track both their size distribution, which depends on the primary ionizing sources, and the relationship between reionization and galaxy evolution. We demonstrate that spectrally resolved z $\gtrsim$ 6 Lyman-alpha (Lyα) emission can constrain properties of reionized regions. Specifically, the distance from a source to a neutral region sets the minimum observable Lyα velocity offset from systemic. Detection of flux on the blue side of the Lyα resonance implies the source resides in a large, sufficiently ionized region that photons can escape without significant resonant absorption, and thus constrains both the sizes of and the residual neutral fractions within ionized bubbles. We estimate the extent of the region around galaxies which is optically thin to blue Lyα absorption, and thus constrains both the sizes of and the residual neutral fractions within ionized bubbles. We estimate the extent of the region around galaxies which is optically thin to blue Lyα photons, analogous to quasar proximity zones, as a function of the source’s ionizing photon output and surrounding gas density. This optically thin region is typically $\lesssim$ 0.3 pMpc in radius (allowing transmission of flux $\gtrsim$ −250 km s$^{-1}$), $\lesssim$ 20 per cent of the distance to the neutral region. In a proof-of-concept, we demonstrate the $z \approx$ 6.6 galaxy COLA1 – with a blue Lyα peak – likely resides in an ionized region >0.7 pMpc, with residual neutral fraction $<10^{-5.5}$. To ionize its own proximity zone we infer COLA1 has a high ionizing photon escape fraction ($f_{esc} > 0.50$), relatively steep UV slope ($\beta < -1.79$), and low line-of-sight gas density ($\sim$0.5 times the cosmic mean), suggesting it is a rare, underdense line-of-sight.

Key words: galaxies: high-redshift – intergalactic medium – dark ages, reionization, first stars.

1 INTRODUCTION

Understanding the process of hydrogen reionization is one of the frontiers of astronomy. It occurred neither homogeneously nor instantaneously, as ionizing photons propagating from nascent galaxies reionized the most overdense regions first, carving out ionized “bubbles” within the then neutral Universe, gradually reionizing the entire intergalactic medium (IGM). Measuring the timeline and morphology of reionization, i.e. studying the redshift evolution and spatial distribution of these ionized regions, is key to understanding how reionization occurred (e.g. Furlanetto, Zaldarriaga & Hernquist 2004; McQuinn et al. 2007; Mesinger 2016).

A key question is what drove reionization, that is, where did the ionizing photons originate from? Identifying ionized or neutral regions of the IGM not only characterizes the morphology of reionization but enables us to address this question by comparing the properties of observed galaxies in those regions to the local ionization state (e.g. Beardsley et al. 2015). Regions that reionize early are likely the first overdensities where galaxy formation is accelerated, thus identifying those regions helps to identify the first generations of galaxies.

Mapping reionized bubbles and measuring their size distribution is a goal of future 21-cm intensity experiments. This requires spatial resolution capable of discerning ionized hydrogen gas on scales of <1 proper Mpc (e.g. Geil et al. 2017). However, sensitivity to these smallest scales is still an observational challenge: It requires large baseline radio telescopes to resolve H I regions (e.g. SKA-low, Koopmans et al. 2015), and detailed spectroscopic follow-up of the galaxies within H II regions to determine their ionizing properties. However, estimates of bubble sizes on small scales are currently feasible with Lyman alpha (Lyα, rest wavelength 1216 Å) spectroscopy of high redshift sources.

Due to its high cross-section for absorption by neutral hydrogen, Lyα is a sensitive probe of neutral gas. Neutral hydrogen affects both the strength and lineshape of Lyα (see, e.g. Dijkstra 2014, for a review). With the advent of sensitive near-IR spectroscopy, Lyα emission from galaxies and quasars at $z > 6$ has been a particularly powerful probe of reionization (e.g. Fan et al. 2006; Malhotra & Rhoads 2006; Dijkstra, Mesinger & Wyithe 2011; Treu et al. 2013; Mesinger et al. 2015; Davies et al. 2018; Mason et al. 2018a; Greig, Mesinger & Bañados 2019). In recent years, the declining flux distribution of Lyα emission from galaxies at $z \gtrsim 6$ has been used to measure the average fraction of the IGM, which is neutral at a given redshift (Schenker et al. 2014; Mason et al. 2018a, 2019; Hoag et al. 2019; Whitler et al. 2020).

The lineshape of Lyα also encodes information about neutral hydrogen structures the photons encountered along their path. Within or in close proximity to the emitting galaxy the Lyα spectrum is shaped by strong scattering of photons close to the Lyα resonant wavelength (resonant scattering) with H I that is not necessarily along the line-of-sight (Eide et al. 2018), and typically produces double-peaked emission-line profiles due to the high optical depth at line centre (e.g. $\lesssim 10^{-5}$). However, sensitivity to these small scales is still an observational challenge: It requires...
Neufeld 1990). However, at larger distances, when the probability of scattering back into the line-of-sight becomes negligible, the impact of intervening $\text{H}i$ can be treated more simply as absorption. In the following, we use ‘resonant absorption’ to refer to the effective absorption of Ly$\alpha$ photons which emerge from galaxies with a blueshift, but encounter significant neutral gas as they redshift into the resonant wavelength. The smooth damping wing, due to $n_\text{HI} \gtrsim 10^{-6}\text{ cm}^{-3}$ gas that can be at large distances, is commonly interpreted as a signature of reionization (e.g. Miralda-Escude 1998). In this case, the optical depth due to damping wing absorption is a function of the distance to the nearest neutral patch and thus could be used to recover the size of ionized bubbles (Malhotra & Rhoads 2006).

Due to the decreasing recombination time at $z \gtrsim 6$, even within ‘ionized’ bubbles, there can be significant residual neutral gas. The amount of neutral hydrogen depends on the local ionization field and can lead to resonant absorption on the blue side of the Ly$\alpha$ resonance (e.g. Gunn & Peterson 1965; Zheng et al. 2010; Laursen, Sommer-Larsen & Razoumov 2011; Byrohl & Gronke 2020) – which makes the detection of blue Ly$\alpha$ peaks towards higher redshift increasingly unlikely. In a number of rare sightlines, however, blue Ly$\alpha$ flux has been observed at $z \gtrsim 6$ (Matthee et al. 2018; Songaila et al. 2018; Bosman et al. 2020), implying a low resonant optical depth and thus low residual neutral fraction in reionized regions. In these cases, it may be possible to directly measure the properties of individual ionized bubbles.

Here, we demonstrate that $z > 6$ Ly$\alpha$ emission lineshapes encode information about the ionized bubbles their host galaxies reside in. While previous works have shown that Ly$\alpha$ can be visible early in the epoch of reionization if galaxies reside in ionized bubbles (Haiman 2002; Mason et al. 2018b) we show here that spectroscopic measurements of such Ly$\alpha$ emitters enable us to calculate the minimum size of the ionized bubble such that Ly$\alpha$ at a given frequency offset is visible to us. Furthermore, we demonstrate that blue-peaked Ly$\alpha$ lines observed at $z \gtrsim 6$ can be used to constrain the residual neutral gas remaining in reionized bubbles. As a proof-of-concept, we investigate the necessary physical conditions for observing the double-peaked Ly$\alpha$ emitted COLA1 (Hu et al. 2016; Matthee et al. 2018).

This paper is organized as follows: we describe our model for the Ly$\alpha$ optical depth in Section 2 and present our results in Section 3. We discuss our results in Section 4 and present conclusions in Section 5. We use the Planck Collaboration VIII (2015) cosmology: $(\Omega_\Lambda, \Omega_m, \Omega_b, n, \sigma_8, H_0) = (0.69, 0.31, 0.048, 0.97, 0.81, 68 \text{ km s}^{-1}\text{Mpc}^{-1})$. Magnitudes are in the AB system. Distances, volumes, and densities are proper unless otherwise stated.

## 2 Model

In this section, we describe the two components of our model: the Ly$\alpha$ optical depth as a function of the distance from a galaxy (Section 2.1) and the properties of ionized bubbles (Section 2.2).

The model provides a way to interpret the necessary conditions to observe a blue-shifted Ly$\alpha$ peak emerging from a galaxy at $z \gtrsim 6$. Of course, there are numerous scattering processes in the ISM, CGM, and IGM which can absorb a blue peak at any redshift (e.g. Gunn & Peterson 1965; Zheng et al. 2010; Laursen et al. 2011), meaning that non-detection of a blue peak does not provide much information about any one of those media. Recently, Hayes et al. (2020) showed that for stacks in the redshift range $z \sim 3–5$ the evolution of the blue peak can be explained entirely by the evolution of the IGM. However, in the rare cases, where blue Ly$\alpha$ flux has made it through a relatively neutral IGM, this model demonstrates that constraints can be placed on the line-of-sight gas properties in front of the source, in particular, that for blue flux to have been detected at $z \gtrsim 6$, the source must reside in a highly ionized region.

### 2.1 Lyman-$\alpha$ optical depth

The Ly$\alpha$ optical depth through hydrogen gas for photon observed at $\lambda_{\text{abs}} = \lambda_{\text{em}}(1 + z_s)$ to a source at redshift $z_s$, observed at $z_{\text{obs}}$, is given by

$$
\tau_{\alpha}(\lambda_{\text{obs}}) = \int_{z_{\text{obs}}}^{z_s} \frac{dz}{1+z} c \frac{d}{dz} x_{\alpha}(z) n_\text{HI}(z) \sigma_\alpha \left( \frac{\lambda_{\text{obs}}}{1+z}, T \right),
$$

where $n_\text{HI}$ is the total number density of hydrogen and $x_{\alpha}$ is the fraction of hydrogen which is neutral. $\sigma_\alpha(\lambda, T)$ is the Ly$\alpha$ scattering cross-section through an ensemble of hydrogen atoms with a Maxwell–Boltzmann velocity distribution, usually expressed as a function of the dimensionless frequency $x = (\nu - \nu_\alpha)/\Delta_1\nu_\alpha$:

$$
\sigma_\alpha(x, T) = \sigma_0 \times \phi(x),
$$

where $\sigma_0 = \frac{1}{\Delta_1\nu_\alpha \sqrt{\pi}} \frac{f_\alpha p c^2}{m_e c}$ is the V"{o}igt function:

$$
\phi(x) = \frac{a_\alpha}{\pi} \int_{-\infty}^{\infty} dy \frac{e^{-y^2}}{(y-x)^2 + a_\alpha^2}.
$$

Here, $a_\alpha \approx 2.46 \times 10^{15} \text{ Hz}$ is the resonant frequency of Ly$\alpha$, at wavelength $\lambda_\alpha \approx 1216 \AA$. $\Delta_1\nu_\alpha = \nu_\alpha \sqrt{2 k_B T/m_e c^2} \approx \nu_\alpha v_s/c$ is the thermally broadened frequency, and the Voigt parameter $a_\alpha \approx 4.7 \times 10^{-4} (T/10^4 \text{ K})^{-1/2}$. Equation (3) is normalized such that $\int dx \phi(x) = 1$. The cross-section is tightly peaked around the core of the line, but has damping wings which extend out to $>1000 \text{ km s}^{-1}$ from the line centre (e.g. Dijkstra 2014). We use the approximation for $\phi(x)$ given by Tassisioni (2006).

Approximating equation (3) as a Dirac delta function, and assuming constant $x_{\alpha}$, we obtain the Gunn & Peterson (1965) optical depth for blue photons emitted from a source at $z_s$:

$$
\tau_{\alpha}(z_s) = \frac{f_\alpha p c^2}{m_e v_\alpha} x_{\alpha} n_\text{HI}(z_s) \frac{H(z_s)}{H(z)} \approx 4.7 \times 10^5 x_{\alpha} \Delta \left( \frac{1 + z_s}{z} \right)^{3/2},
$$

where $\Delta = n_\text{HI}(z)/n_\text{HI}(z_s)$ is the overdensity of hydrogen gas relative to the cosmic mean. We assume that the source galaxy resides inside an ionized region embedded in a neutral homogeneous IGM at a distance $R_{\text{ion}}$. This is representative of reionization’s early pre-overlap phases when ionized bubbles grow around sources of ionizing photons. However, the assumption of an isolated bubble breaks down as reionization progresses, meaning our method provides only a lower limit on the bubble size.

We construct the optical depth to a source galaxy by modelling the two media separately, i.e. breaking the integral into two components: from $z_s$ to $z_{\text{ion}}$ and $z_{\text{ion}}$ to $z_{\text{obs}}$ (following, Cen & Haiman 2000; Haiman 2002; Mesinger, Haiman & Cen 2004). In the ionized bubble, we set $T = 10^4 \text{ K}$ (appropriate for photoionized gas at the mean density, e.g. Hui & Gnedin 1997) and $n_\text{HI}(z) = \Delta n_\text{HI}(z)$. $\Delta n_\text{HI}(z)$ is the comoving cosmic mean hydrogen number density: $\Delta n_\text{HI}(z) \approx 1.88 \times 10^{-7} (1 + z)^3 \text{ cm}^{-3}$. In the neutral IGM, we set $T = 1 \text{ K}$, assuming gas decouples from the CMB at $z \sim 150$ and cools adiabatically thereafter (Peebles 1993), and $n_\text{HI}(z) = \Delta n_\text{HI}(z)$. This approximation of the density profile as a step function is simplistic, but as we show in Section 3.3.1 observing blue peaks likely requires underdense gas...
along the line of sight. More realistic model gas density profiles impacting Lyα transmission are discussed by Santos (2004). Our results are not strongly sensitive to these temperatures choices within a physically motivated range (T < 10^4 K).

The left-hand panel of Fig. 1 shows the Lyα transmission, e−τ(λ), as a function of wavelength – commonly expressed as velocity offset, Δν ≡ c(λ−ν/2Δλ) − 1, and ionized bubble radius, assuming the residual neutral fraction inside the ionized bubble is very low (xHI = 10−8 at 0.1 pMpc from the source, assuming xHI ∝ r−2 – see Section 2.2.2), and Δ = 1. As the bubble size increases more flux is transmitted on both the red and blue side of the line. Blue photons that redshift into resonance at the edge of bubble or at further distances from the source all encounter fully neutral gas when they reach resonance and are thus absorbed with a high optical depth. Photons that have already redshifted past resonance by the time they reach the neutral gas experience the damping wing absorption, which smoothly suppresses flux to red wavelengths. For very small bubble sizes, the transmission on the blue side is therefore negligible and the transmission within 200 km s−1 of the red side can be very low. Lyα lines observed with low-velocity offsets from systemic must reside in large ionized regions.

Note that even in a fully neutral IGM (Rion = 0) Lyα flux can still be transmitted on the red side: It is possible to observe Lyα lines at very high redshifts, providing they emit Lyα ≥ 300 km s−1 from systemic (Dijkstra et al. 2011). Therefore, even at very high redshifts, merely detection of Lyα is not sufficient to identify a reionized bubble: there must be flux < 300 km s−1.

The right-hand panel of Fig. 1 shows the transmission through a bubble of fixed size (1 pMpc), but changing the residual neutral fraction in the ionized region around the source. The damping wing set by Rion acts as an envelope for the maximum possible transmission: For xHI (r = 0.1 pMpc) < 10−4, the bubble is fully optically thin and the maximum blue flux allowed given the damping wing shape can be transmitted. As the residual neutral fraction increases, more flux on the blue side of the line is absorbed, with the ionized region becoming optically thick for xHI (r = 0.1 pMpc) ≥ 10−6 (corresponding to a neutral hydrogen number density of nHI ≥ 5 × 10−10 cm−3). For xHI > 10−4, the transmission displays a strong damping wing on the red side and converges to the Rion = 0 case in the left plot.

2.2 Size and residual neutral fraction of ionized bubbles

The optical depth can be calculated for any values of ionized bubble size, Rion, and residual neutral fraction inside the bubble, xHI, to estimate those parameters in a model-independent way. In the limiting case of a single ionizing source (plus uniform ionizing background), we can also estimate those quantities for a physical model.

2.2.1 Size of ionized region

Assuming ionization by a single source at redshift zS at the centre of the ionized region, the proper radius of the region can be obtained by solving for the evolution of a ionization front (e.g. Shapiro & Giroux 1987; Cen & Haiman 2000; Yajima, Sugimura & Hasegawa 2018):

$$\frac{dR_{\text{ion}}^3}{dt} = \frac{3f_{\text{esc}}N_{\text{ion}}}{4\pi n_{\text{HII}}^2(z)} - C_{\text{HII}}(1)\Delta n_{\text{HII}}(z)\sigma_{\text{HII}}(T)R_{\text{ion}}^3 + 3H(z)R_{\text{ion}}^3,$$

where the first term is due to ionizations from a source with ionizing photon output N_{ion} (in units of s−1) and ionizing escape fraction f_{esc}, the second term is due to recombinations – assuming Case B recombination in a clumpy medium. C_{HII} is the clumping factor of ionized hydrogen, which describes the enhanced rate of recombinations relative to a uniform medium, C_{HII} = (n_{HII}^2/n_{HII}). For
\(\alpha_{\text{e}},\) we use the approximation from Hui & Gnedin (1997) for the hydrogen recombination coefficient as a function of temperature. The third term of equation (5) is the expansion of the region due to the Hubble flow. As described in Section 2.1, we assume the IGM outside the ionized region to be fully neutral with density \(n_{\text{H}}^{\text{IGM}}(z) = \pi_{\text{r}}(z),\) and assume the gas inside the bubble to be fully ionized (except for calculating the optical depth, see Section 2.2.2) and possibly overdense: \(n_{\text{H}}^{\text{IGM}}(z) = \Delta \pi_{\text{r}}(z).\)

For constant \(N_{\text{ion}}\) and \(f_{\text{esc}},\) and simplified cosmology, equation (5) can be solved analytically (Shapiro & Giroux 1987). For instance, for where \(\alpha \gg 1,\) the residual neutral fraction at a proper radius \(r\) from the central source and some diffuse ionizing background, the residual neutral fraction is given by equation (10) exceeds an optical depth threshold \(\tau_{\text{lim}} \approx 10^{-9}\) (Wyithe et al. 2010; Cen & Haiman 2000), so that

\[
N_{\text{ion}}(t) \approx \left( \frac{3 f_{\text{esc}} N_{\text{ion}} t_{\text{age}}}{4 \pi n_{\text{H}}^3(\pi_{\text{r}})} \right)^{1/3},
\]

where \(t_{\text{age}}\) is the time since the ionizing source has switched on. In reality, due to the Hubble expansion the ionized radius grows more rapidly after \(\sim 10^7\) yr than equation (6). Here, we solve equation (5) numerically.

The source emissivity \(N_{\text{ion}}\), in \(s^{-1}\) can be written as

\[
N_{\text{ion}}(t) = \int_{v_{\text{th}}}^{\infty} L_v(t) \frac{dv}{h v},
\]

where \(L_v\) is the ionizing spectrum of the source in erg \(s^{-1}\) Hz\(^{-1}\). We approximate \(L_v\) as a double power law

\[
L_v \propto \begin{cases} v^{\alpha} & v > v_{\text{th}} \\ v^{-\beta} & v \leq v_{\text{th}}, \end{cases}
\]

where \(v_{\text{th}} \approx 3.3 \times 10^{15}\) Hz is the frequency of hydrogen photoionization, \(\alpha\) is the spectral slope of the ionizing continuum, and \(\beta\) is the spectral slope of the non-ionizing ultraviolet (UV) continuum. Typically, \(1 \lesssim \alpha \lesssim 2\) for quasars (e.g. Scott et al. 2004; Stevens et al. 2014; Lusso et al. 2015) and galaxies with massive stars (Steidel et al. 2014; Feltre, Charlot & Gutkin 2016), where stripped stars in binaries can cause the spectral slope to reach \(\sim 1\) (Görgen et al. 2020). For galaxies, \(\beta \approx -2\) (e.g. Dunlop et al. 2013; Bouwens et al. 2014).

Thus we can estimate \(N_{\text{ion}}\) for galaxies from a UV magnitude (measured at 1500 Å) as

\[
N_{\text{ion}} \approx \frac{3.3 \times 10^{54}}{\alpha} 10^{-0.4(M_{\text{UV}}+20)} \left( \frac{912}{1500} \right)^{\beta+2} \text{s}^{-1}.
\]

Galaxy spectra typically have a steeper drop-off beyond the He II limiting ionization (54.4 eV), which is not captured in our simple power-law approximation. However, we note that this has only a small impact on our estimation of \(N_{\text{ion}}\): Assuming the ionizing spectrum is zero for \(v > v_{\text{He}}\) we find \(N_{\text{ion}}\) is \(>0.75\) times that obtained using equation (9).

2.2.2 Residual neutral fraction of ionized region

Due to the recombination of ionized hydrogen, inside the ionized region there will be some residual neutral fraction. This can be computed by equating the recombinant rate to the ionization rate, assuming ionization equilibrium. Assuming ionizations due to the central source and some diffuse ionizing background, the residual neutral fraction at a proper radius \(r\) from the source is (e.g. Mesinger et al. 2004)

\[
x_{\text{in}}(r) = C_{\text{in}} \Delta \pi_{\text{r}}(z) c_{\text{in}}(T) \left( \frac{\Gamma_{\text{bg}}(z)}{4 \pi r^2} + \frac{J_1}{4 \pi r^2} \right)^{-1}.
\]

Here, \(\Gamma_{\text{bg}}\) is the hydrogen ionizing rate due to the background within the ionized region in \(s^{-1}\), and \(J_1\) is the hydrogen ionizing emissivity of the central source in \(cm^2 s^{-1}\):

\[
J_1 = f_{\text{esc}} \int_{v_{\text{th}}}^{\infty} \frac{L_v}{h v} \frac{\alpha}{\alpha + 1} \text{d}v,
\]

with the hydrogen photoionization rate \(\sigma_{\text{ion}} = \sigma_{\text{ion},0}(v/v_{\text{th}})^{3}\), where \(\sigma_{\text{ion},0} \approx 6.3 \times 10^{-18}\) cm\(^2\) (e.g. Draine 2011). Assuming as above an ionizing spectrum \(L_v \propto v^{-\alpha}\) yields

\[
J_1 = f_{\text{esc}} N_{\text{ion}} \frac{\alpha}{\alpha + 1} \sigma_{\text{ion},0},
\]

where \(N_{\text{ion}}\) is given by equation (9).

The gas reaches ionization equilibrium with a characteristic timescale \(\tau_{\text{eq}} = \Gamma_{\text{bg}} + J_1/4 \pi r^2\), so the bubble will be in ionization equilibrium within \(\sim 10^5\) yr assuming constant emissivity (e.g. Davies, Hennawi & Eilers 2020). Thus equation (10) holds for sources with ionizing populations \(> 10^7\) yr, which is reasonable for massive galaxies at \(z \sim 6\)–8, though may break down for galaxies with short bursts of star formation.

We use the ionizing background model by Khaire & Srianand (2019) but note that it does not significantly impact the residual neutral fraction for bubbles at \(z > 6\) as the background is low compared to the local ionization field, leading to \(x_{\text{in}} \approx r^2\). Strictly, \(\Gamma_{\text{bg}}\) accounts for other ionizing sources nearby (e.g. satellite galaxies in the vicinity of the central source) and will therefore vary depending on the density of the environment. We expect \(\Gamma_{\text{bg}} \lesssim 6(\Gamma_{\text{bg}})\) based on fluctuations of density and mean free path (Mesinger & Dijkstra 2008; Davies & Furlanetto 2016). For reference \((\Gamma_{\text{bg}}(z \approx 7) \approx 0.2 \times 10^{-12}\) s\(^{-1}\) in the Khaire & Srianand (2019) model, and has been measured to be \(\lesssim 0.3 \times 10^{-12}\) s\(^{-1}\) at \(z \sim 6\) (Wyithe et al. 2010; Calverley et al. 2011).

Fig. 2 shows some typical neutral fraction profiles inside a H II region. Here, and below, we assume that the neutral fraction is unity outside the H II region at the radius determined by equation 5. We see that more luminous galaxies produce bubbles which are both larger (equation 6) and more highly ionized at a fixed distance from the source. Fig. 3 shows the Lyα for the same set of models. Only UV bright galaxies are capable of producing a sufficiently large ionized region to allow blue flux to be observed.

2.2.3 Optically thin region within ionized region

Importantly, due to the high cross-section of Lyα for scattering around the resonant wavelength (equation 2) an ionized bubble can still be optically thick to Lyα. Thus, blue Lyα flux can be suppressed by residual neutral gas within an ionized bubble. The proper radius at which the bubble becomes optically thick to Lyα is the radius where the Gunn & Peterson (1965) optical depth (equation 4, using \(x_{\text{in}}(r)\) given by equation 10) exceeds an optical depth threshold \(\tau_{\text{lim}} \sim 2.3\) (i.e. transmission \(< 10\%\) per cent):

\[
R_u = \left( \frac{J_1}{4 \pi} \right)^{1/2} \left( \frac{C_{\text{HII}} \Delta \pi_{\text{r}}(z) c_{\text{in}}(T)}{H(z) \tau_{\text{lim}}} \right)^{1/2} \left( \frac{f_{\text{esc}} N_{\text{ion}}}{\Delta} \right)^{1/2} \left( \frac{2.5 \alpha}{\alpha + 3} \right)^{1/2} \times \frac{1}{C_{\text{HII}}^{1/2}} \left( \frac{T}{10^4 K} \right)^{0.4} \left( \frac{1 + z}{8} \right)^{-9/4} \text{Mpc},
\]

where \(J_1\) is given by equation (12). For the latter equality, we assumed \(\Gamma_{\text{bg}} = 0, c_{\text{in}}(T) \approx 2.6 \times 10^{-13}(T/10^4 K)^{-0.8}\) cm\(^3\) s\(^{-1}\) and used \(N_{\text{ion}}\) for a \(M_{\text{UV}} = -20\) galaxy (equation 9).
This radius corresponds to reaching a neutral hydrogen number density of \( n_\text{HI} \gtrsim 2 \times 10^{-10} (\tau_{\text{lim}}/2.3) (1+z)/8 \) \( \text{cm}^{-3} \) \( - \) or \( x_\text{HI} \gtrsim 2 \times 10^{-6} \Delta^{-1} (\tau_{\text{lim}}/2.3) (1+z)/8 \) \( \text{cm}^{-3} \) \( -3/2 \) \( - \) in the ionized region. At higher densities/neutral fractions the gas is optically thick to Ly\( \alpha \) photons.

This is analogous to the quasar near/proximity zones described by Bolton & Haehnelt (2007), except here we include the contribution of other, diffuse sources of ionizing photons. As discussed in Section 2.2.2, we assume the reionized region is in ionization equilibrium, which is valid for for sources with ionizing populations \( > 10^5 \) yr. See Davies et al. (2020) for discussion of the time evolution of such proximity zones around quasars.

A lower limit on \( R_\text{p} \) can be estimated from the minimum observable blue Ly\( \alpha \) velocity offset \( \Delta v_\text{min} \). To be transmitted to us, blue photons must redshift beyond the Ly\( \alpha \) resonant wavelength (i.e. \( \Delta v = 0 \)) within the proximity zone \( R_\alpha \). Thus, the minimum distance photons travel while they redshift from \( \Delta v_\text{min} \) into the resonant wavelength is

\[
R_\alpha > \frac{|\Delta v_\text{min}|}{H(z)}.
\]  

(14)

Previous works, which assumed ionized bubbles are optically thin to Ly\( \alpha \) (e.g. Hashimoto et al. 2018; Matthee et al. 2018) estimated \( R_\alpha \) \( \approx \) \( \Delta v_\text{min} \)/\( H(z) \). From the above, we see this is actually measuring \( R_\alpha \) and it is an underestimate of \( R_\text{min} \). We will show in Section 3.1 that \( R_\alpha \ll R_\text{min} \).

3 RESULTS

3.1 Evolution of optically thin regions around galaxies

The Ly\( \alpha \) optical depth (equation 1) decreases with decreasing redshift, due to the increasing ionizing output of sources, and the reducing density of neutral gas due to cosmic expansion. Thus, we expect the proximity zones around galaxies in reionizing bubbles to grow with decreasing redshift, increasing the observable blue flux.

Fig. 4 shows the total ionized radius \( (R_\text{ion}) \) and the optically thin radius \( (R_\alpha) \) as a function of source redshift, fixing \( f_{\text{esc}} = 1 \), \( C_\text{esc} = 1 \), \( \Delta = 1 \), \( \alpha = 2 \), and \( \beta = -2 \). We compare the sizes of the bubbles and proximity zones for sources with different UV luminosities \( \left( M_\text{UV} = -16, -18, -20, -22 \right) \) and age \( (10^6, 10^7, 10^8 \) yr). Except for very young sources \( R_\alpha \lesssim 0.1 R_\text{ion} \), \( R_\alpha \) does not change in size with age for constant emissivity once ionization equilibrium is reached. As noted above, previous works, which assumed ionized bubbles are fully ionized when estimating blue peak transmission, underestimated the total extent of the ionized region when using the observed blue Ly\( \alpha \) peak. By including recombinations we see the blue Ly\( \alpha \) flux only probes the much smaller proximity zone. In the next section, we show that there are model-independent ways to estimate a lower bound on the size of the full ionized region.

3.2 Observable Ly\( \alpha \) lines in a mostly neutral medium

Fig. 5 shows the minimum Ly\( \alpha \) velocity offset, \( \Delta v \), observable as a function of the distance to the first neutral region \( (R_\text{min}) \) and residual neutral fraction in the bubble \( (x_\text{HI}) \). This can be interpreted as the necessary conditions in the galaxy’s surroundings for us to observe an emission line with given \( \Delta v \). Our estimate does not depend on the intrinsic emission line shape, only on the transmission possible given the conditions inside the bubble. This means that our observations always provide lower limits on \( R_\text{min} \) and upper limits on \( x_\text{HI} \). - Fig. 5 shows that if \( R_\text{min} = 1 \) pMpc we could observe blue flux at \( \approx 400 \text{ km s}^{-1} \), however, if a galaxy inside an ionized region of that size only emits flux at \( > 100 \text{ km s}^{-1} \) we infer \( R_\text{min} < 0.5 \) pMpc.

To calculate the minimum \( \Delta v \), we compute Ly\( \alpha \) transmission \( e^{-\tau_{\text{Ly} \alpha}} \) on a grid of \( R_\text{min} \) and \( x_\text{HI} \) values as described in Section 2.1. Some of the resulting transmission curves are shown in Fig. 1. For


Figure 4. Radii of ionized bubbles and Lyα proximity zones around galaxies as a function of source redshift and age. Note these show optimistic upper limits on the sizes assuming \( f_{\text{esc}} = 1 \), \( C_{\text{HI}} = 1 \), \( \Delta = 1 \), \( \alpha = 2 \), and \( \beta = -2 \). Left-hand panel: ratio of the Lyα proximity zone (\( R_\alpha \), equation 13) to the radius of ionized sphere (\( R_{\text{ion}} \), equation 5) for galaxies with \( M_{\text{UV}} = -16, -18, -20, -22 \) (black, blue, pink, orange lines, respectively). We show the time evolution of \( R_\alpha / R_{\text{ion}} \) for the brightest source. Early on, before the ionization front can grow significantly, \( R_\alpha \sim 0.3 - 0.5 R_{\text{ion}} \), however, for sources \( >100\)-Myr old, \( R_\alpha \lesssim 0.1 R_{\text{ion}} \). Centre panel: the proper size of the proximity zone \( R_\alpha \) in Mpc as a function of source redshift. All lines are the same as the left-hand panel. Right-hand panel: radius of proximity zone expressed as a Lyα velocity offset, i.e. the maximum Lyα blue peak velocity offset that would be observable from a Lyα emitter inside this ionized region. We also show the observed blue-peaked Lyα emitters COLA1 (Hu et al. 2016; Matthee et al. 2018) and MACS1149-JD1 (Hashimoto et al. 2018). NEPLA4 (Songaila et al. 2018) is at the same redshift as COLA1 and has a similar blue peak velocity.

Figure 5. Minimum observable Lyα velocity offset, \( \Delta v_\alpha \), as a function of bubble size and residual neutral fraction, assuming \( >10 \) per cent transmission on the red or blue sides. Left-hand panel: for a constant residual neutral fraction, \( x_{\text{HI}} \), inside the ionized bubble. Right-hand panel: \( x_{\text{HI}} \propto r^2 \), with the quoted value at 0.1 Mpc. For each pair of \( R_{\text{ion}} \) and \( x_{\text{HI}} \) values, we compute the minimum velocity offsets observable if \( >10 \) per cent of the flux emitted at that velocity offset is transmitted through the IGM. We choose 10 per cent as assuming an emitted Lyα EW of 200 Å, this transmitted flux should be observable with current facilities. By using a grid of \( R_{\text{ion}} - x_{\text{HI}} \) values, our estimate does not assume any particular ionizing model (such as those described in Section 2.2), and thus provides a model-independent estimate of the properties of an ionized bubble based on Lyα transmission. For small bubbles with high \( x_{\text{HI}} \), it is only possible to observe Lyα, which is significantly redshifted. Conversely, it is only possible to observe blue Lyα flux if there is a significant distance to the first neutral patch (>0.5 pMpc) and the H II region is highly ionized (\( x_{\text{HI}} < 10^{-5} \)).

The two panels in Fig. 5 compare the minimum observable Lyα velocity offsets in the case of a homogeneous residual neutral fraction in the bubble (\( x_{\text{HI}} \) = constant), approximating reionization by a uniform ionizing background of ultrafaint sources) and in the limiting case of the Lyα emitter as the sole reionizing source (\( x_{\text{HI}} \propto r^2 \), equation 10), with the value on the y-axis \( x_{\text{HI}}(r = 0.1 \text{Mpc}) \). The trend of increased red–blue visibility with increasing bubble size is the same in both cases.

3.3 The ionized environment around observed blue-peaked Lyα emitters

3.3.1 COLA1

COLA1 is a \( z \approx 6.6 \) galaxy with a blue Lyα peak with flux up to \(-250\) km s\(^{-1}\) from systemic (Hu et al. 2016; Matthee et al. 2018). From Fig. 5, we see that this requires it to reside in an ionized region at least 0.7 pMpc to the nearest neutral patch, with a residual
neutral fraction $x_{\text{HI}} < 10^{-6}$. Our estimate of the extent of the ionized region is roughly double than that of Matthee et al. (2018), who estimated $0.3 \text{pMpc}$ (2.3 cMpc). This is due to their assumption that the entire bubble is optically thin. As discussed in Section 3.1, with just the minimum observed blue flux velocity we can only calculate $R_\alpha$ (equation 14), but the total ionized region is much larger.

To investigate in more detail the necessary conditions for COLA1’s blue peak to be observable, we perform a Bayesian inference to infer the parameters in equation (13). We define the likelihood of the blue peak velocity offsets, steep UV spectral slope $\beta$, and low gas density, whilst the ionizing spectral slope makes a negligible impact on the proximity zone size.

To investigate in more detail the necessary conditions for COLA1’s blue peak to be observable, we perform a Bayesian inference to infer the parameters in equation (13). We define the likelihood $p(R_\alpha > |\Delta v|/H(z))$ of the model parameters $\theta$ is

$$p(R_\alpha > |\Delta v|/H(z)) = \frac{1}{2} \text{erfc} \left( \frac{|\Delta v|/H(z) - R_{\alpha,\text{mod}}(\theta)}{\sqrt{2} \sigma_{R_\alpha}} \right),$$

where $\sigma_{R_\alpha}$ is the variance of matter fluctuations. With equal probability $p(R_\alpha > |\Delta v|/H(z)) = 0.5$, the normal distribution with mean $R_{\alpha,\text{mod}}(\theta)$ (equation 13) and variance $\sigma_{R_\alpha}^2 = (\sigma_{\Delta v}/H(z))^2$. We use uniform priors on the parameters $[f_{\text{esc}}, C_{\text{ini}}, \alpha, \beta, \log_{10}(\Gamma_{bg})]$, $0 \leq f_{\text{esc}} \leq 1$, $0.2 < C_{\text{ini}} < 10$, $1 \leq \alpha \leq 2.5$, $-3 < \beta < -1$, and $-14 < \log_{10}(\Gamma_{bg}/s^{-1}) < -10$. We use a lognormal prior on $\Delta$: $p(\ln \Delta) = N(\sigma_{\Delta}/\sqrt{2}, \sigma_{\Delta})$, where $\sigma_{\Delta}$ is the variance of matter fluctuations on the filter on $\Delta$. We use $\sigma_{\Delta} \approx 1$ appropriate for ionized IGM at $z = 6.6$ (e.g. Bi & Davidsen 1997; Bi et al. 2003).

We run two versions of the model: one where we fix the ionizing background $\Gamma_{bg} = 0$ (i.e. assuming COLA1 ionizes its proximity zone alone), and one where $\Gamma_{bg}$ is a free parameter. To estimate the posteriors and the evidence for each model, $Z = \int d\theta \ p(\theta|R_\alpha)$, we use Dynamic Nested Sampling implemented in dynesty (Speagle 2020).

Fig. 7 shows the posteriors for these parameters and their median and 16–84 per cent credible intervals or 68 per cent upper/lower limits, and the evidence $Z$. In both cases, gas density is inferred to be low compared the mean (log 0.1 $\Delta = -0.71_{-0.28}^{+0.24}$ with no ionizing background, log 0.1 $\Delta = -0.52_{-0.33}^{+0.34}$ with an ionizing background, the UV slope $\beta$ inferred to be relatively steep ($\beta < -1.79 \sigma$ for $\Gamma_{bg} = 0$) and the spectral slope of the ionizing continuum, $\alpha$, is not particularly well constrained by the proximity zone, due to the smaller range of possible $\alpha$ having a minimal impact on the size of the proximity zone (see Fig. 6). In the model without an ionizing background, high escape fractions are inferred ($>0.50,1\sigma$), while when we include an ionizing background there is a degeneracy between high single source $f_{\text{esc}}$ and low ionizing background, or low $f_{\text{esc}}$ and high ionizing background. In general, a high ionizing background (log 0.1 $\Gamma_{bg}/s^{-1} > -11$) will produce a large optically thin region, regardless of the other parameters, thus in the extreme case of a very high ionizing background the posteriors for the other parameters are prior dominated. However, note that the maximum of our $\Gamma_{bg}$ prior still constrains $\Delta \lesssim 1.5$: to see blue peaks in very overdense regions requires $\Gamma_{bg} \gg 10^{-10} s^{-1}$. Neither model is strongly preferred, with a Bayes factor $Z_{\text{nobg}}/Z_{\text{modb}} \approx 2$ (e.g. Trotta 2008).

Figure 6. Radius of proximity zone produced by a single source of a given UV magnitude. We show the minimum observable blue-shifted velocity offset from systemic. The black solid line shows a fiducial galaxy model ($f_{\text{esc}} = 1$, $C_{\text{ini}} = 1$, $\Delta = 1$, $\alpha = 2$, and $\beta = -2$). The other lines show the impact of changing one of these parameters to a more extreme value: $f_{\text{esc}} = 0.2$ (blue dash), $C_{\text{ini}} = 3$ (orange dots), $\Delta = 0.5$ (thin green dash), $\alpha = 2$ (red dotted dash) $\beta = -2.5$ (thin purple solid). We also show the observed blue-peaked Lyα emitters COLA1 (Hu et al. 2016; Matthee et al. 2018) and MACS1149-JD1 (Hashimoto et al. 2018).

Figure 7. Posterior distributions for $f_{\text{esc}}$, $C_{\text{ini}}$, $\Delta$, $\alpha$, $\beta$, and $\Gamma_{bg}$ inferred from the observed maximum blue Lyα peak of COLA1 ($-250 \text{km s}^{-1}$). We show $1\sigma$ and $2\sigma$ contours of the 2D posteriors, and histograms of marginalized 1D posteriors for the parameters. Blue lines show the model with $\Gamma_{bg} = 0$, grey lines the model with $\Gamma_{bg}$ as a free parameter. The likelihood and priors are described in Section 3.3.1.
the proximity zones produced by galaxies of a given luminosity function (e.g., Laursen et al. 2011), it is impossible for it to produce such a large proximity zone, even with high $f_{\text{esc}}$, steep $\alpha$ and low gas density. We thus agree with a possible interpretation by Hashimoto et al. (2018) that the Ly$\alpha$ emission comes from a different, slightly lower redshift, source compared to the [O III] emission in MACS1149-JD1.

NEPLA4 (Songaila et al. 2018) is a narrow-band selected Ly$\alpha$ emitter at $z = 6.6$ with blue flux up to $\sim 250$ km s$^{-1}$, similar to COLA1. As the UV continuum is not known, we cannot place it on Fig. 6.

### 3.3.2 Other $z > 6$ blue peaks

Hashimoto et al. (2018) reported a 4$\sigma$ detection of a Ly$\alpha$ line in the $z = 9.11$ source MACS1149-JD1. The Ly$\alpha$ line is offset by $\pm 450 \pm 60$ km s$^{-1}$ from their detection of [O III] 88 $\mu$m.

Based on Fig. 5, if the Ly$\alpha$ comes from the same source as the [O III], the environment of MACS1149-JD1 must be extremely highly ionized ($> 10^{-6}$) and in a bubble $\gtrsim 1$ pMpc. Fig. 6 shows the size of the proximity zones produced by galaxies of a given $M_{\text{UV}}$. Given the observed faintness of MACS1149-JD1 ($M_{\text{UV}} = 18.5 \pm 0.1$ based on lens modelling and fits to photometry and grism spectroscopy, Hoag et al. 2018), it is impossible for it to produce such a large proximity zone, even with high $f_{\text{esc}}$, steep $\alpha$ and low gas density. We thus agree with a possible interpretation by Hashimoto et al. (2018) that the Ly$\alpha$ emission comes from a different, slightly lower redshift, source compared to the [O III] emission in MACS1149-JD1.

### 4 DISCUSSION

#### 4.1 Ly$\alpha$ constraints on bubble properties

Blue Ly$\alpha$ peaks can reveal conditions inside individual reionized bubbles, however, we expect blue peaks to be rare at $z > 6$, due to the high IGM opacity (see Section 3.1 and e.g., Laursen et al. 2011). By contrast, Ly$\alpha$ lines that are redshifted with respect to systemic may arise more often at high redshift due to outflows, which aids the transmission of photons through the IGM (Dijkstra et al. 2011). Fig. 5 demonstrates that the velocity offset of an observed red peak can also place lower limits on the size of an ionized region (see also Malhotra & Rhoads 2006).

Not only can a single source place constraints on bubbles sizes, with a deep spectroscopic survey in a single field it could be possible to map an ionized bubble directly. Due to the ionization gradient across bubbles the transmission of Ly$\alpha$ will vary radially across a bubble (see Fig. 8). As we demonstrate in Fig. 5, the observable minimum velocity offset from systemic varies as a function of the distance from the nearest neutral region. Likewise, the transmitted Ly$\alpha$ flux will decrease for sources further from the centre of bubbles. If the faint-end of Ly$\alpha$ luminosity function is steep (e.g., $\alpha = -2.8$; Drake et al. 2017) at $z = 7$, using the luminosity function model by Gronke et al. (2015) (setting $\alpha = -2.8$) we expect $\sim 12$ Ly$\alpha$ emitting galaxies with a luminosity $L \gtrsim 10^{41}$ erg s$^{-1}$ ($\text{flux} \gtrsim 1 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$) located within $R_{\alpha} \sim 0.3$ pMpc (the lower limit on COLA1’s proximity zone – see Fig. 4). Note, this estimate does not account for galaxy clustering – if Ly$\alpha$ emitters live in overdense regions (Ouchi et al. 2018), we expect higher number counts. Within this proximity zone, we would expect the fraction of galaxies with blue Ly$\alpha$ peaks to be comparable to those seen at lower redshifts, when the IGM is highly ionized.

With a large near-infrared spectroscopic survey to measure Ly$\alpha$ flux and high S/N resolved lineshapes, as well as systemic redshift from other emission lines (e.g. rest-frame optical lines visible with JWST) it could be possible to directly map ionized bubbles and place constraints on the bubble size distribution during reionization using observations of both red and blue peaks. To accurately measure double-peaked Ly$\alpha$ line shapes requires a spectral resolution $R \gtrsim 4000$ with S/N $\gtrsim 2$ per pixel (e.g., Verhamme et al. 2015). These deep measurements will be feasible with 30-m telescope spectroscopy.
(e.g. E-ELT/MOSAIC is expected to reach $1 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ in 40 h, Evans et al. 2015).

To fully interpret such data require a more realistic treatment of the neutral gas distribution than the uniform model used here. For example, Gronke et al. (2020) explores the prevalence of blue Lyα peaks in the cosmological radiative hydrodynamical simulation CoDaII (Ocvirk et al. 2020), and finds large line-of-sight variation in Lyα transmission due to inhomogeneous gas distributions.

While the visibility of blue peaks (or red peaks with small velocity offset) can put lower limits on $R_\alpha$, measuring the size more accurately is difficult. However, given sufficient spectral quality, it might be possible to detect a sharp cutoff on the blue side of a blue peak – a signature of absorption, since frequency redistribution yields smoother profiles towards the wings (Neufeld 1990). A sharp cutoff would be expected if there is a sharp transition from an optically thin ionized region to one that is optically thick, for example, from galaxies sustaining their own $R_\alpha$ surrounded by homogeneous $10^{-3} \lesssim x_{HI} \lesssim 10^{-3}$ ionized gas (which may be typical of the IGM at the end of reionization e.g. Fan et al. 2006). This would enable a direct measurement of $R_\alpha$ and thus tighter constraints on $f_{esc}$. In contrast, a sharp cutoff of the red peak towards line centre can be due to either the IGM or radiative transfer effects and is commonly found also at low redshifts (e.g. Rivera-Thorsen et al. 2015; Yang et al. 2017), thus, this is harder to use as a measurement for $R_\alpha$. However, one could use this signature in a statistical sense: intragalactic radiative transfer sets a characteristic correlation between the width and velocity offset of red Lyα peaks (e.g. Neufeld 1990; Verhamme et al. 2018), and this trend should be altered at high redshift due to the IGM absorption yielding a flatter slope in the width-offset relation.

Naturally, the above discussion depends on the ‘intrinsic’ Lyα line, i.e. the one shaped by radiative transfer in the ISM/CGM, with the most and least constraining intrinsic lines (see Fig. 5) being a wide double peak (with significant flux on the blue side), and a single red peak with large velocity offset , respectively. While in principle, the intrinsic spectrum (and its evolution) is unknown, we can assume a similar fraction of $\sim 20–50$ per cent of intrinsic spectra with significant blue flux – as seen in low-redshift observations (Yamada et al. 2012; Erb et al. 2014; Henry et al. 2015; Rivera-Thorsen et al. 2015; Yang et al. 2016; Herenz et al. 2017). The assumption of weak evolution in the blue peak fraction with redshift is supported by high redshift studies that find similar spectral properties to low redshift galaxies (Matthee et al. 2017; Songaila et al. 2018), and, in any case, would only affect our estimates, e.g. on the number of detected Lyα emitters with a blue peak by a factor of $\sim 2$.

4.2 Impact of resonant absorption on EoR inferences

The increase in the size of the proximity zone means that more blue flux will be observed at lower redshifts, even if the size of the ionized bubble remains the same. The evolving flux distribution of Lyα emission from $z > 6$ galaxies has been used to measure the average neutral hydrogen fraction of the IGM (Mesinger et al. 2015; Mason et al. 2018a), under the assumption that the declining flux is due to damping wing absorption alone. However, an increase in resonant absorption may also account for some of the decrease observed in the Lyα flux distribution at $z > 6$ (see e.g. Bolton & Haehnelt 2013; Mesinger et al. 2015).

Given current constraints on the neutral fraction at the end of reionization ($z < 6$, Fan et al. 2006), we can ask under what conditions could the increased optical depth due to an increased residual neutral fraction in ionized bubbles cause the observed decline in Lyα emission.

Assuming a double-peaked Gaussian Lyα lineprofile, with red:blue flux ratio $R$: 1, the resulting Lyα transmission fraction through the IGM can be written as

$$T(z = 7) = \frac{e^{-x_{HI}(z=7)} + R}{e^{-x_{HI}(z=6)} + R}$$

Fig. 9 shows this as a function of the relative increase in the average residual neutral fraction between $z \sim 6$ and $z \sim 7$, $x_{HI}(z=7)/x_{HI}(z=6)$. In order to produce a drop in the observed Lyα fraction of $T_l/T_b \sim 0.5$, either the neutral fraction at $z = 6$ must be $< 10^{-4}$, i.e. not optically thick, or if $x_{HI}(z=6) \sim 10^{-3}$ the blue peak flux must be $\gtrsim 100$ times stronger than the red peak. Both of these scenarios are unlikely: The $z \sim 6$ Lyα forest is optically thick on average [e.g. Fan et al. 2006, find $x_{HI}(z \sim 6) \gtrsim 10^{-4}$] and the observed Lyα line shapes of galaxies at all redshifts show dominant red peaks (e.g. Rivera-Thorsen et al. 2015; Trainor et al. 2015; Yang et al. 2017; Steidel et al. 2018). Therefore, while the residual neutral fraction in ionized regions will increase between $z \sim 6$ to $z \sim 7$ due to a lower ionizing background and increased recombinations, it is unlikely to significantly impact the integrated transmission of Lyα on average, and thus has a small impact on reionization inferences.

5 CONCLUSIONS

We have used an analytic model to estimate the Lyα optical depth within reionized bubbles and investigate the impact of reionization on Lyα lineshapes. Our conclusions are as follows:
(i) Both the size of, and residual neutral hydrogen fraction within, reionized bubbles affect the observed lineshape of Lyα emission during reionization. As such, measurements of the Lyα velocity offset from systemic can provide lower limits on the source’s distance to the first large neutral patch along the line of sight, and upper limits on the residual neutral fraction inside its H II bubble.

(ii) Galaxies with Lyα lines observed with low-velocity offsets from systemic must reside in large reionized regions. Detecting blue-spectroscopy with, e.g. the HST can provide lower limits on the source's distance to and their ionized regions. Including to be used to constrain the properties of reionized regions, including to provision of the Lyα escape fraction, $(f_{\text{esc}} > 0.50)$, and steep UV spectral slope, $\beta < -1.79$, and for the total gas density along the line of sight to be low $< 0.3 \text{pMpc}$, including an ionizing background alleviates the need for a high $f_{\text{esc}}$ and steep $\beta$, but still requires a low gas density.

Detailed measurements of Lyα lineshapes and velocity offsets can be used to constrain the properties of reionized regions, including to place lower limits on ionized bubble sizes. With rest-UV – optical spectroscopy with, e.g. the James Webb Space Telescope (JWST) these methods enable direct comparison between galaxy properties and their ionized regions.

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DATA AVAILABILITY

The source code underlying this paper is available on GitHub at https://github.com/charlottenosam/LyalphaLineshapes.

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