IGM Transmission Bias for $z \geq 2.9$ Lyman Continuum Detected Galaxies

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ABSTRACT

Understanding the relationship between the underlying escape fraction of Lyman continuum (LyC) photons ($f_{\text{esc}}$) emitted by galaxies and measuring the distribution of observed $f_{\text{esc}}$ values at high redshift is fundamental to the interpretation of the reionization process. In this paper we perform a statistical exploration of the attenuation of LyC photons by neutral hydrogen in the intergalactic medium using ensembles of simulated transmission functions. We show that LyC detected galaxies are more likely to be found in sightlines with higher-than-average transmission of LyC photons. This means that adopting a mean transmission at a given redshift leads to an overestimate of the true $f_{\text{esc}}$ for LyC detected galaxies. We note, however, that mean values are appropriate for $f_{\text{esc}}$ estimates of larger parent samples that include LyC non-detected galaxies. We quantify this IGM transmission bias for LyC detections in photometric and spectroscopic surveys in the literature and show that the bias is stronger for both shallower observations and for fainter parent samples (i.e. Lyman $\alpha$ emitters versus Lyman break galaxies). We also explore the effects of varying the underlying probability distribution function (PDF) of $f_{\text{esc}}$ on recovered values, showing that the underlying $f_{\text{esc}}$ PDF may depend on sample selection by comparing with observational surveys. This work represents a first step in improved interpretation of LyC detections in the context of understanding $f_{\text{esc}}$ from high redshift galaxies.

Key words: intergalactic medium – galaxies: ISM – dark ages, reionization, first stars

1 INTRODUCTION

Understanding the details of cosmic reionization, the epoch at $z \approx 6 – 10$ during which the hydrogen content of the intergalactic medium (IGM) transitioned from neutral to mostly ionized (e.g. Fan et al. 2006; Planck Collaboration et al. 2016; Greig & Mesinger 2017; Mason et al. 2018), is a major goal of the international astronomical community. The general consensus currently favours a picture in which ionizing, or Lyman continuum (LyC), photons originating from young, massive stars and/or X-ray binaries and Wolf-Rayet stars in star-forming galaxies are the primary driver. This picture is supported by extensive theoretical (e.g. Wise & Cen 2009; Yajima et al. 2011; Paardekooper et al. 2015) and observational (e.g. Inoue et al. 2006; Ouchi et al. 2009; Robertson et al. 2015) efforts. Active galactic nuclei (AGN), though prigious producers of LyC emission, are expected to play only a minor role due to their low number density at $z > 6$ (e.g. Hopkins et al. 2007; Parsa et al. 2018; Kakiichi et al. 2018).

Detailed modelling of the reionization process critically requires an accurate census of the fraction of LyC photons (with respect to ultraviolet, UV, continuum photons) produced in galaxies that manage to escape into the IGM, typically referred to as the LyC escape fraction ($f_{\text{esc}}$). The first major challenge in using $f_{\text{esc}}$ to understand reionization is the fact that no LyC photons from galaxies during the Epoch of Reionization (EoR) will ever reach a telescope due to absorption from intervening hydrogen. The second is the inherent faintness of LyC emission from galaxies (as demonstrated by pioneering works of Giallongo et al. 2002; Fernández-Soto et al. 2003; Inoue et al. 2005), which is driven largely by two key factors. The first factor driving the faintness of LyC emission is that $f_{\text{esc}}$ is typically found to be very low (or zero) as inferred from the lack of LyC detections in (e.g. Boutsia et al. 2011; Japelj et al. 2017; Bian & Fan 2020). This may, in part, be due to the fact that observations of galaxies, and thus, their LyC emission, at high redshift ($z \geq 2.9$)
are limited to relatively high stellar mass \((M_\star \geq 10^9 M_\odot)\) galaxies that are likely to contain significant quantities of neutral hydrogen (consistent with their high star-formation rates, SFRs, e.g. Steidel et al. 2001; Iwata et al. 2009; Nestor et al. 2011; Grazian et al. 2016) that absorbs ionizing radiation before it can enter the IGM and drive reionization. Indeed, for the small sample of such known LyC emitting galaxies at \(z \geq 2.8\), the observed LyC flux is relatively faint (e.g. Shapley et al. 2006; Mchedlishvili et al. 2017; Vanzella et al. 2018). Even if \(f_{\text{esc}}\) is lower in mass larger galaxies, such galaxies are inherently faint and their LyC emission will likely be at least as difficult to detect as their higher mass counterparts (apart from the rare cases of strong gravitational lensing, Bian et al. 2017; Rivera-Thorsen et al. 2019). The most straightforward way past this problem is to perform larger and deeper surveys targeting LyC emission across a range of redshifts. A variety such surveys are currently in progress.

The second issue resulting in faint LyC emission is that the IGM itself contains large fractions of neutral hydrogen above \(z \approx 3\) (e.g. Inoue et al. 2014). This means that after LyC escapes from a galaxy it is largely absorbed in the IGM before reaching Earth. For any individual LyC detection, there is currently no reliable method for inferring the IGM transmission \((T_{\text{IGM}})\) of LyC photons for that particular sightline. This is troubling as observationally \(T_{\text{IGM}}\) and \(f_{\text{esc}}\) are degenerate meaning that, in order to estimate \(f_{\text{esc}}\), a value of \(T_{\text{IGM}}\) must be assumed that may or may not be appropriate for a given IGM sightline. There is, however, hope of a way forward as the differential column density distribution of HI absorption systems is well constrained (e.g. Meiksin 2006; Becker et al. 2013; Rudie et al. 2013), providing a statistical description of the probability that LyC photons escaping galaxies will be absorbed by hydrogen in the IGM at a given redshift.

Such a statistical approach to estimate \(T_{\text{IGM}}\) in a theoretical context has been explored using Monte Carlo (MC) simulations for around three decades (e.g. Moller & Jakobsen 1990; Bershadsky et al. 1999; Inoue et al. 2014). Similarly, the application of such MC simulations of \(T_{\text{IGM}}\) to detections (and non-detections) of LyC radiation has a long history (e.g. Shapley et al. 2006; Siana et al. 2007; Steidel et al. 2018). It is possible that the underlying PDF of \(f_{\text{esc}}\) values seem to be preferred, which is not reflected in current \(f_{\text{esc}}\) calculations. It is possible that the broad behaviour of the \(f_{\text{esc}}\) PDF may be inferred through consideration of the detection rates in LyC surveys (this intriguing idea is explored further in Section 4.3).

In this paper, we explore in detail the probability distributions of both \(T_{\text{IGM}}\) and \(f_{\text{esc}}\) in the context of known LyC surveys at high redshift. Our goal is to provide a statistically sound framework within which astronomers can calculate meaningful estimates of \(f_{\text{esc}}\) for both individual LyC detections as well as stacked samples. In particular, we show that both the assumption of the mean \(T_{\text{IGM}}\) value and (to a lesser extent) a lack of consideration of the underlying \(f_{\text{esc}}\) PDF result in an overestimate of \(f_{\text{esc}}\) for LyC detected galaxies. Here we quantify the IGM transmission bias, \(T_{\text{bias}}\) as \((T_{\text{det}}) - (T_{\text{IGM}})\) where \((T_{\text{det}})\) is the average IGM transmission for LyC detected galaxies for a given observational detection limit. We note that, although a transmission value is not inherently an additive quantity, our definition leads to a roughly redshift independent correction to \((T_{\text{IGM}})\) as opposed to an alternative definition such as \(T_{\text{bias}} = (T_{\text{det}})/(T_{\text{IGM}})\) (see Section 4 for further discussion).

This paper is organised as follows: in Section 2 we describe our method of generating simulated IGM sightlines and spectra of mock LyC emitting galaxies, in Section 3 we describe the results of our various models, in Section 4 we explore the implications of our results in the context of past and on-going LyC surveys, and in Section 5 we provide a brief summary of our findings.

2 SIMULATING LYC LEAKING GALAXIES

In this Section we describe our method of producing mock observations of LyC flux from high redshift galaxies. There are three primary ingredients in creating an individual high redshift galaxy observation for our simulation: an IGM transmission function, \(f_{\text{esc}}\), and the input SED model. Our method for producing an IGM transmission function is described in Section 2.2. Although the underlying PDF of \(f_{\text{esc}}\) for galaxies is largely unknown, we test two models described in Section 2.2.2. Finally, we take our input SED model from BPS2014 (Eldridge et al. 2017) described further in Section 2.2.3, matching the assumed LyC to non-ionizing UV flux ratio from previous studies. In particular we compare with results from the Keck Lyman Continuum Survey (KCLS, S18), the LymAn Continuum Escape Survey (LACES, F19), and the ground based photometric work of M20 based on deep \(u\)-band photometry from the Canada
All code for producing IGM transmission curves is open source and available at https://github.com/robbassett/TAOIST_M.C.

France Hawaii Telescope (CFHT) Large Area U-band Deep Survey (CLAUDS, Sawicki et al. 2019).

2.1 IGM Transmission Functions

We perform a Poisson sampling of the number of HI absorbers in redshift intervals, $\Delta z$, from $z = 0$ to a specified redshift, $z_{\text{em}}$. Following Inoue et al. (2014) we select a value of $\Delta z = 5 \times 10^{-5}$, noting however that deviations from this value would not affect our results. The value of $z_{\text{em}}$ for a given analysis is determined by the redshift of the galaxy, or sample of galaxies, being considered. In this work we create suites of 10,000 IGM transmission functions at 10 discrete $z_{\text{em}}$ values in the range 2.9-3.9 with $\Delta z_{\text{em}} = 0.1$ (we also explore IGM transmission bias at $z = 2.4$ and $z = 4.4$ for HST F275W and F435W observations, respectively, in Section 5).

To generate a single $T_{\text{IGM}}$ function at a given $z_{\text{em}}$ we must first produce a random sampling of hydrogen absorption systems in redshift bins of $\Delta z = 5 \times 10^{-5}$ from $z = 0$ to $z_{\text{em}}$. This is achieved assuming a differential HI column density distribution, $f(N_{\text{HI}}, X)$, following the prescriptions outlined for the “IGM+CGM” model in S18 Appendix B. In each redshift interval we derive the expected number of absorption systems in each bin of $\log(N_{\text{HI}})$ (sampled from $\log(N_{\text{HI}}) = 12.0 - 21.0$ with $\Delta \log(N_{\text{HI}}) = 0.1$) as:

$$N_{\text{abs}} = \int_{N_{\text{HI},\text{min}}}^{N_{\text{HI},\text{max}}} \int_{z}^{z + \Delta z} N_{\text{HI}}^{-\beta} A(1 + z)^{\gamma} dN_{\text{HI}} dz$$

where $N_{\text{HI},\text{min}}$ and $N_{\text{HI},\text{max}}$ are the lower and upper bounds, $\beta$ is the slope of $f(N_{\text{HI}}, X)$, $A$ is a constant chosen to match observed $N_{\text{abs}}$, and $\gamma$ describes the redshift evolution of $N_{\text{abs}}$. Values for $\beta$, $A$, and $\gamma$ are taken directly from Table B1 of S18. We assume the presence of absorption systems is a Poissonian process, thus for each sightline the number of absorption systems at a given $z$ and $N_{\text{HI}}$ is calculated using NUMPY.RANDOM.POISSON with $\lambda = N_{\text{abs}}$.

For each individual absorber in a given observed sightline, we then apply the transmission function for LyC photons at $\lambda_{\text{rest}} \leq 911.8$ Å and a transmission for Lyman series forest for photons with $\lambda_{\text{rest}} \geq 911.8$ Å, noting that in this case we are considering the rest wavelength at the redshift of the absorption system and not the LyC emitting galaxy. For LyC photons we apply the functional form:

$$T_{\text{HI}}(\nu_{\text{rest}}) = 1 - e^{-\sigma_{\text{HI}}(\nu_{\text{rest}}, N_{\text{HI}})}$$

where $\nu_{\text{rest}}$ is the photon frequency at the rest frame of a given absorption system and $\sigma_{\text{HI}}(\nu_{\text{rest}}, N_{\text{HI}})$ is the frequency dependent interaction cross section of HI to ionising photons given by the Osterbrock [1989]. For Lyman series lines we use the following...
for each Lyman transition, \(i\) (e.g.\[Inoue & Iwata 2008\]):

\[
\tau_i(\nu_{\text{rest}}) = N_{\text{HI}} \sqrt{\pi \epsilon^2 f_i} \frac{\phi_i(\nu_{\text{rest}})}{m_e c v_D}
\]

(3)

where \(m_e\) and \(\epsilon\) are the electron mass and charge, respectively, and \(c\) is the speed of light. The parameter \(f_i\) is the oscillator strength of Lyman transition \(i\), which we take from tables provided with the VPFIT package (\[Caswell & Webb 2014\]). In our calculation we include the first 32 Lyman series transitions. \(v_D = v_i(b/c)\) is the Doppler broadening of the Lyman line at frequency \(v_i\), where \(b\), the Doppler parameter, is randomly sampled from (\[Hui & Rutledge 1999\]).

\[
h(b) = \frac{4 b^4}{b^8} e^{-b^4/b^4}
\]

(4)

with \(b_p = 23 \text{ km s}^{-1}\) (e.g.\[Janknecht et al. 2006\]). Finally, \(\phi_i(\nu)\), the absorption profile, is taken as the analytic approximation of the Voigt profile given by (\[Tepper-Garcia 2005\]). Here, as with \(f_i\), we also sample \(\Gamma_i\), the damping constant for transition \(i\), from the VPFIT values. The total optical depth of an individual absorber is then taken as \(\tau(\nu) = \tau_{\text{LyC}}(\nu_{\text{rest}}) + \Sigma \tau_i(\nu_{\text{obs}})\), where \(\nu\) refers to the observed frame frequency, \(\nu = \nu_{\text{rest}}/(1 + z)\). The total \(\tau(\nu)\) for a given sightline is the sum of the ensemble of \(\tau(\nu)\) for all absorbers in that sightline.

It is worth mentioning that our transmission curves are produced as a function of wavelength, rather than frequency, and we employ a fixed resolution of \(\Delta \nu = 2.2 \text{ Å per pixel}\) in the observed frame. This choice is motivated by the fact that we compare extensively with LRIS spectroscopy of S18, who quote a spectral resolution of 2.18 Å per pixel for their observations.\[Inoue & Iwata 2008\] note that spectral resolution can have a significant impact on the resultant IGM transmission, we have tested the effect of increasing the spectral resolution to 0.4 Å per pixel, finding no statistically significant difference compared to our standard 2.2 Å per pixel transmission curves.

Throughout this paper we consider values in terms of IGM transmission, \(T_{\text{IGM}} = e^{-\tau}\), rather than considering \(\tau\) computed as described above. The reasons first that the value of \(T_{\text{IGM}}\) is typically included in calculations of \(f_{\text{esc}}\), and second that \(T_{\text{IGM}}\) has a dynamic range between 0 and 1, which provides more intuitive comparisons. We note that throughout this paper the symbol \(T_{\text{IGM}}\) may refer to a wavelength dependent transmission function or a single value at some specified wavelength. We avoid introducing an explicitly wavelength dependent symbol, i.e. \(T_{\text{IGM}}(\lambda)\), as the usage here is consistent with the conventions in the literature (e.g.\[Inoue & Iwata 2008\]).

Example IGM transmission functions at \(z = 3.1\) are shown in Figure 3. In the left panel in black we show the mean transmission curve of all 10,000 simulated sight lines at \(z = 3.1\) while gold and cyan curves show two individual sight lines having the highest and lowest \(A_{\text{esc}} = 910 \text{ Å Transmission}\), respectively. At a given redshift the transmission of LyC in the IGM may vary from 0.0 to nearly 1.0. In the right panel we show the redshift evolution of the mean LyC and Ly\(\alpha\) transmission predicted by TAOIST-MC in comparison with observational and theoretical estimates from the literature. In all cases, our model agrees, within errors, with previously reported results.

We note that our measurements are systematically lower than some previous results, which can be attributed to the inclusion of the circumgalactic medium component introduced in S18. Furthermore, a single statistic (such as the mean) belies the complexity of the underlying \(T_{\text{IGM}}\) distribution as shown in Figure 3. Thus, we do not place a large emphasis on differences between the average values of \(T_{\text{IGM}}\) between different studies. For theoretical \(T_{\text{IGM}}\) functions this behaviour may be, in part, attributed to the exact form of the differential \(N_{\text{HI}}\) distribution assumed and the details of the implementation. For example,\[Inoue & Iwata 2008\] and S18 assume different behaviours for the exponent \(\beta\) of \(f(N_{\text{HI}}, \chi)\) producing different relative numbers of low and high \(N_{\text{HI}}\) systems. These differences will affect the \(T_{\text{IGM}}\) of LyC and Ly\(\alpha\) differently and will appear as complex systematic offsets between the mean \(T_{\text{IGM}}\) at a given redshift between the two implementations. It should also be mentioned that, to our knowledge, no study employing MC simulations of IGM transmission curves have accounted for the effects of \(\chi\) clustering, which may further alter the mean \(T_{\text{IGM}}\) curve (see, however,\[Kakiichi & Dijkstra 2018\] who demonstrate Ly\(\alpha\) may be more attenuated from galaxies in high density environments).

Differences in the behaviour between theoretical \(T_{\text{IGM}}\) implementations are only apparent from the mean transmission curves while individual IGM transmission curves are likely indistinguishable. The implications regarding the statistical behaviour of IGM sightline ensembles, however, is precisely the topic of this paper. As we will repeat, the absolute values of quantities calculated throughout will be imprinted with the assumptions regarding our \(N_{\text{HI}}\) distribution sampling and may change slightly if different implementations are used. Thus, it is key to keep in mind that the absolute results are for our implementation only. Qualitatively, however our results are independent of the various input parameters.

2.2 \(f_{\text{esc}}\) Distribution Functions

One of the key unknowns in this study is the distribution function of \(f_{\text{esc}}\) for galaxies at \(z \geq 2.9\). While quantifying \(f_{\text{esc}}\) from galaxies has been a long standing goal in the astrophysics of reionization, this parameter remains elusive. In a broad sense, a number of studies have estimated the average \(f_{\text{esc}}\) required for all galaxies in order to match the constraints on the timing of reionization,
A constant and/or single valued radiative transfer, however, the likelihood that all galaxies will have hydrodynamical simulations of individual galaxies employing full resolution of 10,000 sampled values for our mock galaxy spectra produced using cdf_sampler.py (see footnote 2) with the open histograms as inputs. Values on the left y-axis refer to observed samples (open histograms) and on the right y-axis refer to mock samples (closed histograms), noting in the latter case these values are based on an arbitrarily selected “parent sample” size.

finding values in the range 0.05 < $\langle f_{\text{esc}} \rangle$ < 0.20 (e.g. Bouwens et al. 2015, Robertson et al. 2015, Finkelstein et al. 2019). From hydrodynamical simulations of individual galaxies employing full radiative transfer, however, the likelihood that all galaxies will have a constant and/or single valued $f_{\text{esc}}$ over their lifetime seems vanishingly small (Kimm & Cen 2014, Paardekooper et al. 2015, see also Section 4.1 for a brief discussion of the 3D versus line-of-sight $f_{\text{esc}}$ values).

Given the lack of strong constraints on $f_{\text{esc}}$ from the literature, for the fiducial model of our analysis, presented in Section 3.1 we simply uniformly apply values of $f_{\text{esc}}$ between 0.0 and 1.0 to our mock spectra. This allows for mock spectra with the highest possible LyC flux for a given IGM sightline, representing the most likely galaxies to be detected in a LyC survey. As such, the results of our fiducial model should be interpreted as the minimum level of $T_{\text{IGM}}$ bias expected for LyC detected galaxies.

It seems most likely that allowing extremely high $f_{\text{esc}}$ is unrealistic for the vast majority of real galaxies (e.g. Vanzella et al. 2010, Stiana et al. 2015, Japelj et al. 2017). In Section 3.2 we test the effects on our measured $T_{\text{IGM}}$ bias of applying an additional, more realistic $f_{\text{esc}}$ distribution, to our simulations. For this test, we assume an exponentially declining $f_{\text{esc}}$ PDF, i.e. $P(f_{\text{esc}}) \sim e^{-f_{\text{esc}}/\eta}$, resulting in a model with the most probable value of $f_{\text{esc}}$ being zero. For our exponentially declining $f_{\text{esc}}$ PDF we choose a value of $\eta = 0.5$, which is motivated by the observed detection rates of KLCS (S18, see Section 4.3). We illustrate the relative PDF shapes of our fiducial and exponentially declining models in Figure 3 for clarity.

2.3 Producing Mock Galaxy Spectra

As mentioned above, the process of producing mock galaxy spectra for our simulations requires three inputs: an underlying SED model, an IGM attenuation function, and a value for $f_{\text{esc}} (L_{\text{LyC}})$. We note that in much of this work we ignore the effects of dust attenuation (see, however, Section 4.4) simply noting that most LyC detections appear to originate from relatively dust free galaxies (e.g. S18). Similar to S18 we construct our SEDs from the BPASSv2.1 (El-Bridge et al. 2017) models with $Z_\star = 0.001$, IMF slope $\alpha = -2.35$, and stellar mass limit of 300 $M_\odot$. We employ a model with an exponentially declining SFR with an $e$-folding time of 0.1 Gyr sampled at an age of ~200 Myr. This provides an input spectrum with an intrinsic LyC to UV flux ratio, $(L_{\text{LyC}}/L_{1500})_{\text{int}}$, of 0.18 (e.g. S18). Our SED model corresponds to a LyC photon production efficiency, $\xi_{\text{ion}}$, of $\log_{10}(\xi_{\text{ion}}) = 25.61 \text{ Hz erg}^{-1}$, consistent with estimates for high redshift star-forming galaxies (e.g. Bouwens et al. 2016). We explore the effect of altering $(L_{\text{900}}/L_{1500})_{\text{int}}$ on our results in Section 3.3.

Each mock spectrum is scaled such that the non-ionizing UV flux matches a randomly sampled value characteristic of high redshift, highly star-forming galaxies. The sampling of UV fluxes is one key factor in our analysis as this ultimately determines the intrinsic level of LyC flux from galaxies in our mock samples. In this work we test samples taken two different UV flux distributions: one based on the full sample of galaxies observed by the KLCS, which is composed of a representative subsample of bright Lyman Break Galaxies (LBGs) at $2.9 < z < 3.2$ from the flux-limited sample of Reddy et al. (2012), and a second based on $z = 3.1$, narrowband selected Lyman $\alpha$ emitters (LAEs) characteristic of galaxies targeted by LACES (F19). For our LBG comparison UV values used in our work are sampled from measurements of LRIS spectra at $\lambda_{\text{rest}} = 1500\AA$ taken directly from reported values of S18. For the comparison with LAEs, UV values are sampled based on the histograms presented in F19, Figure 15, based on ground based photometry. We compare the absolute magnitude distributions of the two distributions in Figure 4 showing LAEs to be significantly fainter than LBGs. We note, however, that some LBGs have been shown to also exhibit Ly$\alpha$ emission (e.g. Shapley et al. 2003), thus LBG and LAE classifications are based on selection methodology. Here, the important distinction is the relative non-ionizing UV flux with LBGs being significantly brighter.

The sample of S18 covers a redshift range of $z = 2.8-3.5$ and the sample of F19 is at a roughly fixed redshift of 3.1. The mock galaxies in our analysis, however, are produced at 10 discrete redshift values with $\Delta z = 0.1$ from $z = 2.9$ to $z = 3.9$. Thus, we must include a method to account for cosmological dimming of each of these samples when considering higher redshifts. In each case, we begin with the absolute magnitude distributions shown in Figure 3 and assume that this distribution is roughly representative of a similarly selected sample in each $\Delta z = 0.1$ redshift bin. We then sample magnitudes from the above distributions then convert each value to an observed 1500 $\AA$ flux at a given redshift. We note that this is equivalent to a slight increase in depth with redshift, however we expect this to have a negligible effect on our results as we are most sensitive to the brightest galaxies at any redshift.

For each of the 10,000 IGM sightlines in a given redshift bin we produce 100 mock spectra for both the LBG and LAE comparison samples. For each trial we randomly sample a 1500 $\AA$ flux (as described above) and a value of $f_{\text{esc}}$, the latter following Section 2.2. The current $T_{\text{IGM}}$ function is applied to the input BPASSv2.1 spectrum, then at all wavelengths shortward of 911.8 $\AA$ it is scaled uniformly by the randomly selected $f_{\text{esc}}$ value. The resulting spectrum is then scaled to match the randomly selected 1500 $\AA$ flux.

In both cases sampling of UV fluxes is achieved using the histogram_oversampler class of the code cdf_sampler.py (https://github.com/robbashett/cdf_sampler) with spline fitting enabled to remove sharp edges of the histogram bins.
Thus, in each redshift bin we produce one million galaxy spectra ensuring that the 1500 Å flux and $f_{\text{esc}}$ distributions are well sampled. Example spectra can be seen in Figure 5.

We can summarise the construction of each individual mock spectrum with the following equation:

$$ F_v^{i,j}(\lambda, z) = F_{v,\text{mod}}(\lambda) \frac{F_{1500,\text{obs}}^{i,j}}{F_{1500,\text{mod}}^{i,j}} f_{\text{esc}}^j(\lambda) $$

where $F_{v,\text{mod}}(\lambda, z)$ is the input BPASS spectrum, $F_{1500,\text{obs}}^{i,j}$ is the $i$th randomly sampled 1500 Å flux (noting again that here we have included cosmological dimming), $F_{1500,\text{mod}}$ is the 1500 Å flux of the BPASS model (taken as the mean value at 1450 < $\lambda$ < 1550 Å), $T_{\text{IGM}}^j$ is the current IGM transmission curve (we use the superscript $j$ to indicate that the same IGM transmission curve will be used 100 times, thus it is not unique to mock spectrum $i$), and $f_{\text{esc}}^j(\lambda)$ is a step function representation of the $i$th randomly sampled $f_{\text{esc}}$ value given as:

$$ f_{\text{esc}}^j(\lambda) = \begin{cases} 0 & \text{if } \lambda < 911.8 \\ 1 & \text{if } \lambda \geq 911.8 \end{cases} $$

3 RESULTS

The primary results of this paper concern quantifying the observational bias in IGM transmission for samples of LyC detected galaxies. We reiterate that the initial results are based on tests performed on a fiducial dust-free, exponentially declining SFR SED models at fixed metallicity, IMF slope, and age (see Section 2.3 for a full description). We have selected our fiducial model to have $(L_{1400}/L_{1500})_{\text{int}}=0.18$ (comparable to other studies in the literature, e.g. S18, F19), which is expected to be representative of young, star-forming galaxies responsible for driving reionization.

Additionally, as described in Section 2.3, our fiducial model assumes the unrealistic case of a flat probability distribution for $f_{\text{esc}}$ between 0 and 1.0. High $f_{\text{esc}}$ will correspond to a bright LyC flux, thus, we expect a preference towards detections at high $f_{\text{esc}}$ in our fiducial model. $f_{\text{esc}}$ for real galaxies will be, on average, lower than the average of our fiducial model given the typically low value for observed LyC emitters (e.g. S18). This means that the level of bias in $T_{\text{IGM}}$ for detections seen in our fiducial model can be seen as a lower limit to the true bias for observed galaxy samples.

We explore the quantitative effects of both altering the input PDF of $f_{\text{esc}}$ and changing the value of $(L_{1400}/L_{1500})_{\text{int}}$ in Sections 3.2 and 3.3 respectively. In the case of SED variations we test SEDs with $\xi_{\text{ion}}$ values covering the range for exponentially declining SFR models using BPASSv2.1 spectra over available range of stellar population ages provided.

3.1 Fiducial IGM Bias

Here we quantify the bias in $T_{\text{IGM}}$ affecting samples of LyC detected galaxies when compared with the average $T_{\text{IGM}}$ of all random sightlines. Formally, we define this bias as:

$$ T_{\text{bias}} = \langle T_{\text{det}} \rangle - \langle T_{\text{IGM}} \rangle $$

where $\langle T_{\text{det}} \rangle$ is the average $T_{\text{IGM}}$ for galaxies with LyC detected above a specified detection limit and $\langle T_{\text{IGM}} \rangle$ is the average $T_{\text{IGM}}$ for all sightlines. It is worth noting that transmission values are not inherently additive quantities and it could be argued that the definition $T_{\text{bias}} = \langle T_{\text{det}} \rangle / \langle T_{\text{IGM}} \rangle$ is more sensible, and possibly more physically motivated as it relates directly to a difference in optical depth/HI column density. Our choice of definition is motivated by the fact that the resulting $T_{\text{bias}}$ values are roughly redshift independent at fixed observational detection limit (see, e.g., Section 3.1.3), providing a simplified framework for applying $T_{\text{bias}}$ to a given set of observations. We also point out that, by definition, such a correction will never result in an unphysical transmission value for LyC detections $> 1.0$. Furthermore, any evolution in $T_{\text{bias}}$ with redshift when assuming a fractional definition is primarily reflective of the redshift evolution of $\langle T_{\text{IGM}} \rangle$ as one is dividing by a value increasingly

Figure 5. Top: Example BPASSv2.1 spectra used in this study. In black is shown the input spectrum and in gold and cyan we show the output spectra for the high IGM transmission spectrum shown in the top panel with $f_{\text{esc}}$ varying from 0.0 to 1.0. For all spectra in both panels, we show the flux in $F_v$ normalised to the flux at a rest wavelength of 1500 Å.
close to zero. Regardless, either $T_{\text{bias}}$ definition mentioned here will provide an equivalent correction, thus the choice is somewhat arbitrary.

In this work, the calculation of $T_{\text{bias}}$ is performed at 11 discrete redshifts in the range $2.9 \leq z \leq 3.9$ with $\Delta z = 0.1$. We also note that, similar to $T_{\text{IGM}}$ and $(T_{\text{IGM}})$, $T_{\text{bias}}$ can refer to a wavelength dependent function, a single value at a specified wavelength, or an average value across a specified wavelength range. Due to technical differences between LyC searches employing spectroscopy (e.g. S18) and photometry (F19, M20), we present the two cases separately: spectroscopic biases are presented in Section 3.1.1 and photometric biases are presented in Section 3.1.2. In all cases, we have performed this experiment twice: once for an LBG-like sample and once for a fainter, LAE-like sample (see Figure 4). Due to the inherent faintness, our mock LAE samples are typically only detected deep HST F336W observations, which compare to F19 (particularly in our higher redshift bins) who achieve a depth of 30.24 mag. Thus, in most cases we only provide $T_{\text{bias}}$ measurements for this comparison (as opposed to spectroscopy or CFHT z photometry). We provide a summary of our fiducial model in Section 3.1.3.

3.1.1 Spectroscopic Detections

Spectroscopic detection of LyC radiation provides a key advantage over photometric detections in terms of interpretation in the context of estimating $f_{\text{esc}}$. The reason being that spectroscopy allows one to probe the same rest frame wavelengths just shortward of the Lyman limit, typically probed between 880-910 Å, independent of redshift in theory. In practice, of course, the redshift range in which LyC can be probed by a given set of spectroscopic observations is defined by the wavelength coverage of the instrument used. Furthermore, the detection limits of a given instrument will be wavelength dependent due to response variations of the detector. Thus, the experiment presented here should be considered as a simulation of an idealised spectroscopic instrument with uniform sensitivity to LyC radiation at 880-910 Å across the entire redshift interval from $2.9 < z < 3.9$. The black $(T_{\text{IGM}})$ functions in Figure 7 show that this wavelength range exhibits the largest $(T_{\text{IGM}})$ values at $\lambda_{\text{rest}} < 911.8$ Å meaning that at all redshifts spectroscopic observations probe LyC emission at the highest $(T_{\text{IGM}})$ and, thus, the highest probability of detection (at fixed depth). This is simply due to the fact that the redshift interval of LyC absorption systems that affect a given wavelength increases with decreasing wavelength. This means that at lower wavelengths the probability of encountering a high column density system in any individual sightline is higher.

As we discuss later, this is not the case for photometric observations which instead probe a fixed $\lambda_{\text{rest}}$ range, thus a decreasing $\lambda_{\text{rest}}$ with increasing redshift. Another important and related point is that ionizing radiation escaping from galaxies will be completely absorbed by intervening, high HI column density systems, resulting in rapid drops in flux based on the redshift of that intervening system (e.g. the drop at ~810 Å in Figure 1). This means that escaping ionizing radiation from high redshift galaxies may only be visible in a very small wavelength range and this behaviour will be difficult to capture and interpret from photometric observations, but will be seen clearly in spectroscopy. As a caveat, however, we note that, without ancillary, high spatial resolution, space-based photometric data, it can be difficult to rule out the possibility of low redshift contamination from ground-based spectroscopic LyC detections (Vanzella et al. 2010, 2012).

The fact that spectroscopy probes the most transparent portion of the emitted spectrum from high redshift galaxies also suggests that spectroscopic detections of LyC may suffer from relatively low $T_{\text{bias}}$ at fixed detection limits (noting however that photometric detections are significantly deeper for the same exposure time). We show this in Figure 8, where we show $(T_{\text{IGM}})$ for all 10,000 sightlines in black and $(T_{\text{IGM}})$ for those where galaxies are detected with a flux above 0.025 $\mu$Jy, equivalent to ~27.9 mag, at $z = 3.1$, with coloured lines. It should be clarified here that this detection limit is chosen to be roughly matched to the faintest LyC detection reported in S18 for the galaxy Westphal-MM37 (0.026 $\mu$Jy). Considering the full parent sample of S18, 0.025 $\mu$Jy corresponds to a 1-5σ detection as the observational limits and noise characteristics exhibit complex dependencies on factors such as observational depth and source redshift (i.e. the observed wavelength of emitted LyC radiation). Thus, we reiterate that our results are representative of an idealised version of the S18 survey as we have not attempted to simulate the full complexity of their spectroscopic observations.

Returning to Figure 8, the cyan and gold lines indicate the mean and median $(T_{\text{IGM}})$ curves for LyC detected, LBG-like galaxies (comparable to the S18 sample) while the green line shows the mean $(T_{\text{IGM}})$ curve for LAE-like detections (comparable to the F19 sample). Here we measure $(T_{\text{IGM}})$ in the rest frame wavelength range 880 ≤ $\lambda_{\text{rest}}$ ≤ 910 Å (indicated in Figure 6), also following S18. We note that LAE-like galaxies are not representative of the S18 sample and are only detected at these spectroscopic limits in our lowest redshift bins. In fact, overall detection rates at all redshifts is lower for the more faint sample of LAEs, which accounts for the increased dispersion seen in the $(T_{\text{IGM}})$ curve for LyC detected...
LAEs. Given this comparison is to S18 who focus on LBGs, we do not place a large emphasis on this mock sample for spectroscopic observations.

Also shown in Figure[3] is the median and 68 percentile range for LyC detected LBGs in gold for comparison. The median value of \( T_{\text{IGM}} \) for detections is seen to be larger in the Ly\( \alpha \) forest and lower beyond the Lyman limit, with a cross-over value around 880 Å. The significant differences between the mean and median IGM transmission functions for detected galaxies is a reflection of the non-Gaussian nature of the underlying \( T_{\text{IGM}} \) distribution (see Figure[3]). Regardless, the median and mean values of \( T_{\text{IGM}} \) for detected galaxies are similar and throughout the remainder of this work we focus on the mean value.

In the right column of Figure[6] we compare the histograms of \( T_{\text{IGM}} \) at 880-910 Å between all sightlines (black) and those associated with LBG-like galaxies detected above 0.025 \( \mu \)Jy (cyan). We can see that the underlying distribution is bimodal with the most probable value of \( T_{\text{IGM}} \) being \( \sim 0 \) while the distribution for detections is unimodal with the most probable value being close to the upper mode of the underlying distribution (the distribution for fainter, LAE-like samples, shown in green, is skewed towards even higher values). This is not surprising as for galaxy to be detected at LyC wavelengths the value of \( T_{\text{IGM}} \) must not be zero. It is clear that the mean value of \( T_{\text{IGM}} \) for all sightlines falls between the peaks of the underlying \( T_{\text{IGM}} \) distributions and is thus not among the most probably values for detected galaxies.

The fact that LyC detections can not occur at \( T_{\text{IGM}} = 0 \) may occasionally be overlooked in calculations of \( f_{\text{esc}} \) for LyC detected galaxies, and is key to the narrative of this work. Careful consideration of \( T_{\text{IGM}} \) variation in the estimate of \( f_{\text{esc}} \) for individual detections is common practice (e.g. Shapley et al. 2003; Inoue et al. 2011; Vanzella et al. 2016). Ultimately, the goal of this paper is to provide a clear quantification of this effect. A primary application of our results will be for estimating \( f_{\text{esc}} \) for larger samples of LyC detected galaxies that may be returned by future, extremely deep surveys (see § 5). It should also be mentioned that, when estimating upper limits in \( f_{\text{esc}} \) for samples including LyC non-detections, \( f_{\text{esc}} \) considering all simulated sightlines is appropriate (i.e. inclusion of \( T_{\text{IGM}} \) is unnecessary).

The level of \( T_{\text{bias}} \) for LyC detections will also be sensitive to the detection limits, \( F_{\text{lim}} \), of a given set of observations. We explore the dependence between \( T_{\text{bias}} \) and spectroscopic detection limits in Figure[7]. In the top panel of Figure[7] we show the value of \( f_{\text{esc}} \) for galaxies with spectroscopically detected LyC emission as a function of detection limit at redshifts in the range 2.9 \( \leq z \leq 3.9 \). For each redshift, we also show the corresponding \( T_{\text{IGM}} \) for all sightlines with a dotted line of the same colour. The detection limit assumed in Figure[7] of 0.025 \( \mu \)Jy is shown with a green, vertical, dotted line. We find that at low detection limits the dependence between \( T_{\text{IGM}} \) and \( F_{\text{lim}} \) is similar in all redshift bins apart from the expected vertical offsets due to the drop in \( T_{\text{IGM}} \) with redshift (reiterating, however, that the definition \( T_{\text{bias}} = \langle f_{\text{esc}} \rangle / \langle T_{\text{IGM}} \rangle \) will result in a clear redshift dependence). At each redshift the curve can be well fit by a power law of the form \( T_{\text{IGM}} \propto F_{\text{lim}}^{-\beta} \), however we refrain from doing so as we would consider any application of such a function as an overinterpretation of Figure[7] which results from our particular implementation for producing \( T_{\text{IGM}} \) functions as well as the various inputs of our fiducial model (e.g. here we have only shown results for LBG-like samples). For illustrative purposes we have fit a power law to the combined \( T_{\text{bias}} \) vs \( F_{\text{lim}} \) curves \( T_{\text{bias}} \propto F_{\text{lim}}^{-0.29} \). This fit is shown in the bottom panel of Figure[7] with a black dashed line. Here, the choice of a power law is ad hoc, and no specific significance is assigned to the fit parameters.

It is useful here take a step back and recall two important points: first there is significant variation in \( T_{\text{IGM}} \) for individual sightlines at any redshift (see, e.g., Figure[1] and second the fact that we allow high \( f_{\text{esc}} \) values (up to 1.0) in our fiducial model meaning \( T_{\text{bias}} \) observed in our fiducial model represents the absolute minimum \( T_{\text{bias}} \) for a given detection limit. Thus, we caution the reader from applying values of \( T_{\text{bias}} \) calculated using a similar model of \( F_{\text{lim}} \) at the same discrete \( z \) values between 2.9 and 3.9 with \( \Delta z = 0.1 \). Overall we find a very small scatter in \( T_{\text{bias}} \) with the difference between the maximum and minimum \( T_{\text{bias}} \) at fixed \( F_{\text{lim}} \) less than 0.01 at all redshifts in the range considered. Given the smooth curves seen in Figure[7] it is tempting to provide the power law fit (of the form \( T_{\text{IGM}} \propto F_{\text{lim}}^{-\beta} \), dashed lines in Figure[7], top panel) at each redshift giving an analytical function for estimating \( T_{\text{bias}} \) as a function of \( z \) and \( F_{\text{lim}} \), however we refrain from doing so as we would consider any application of such a function as an overinterpretation of Figure[7] which results from our particular implementation for producing \( T_{\text{IGM}} \) functions as well as the various inputs of our fiducial model (e.g. here we have only shown results for LBG-like samples). For illustrative purposes we have fit a power law to the combined \( T_{\text{bias}} \) vs \( F_{\text{lim}} \) curves \( T_{\text{bias}} \propto F_{\text{lim}}^{-0.29} \).
these redshift windows can be targeted using photometric
surveys. The fact that such a drop may occur in the middle of the
Lyman limit occurring at the wavelength of the drop in flux of our simulated
spectra. The fact that such a drop may occur in the middle of the
wavelength sensitivity of a given filter will result in an underestimation of the flux level of the emergent LyC radiation. This results from the fact that calculation of the reported photometric flux inherently assumes a flat flux density across the filter. Of course, the interpretation of the photometric flux can include more complex spectral behaviour, e.g. extreme [(OIII)+Hβ] emitters presented in Forrest et al. (2017).

The second drawback is that the observed wavelengths of photometric bands are fixed. This means that the ideal redshift for such surveys is at the point where the red cutoff of the filter in question falls just below the Lyman limit (thus filter dependent). LyC radiation can be detected to higher redshifts (more likely for extremely deep observations), however at high redshift the filter moves to bluer rest wavelengths where (TIGM) is significantly lower. This fact causes significant complications when making comparisons of LyC escape from photometric detections at different redshifts. We also mention briefly here that some photometric filters suffer from so-called “red leak” with a small amount of radiation at wavelengths longer than the optimal cutoff of the filter being transmitted (though this is minimized for the new CFHT u filter used in M20, Sawicki et al. 2019). As such features will be included in the filter curves used in our analysis, this effect is implicitly accounted for.

With these two drawbacks in mind we present the simulated $T_{\text{bias}}$ for LyC detected galaxies for HST F336W and CFHT u detected galaxies in Figure 8. Here we use fixed detection limits of 30.24 and 27.82 mag for F336W and CFHT u, respectively (matched to F19 and M20). (TIGM) for F336W and CFHT u detected LBG-like galaxies are shown in gold and cyan, respectively, and (TIGM) for all sightlines is shown in black. The green line indicates (TIGM) for LAE-like galaxies detected with the F336W filter, more similar to the sample of F19. The increased dispersion of the green line relative to the gold line is driven by a decrease in the total number of detected galaxies. The Lyman limit is indicated in each panel by a vertical dotted line.

Figure 8. $T_{\text{bias}}$ for photometrically detected LyC emission in the HST F336W and CFHT u filters. Results are shown at $z = 3.2$ and $z = 3.6$. F336W and CFHT u transmission curves are shown as dashed gold and cyan lines, respectively. Detection limits are fixed at 30.24 and 27.82 mag for F336W and CFHT u, respectively (matched to F19 and M20). (TIGM) for F336W and CFHT u detected LBG-like galaxies are shown in gold and cyan, respectively, and (TIGM) for all sightlines is shown in black. The green line indicates (TIGM) for LAE-like galaxies detected with the F336W filter, more similar to the sample of F19. The increased dispersion of the green line relative to the gold line is driven by a decrease in the total number of detected galaxies. The Lyman limit is indicated in each panel by a vertical dotted line.

3.1.2 Photometric Detections

While spectroscopic detection of LyC radiation from galaxies provides distinct advantages in terms of (TIGM), achieving this for large samples of galaxies is inefficient. Photometric surveys have the potential for detecting large samples of LyC emitting galaxies simultaneously. Another important benefit of photometric surveys when compared to spectroscopy is that photometry is significantly more sensitive (i.e. deeper) for the same exposure time. Furthermore, in the case of space-based LyC detections, ancillary data is not necessary to rule out the possibility of low redshift contamination. Photometric LyC surveys must be performed in well studied fields in which targeted galaxies already have accurate photometric redshift estimates (e.g. ZFOURGE fields [Straatman et al. 2016] or, ideally, secure spectroscopic redshifts (e.g. 3DHST, DEIMOS10K, VANDELS, MUSE-wide, [Momcheva et al. 2016] Hasinger et al. 2018) Pentericci et al. 2018 [Irrutia et al. 2019]. In fields such as these, specific redshift windows can be targeted using photometric bands probing LyC emission such as HST F336W at $z \sim 3.0$ or CFHT u at $z \sim 3.4$ (e.g. F19, M20). There are two key drawbacks in the case of photometric LyC surveys when compared to spectroscopy, however (see also S18, Section 7.2).

The first drawback in photometric searches for LyC emission when compared to spectroscopic studies is that the ionizing radiation may only be observable in a narrow wavelength range just short of 912 Å as shown in Figure 8. This is due to intervening, high HI column density systems at redshifts corresponding to the Lyman limit occurring at the wavelength of the drop in flux of our simulated spectra. The fact that such a drop may occur in the middle of the wavelength sensitivity of a given filter will result in an underestimation of the flux level of the emergent LyC radiation. This results from the fact that calculation of the reported photometric flux in...
increased sensitivity to the stochasticity of our IGM transmission functions. The dashed lines in Figure 9 also demonstrate why we find so few LyC detected LAEs for our mock spectroscopic and CFHT $u$ observations given the depth of these two comparisons are fixed at $\sim 27.9$ and 27.82 mag, respectively.

3.1.3 Fiducial Model Summary

The results of our fiducial model for fixed detection limits of 0.025 $\mu$Jy ($\sim 27.9$ mag), 30.24 mag, and 27.82 mag for spectroscopy, F336W, and CFHT $u$, respectively, are summarised in Figure 10 for mock observations of galaxies with 1500 Å flux distributions characteristic of LBGs (F336W results for fainter, LAE-like galaxies are also shown with dotted lines). As described in Sections 3.1.1 and 3.1.2, spectroscopic detections at this depth (targeting a fixed rest wavelength window at $880 < \lambda_{\text{rest}} < 910$ Å) experience a roughly constant $T_{\text{bias}}$ of $-0.15-0.17$ ($-0.32$ for fainter, LAE-like samples). We find a slight redshift dependence on $T_{\text{bias}}$, which increases from 0.157 at $z = 2.9$ to 0.173 at $z = 3.7$ then decreases slightly to 0.169 at $z = 3.9$. This change in $T_{\text{bias}}$ of less than 2% is significantly smaller than the variance seen at any given redshift and is driven entirely by our cosmological dimming (see Equation 6). Thus, we conclude that $T_{\text{bias}}$ is effectively constant at $3.0 < z < 3.9$ for our chosen definition.

The fact that $T_{\text{bias}}$ is found to be constant with redshift is somewhat counterintuitive. Instead, one may expect a monotonic increase in $T_{\text{bias}}$ with redshift due to the fixed detection limit and linear decrease in $\langle T_{\text{IGM}} \rangle$. For our additive definition of $T_{\text{bias}}$, the constant $T_{\text{bias}}$ observed can be explained by a decrease in detection rate with redshift where only the brightest galaxies contribute to $T_{\text{bias}}$ at the high $z$ end. This is illustrated in Figure 10 with the detection percentages for spectroscopy at each redshift indicated in black.

Considerig photometric detections, $T_{\text{bias}}$ is seen to increase while the Lyman limit passes through the filter in question. At redshifts where a given filter has passed fully blueward of the Lyman limit, the level of $T_{\text{bias}}$ is seen to level off (within errors) at a value dependent on the photometric depth. For our fiducial depths, this plateau level is $\sim 0.11-0.14$ and $\sim 0.22-0.31$ for the F336W (magnitude limit = 30.24) and CFHT $u$ filters (magnitude limit = 27.82), respectively. In the case of LAE-like 1500 Å flux distributions, we show results only for F336W as this comparison has significantly deeper flux limits compared with spectroscopy and CFHT $u$ (where detections of LAE-like samples are vanishingly rare). In the case of LAEs, we find that $T_{\text{bias}}$ is roughly 0.1 higher than for LBGs at fixed redshift, with values in the range $\sim 0.21-0.24$ across the redshift range sampled.

We also observe a slight dip in $T_{\text{bias}}$ for photometric detections at the highest redshifts in the bottom panel of Figure 10. Unlike spectroscopic detections, by $z \sim 3.8$ our photometric filters are probing very blue $\lambda_{\text{rest}}$ where $\langle T_{\text{IGM}} \rangle$ is near zero. Furthermore, as seen in Figure 2 the $T_{\text{IGM}}$ distribution at these wavelengths is a skewed, unimodal distribution peaked at $T_{\text{IGM}} = 0$. This means that the probability of finding a sightline with $T_{\text{IGM}}$ much higher than zero is very low. This could explain why $T_{\text{bias}}$ for photometry dips at high $z$, as even those small number of detected galaxies will be found in sightlines approaching zero transmission at wavelengths probed by a given filter. This means that the level of $T_{\text{bias}}$ seen at lower redshifts simply cannot be maintained given the underlying...
The IGM Transmission of LyC Detections

The IGM distribution for the wavelengths probed. At higher redshifts the $T_{\text{IGM}}$ distribution becomes so strongly peaked at $T_{\text{IGM}} = 0.0$ that no detections are expected, thus we do not expect the results presented here for $2.9 < z < 3.9$ to be generalizable towards higher redshifts. This is not necessarily the case for spectroscopic detections as the $T_{\text{IGM}}$ distribution at $880 < \lambda_{\text{rest}} < 910$ Å remains bimodal even at high redshift, thus no obvious dip in $T_{\text{bias}}$ is seen. Regardless, in all cases $\langle T_{\text{IGM}} \rangle$ is decreasing with redshift, thus detections become rarer. This manifests as a decreasing 68 percentile range for $T_{\text{bias}}$, a reflection of the drop in the numbers of detected galaxies with redshift.

Finally, as mentioned at the start of Section 3.1, the definition $T_{\text{bias}} = \langle T_{\text{det}} \rangle / \langle T_{\text{IGM}} \rangle$ is equally valid to the definition adopted in this work. Under this alternative definition, a very clear trend between $T_{\text{bias}}$ and redshift is apparent increasing from ~1.3 to ~1.8 for spectroscopic observations and from ~3 to ~35 for F336W observations for LAE samples. We reiterate that, although a fractional definition may be more physical (in the sense that it relates directly to a ratio of HI column densities), the redshift evolution of $T_{\text{bias}}$ in this case reflects primarily the fact that $\langle T_{\text{IGM}} \rangle$ moves increasingly close to zero with redshift while the actual difference in the mean IGM transmission between detections and all sightlines is roughly constant, as our chosen definition illustrates. Thus, our definition provides a simplified correction when calculating $f_{\text{esc}}$ for LyC detected samples from an observational point of view.

3.2 An Alternative $f_{\text{esc}}$ Distribution

It is expected that if LyC emission is detected from a given galaxy, it must have a high $f_{\text{esc}}$ and/or a high $T_{\text{IGM}}$. From current observations of LyC emitters (particularly considering the large number of non-detections), it seems that $f_{\text{esc}}$ values, i.e. 0.0-0.2, are most common (e.g. Boutsia et al. 2011; Grazian et al. 2016; Smith et al. 2018). The results presented for our fiducial model in Section 3.1, however, allow for $f_{\text{esc}}$ values from 0.0 to 1.0 with no preference. This means that a large number of detections from our fiducial model exhibit a large $f_{\text{esc}}$ and are detected in sightlines with relatively low $T_{\text{IGM}}$. If we instead choose an underlying $f_{\text{esc}}$ distribution skewed towards low $f_{\text{esc}}$, we might expect that the average $T_{\text{IGM}}$ for detections will increase, thus increasing $T_{\text{bias}}$.

In this Section, we explore how altering the PDF of selected $f_{\text{esc}}$ values affects the level of $T_{\text{bias}}$ and the distributions of $f_{\text{esc}}$ for LyC detections. For comparison, the fiducial model can be treated as a flat PDF between 0 and 1. Here we test an alternative $f_{\text{esc}}$ PDF model designed to give more weight to lower $f_{\text{esc}}$ values. In this cases we choose an exponentially declining $f_{\text{esc}}$ PDF of the form:

$$PDF(f_{\text{esc}}) \propto e^{-f_{\text{esc}}/\eta}$$

(8)

where $\eta$ represents an exponential cut off in $f_{\text{esc}}$. Here we test the value $\eta = 0.50$ (see Figure 3) motivated by LyC detection rates from S18 (see Section 2.3). For brevity our fiducial model will be described as “flat” and our alternative model will be referred to as $\eta = 0.50$. As with our fiducial model, for our $\eta = 0.50$ model we recreate 100 mock spectra for each of our 10,000 IGM transmission functions at each discrete redshift value as described in Section 2.3.

We show example $T_{\text{IGM}}$ curves at $z = 3.1$ for detected LBG-like galaxies in each of our two models in Figure 11. Though not shown here, results for LAE-like galaxies are qualitatively similar. Here we see that the flat $f_{\text{esc}}$ PDF exhibits a lower $T_{\text{bias}}$ than the $\eta = 0.50$ as expected. The increases in $T_{\text{bias}}$ for both spectroscopic and photometric detections are found to be only 0.01 and 0.02, respectively. These increases in $T_{\text{bias}}$ are essentially negligible considering the spread in $\langle T_{\text{IGM}} \rangle$ for LyC detections seen in Figure 10. Thus, in the case of our $\eta = 0.5$ model, we find no significant difference in $T_{\text{bias}}$ when compared to the fiducial, flat $f_{\text{esc}}$ PDF and note that this behaviour is the same in all redshift bins. In cases where the underlying $f_{\text{esc}}$ is more strongly skewed towards $f_{\text{esc}} = 0$ (i.e. smaller values of $\eta$), the difference in $T_{\text{bias}}$ when compared to a flat PDF is certain to increase. Such a low $\eta$ model (or any other similarly skewed $f_{\text{esc}}$ PDF) may be appropriate for galaxy samples with selection biases different from the LBG and LAE samples considered here if $f_{\text{esc}}$ does indeed vary with galaxy properties (see Section 4.3 for more discussion).

The fact that $T_{\text{bias}}$ for our $\eta = 0.5$ model is only negligibly larger than our flat $f_{\text{esc}}$ PDF does not mean the two models are interchangeable in regards to estimates of $f_{\text{esc}}$ from observed samples. To illustrate this, we show in Figure 12 the histograms of $f_{\text{esc}}$ for detections only vs all trials at $z = 3.1$ for spectroscopy (left) and F336W (right). Filled histograms show the underlying $f_{\text{esc}}$ distributions and open histograms show the $f_{\text{esc}}$ distribution for LyC detections. We find that the $f_{\text{esc}}$ distributions of LyC detections (i.e. the posterior) for both observational methods is skewed towards $f_{\text{esc}}$
Figure 12. Histograms of $f_{\text{esc}}$ for our two $f_{\text{esc}}$ PDF models: flat in the top row and $\eta = 0.5$ on the bottom. The left column shows results for spectroscopy and the right for F336W. In each panel the underlying $f_{\text{esc}}$ distribution is shown with a filled histogram, the $f_{\text{esc}}$ distribution of detections with an open histogram, and the mean value for detections is shown with a vertical dotted line and indicated in the top left of each panel. Note that each histogram has been normalised by the maximum value for ease of comparison.

= 1.0, inconsistent with the low values typically seen in observations. The posterior for the $\eta = 0.5$ model, on the other hand peaks at lower values, more consistent with estimates in the literature. We show the mean values for posterior distributions in each panel with a vertical dotted line. When assuming an $\eta = 0.5$ model, the inferred average $f_{\text{esc}}$ value is lower by 0.07 and 0.12 for spectroscopy and F336W detections, respectively. Thus, although $T_{\text{bias}}$ is roughly the same between the two $f_{\text{esc}}$ PDF models, the differences when considering the inferred $f_{\text{esc}}$ for galaxy samples is significant.

We note that the posterior distribution for the $\eta = 0.5$ model for a given detection method is equivalent to the posterior for the flat $f_{\text{esc}}$ PDF model multiplied by the input $\eta = 0.5$ distribution (the prior) in line with the framework of Bayesian statistics. This is true in general, thus one can simply determine the posterior distribution for any arbitrarily defined $f_{\text{esc}}$ PDF once the posterior for a flat distribution is determined for a given observational method and detection limit without the need to run a separate analysis. We stress again that the actual distribution of $f_{\text{esc}}$ is essentially unknown, however we discuss possibilities for placing some constraints on this in Sections 3.3 and 4.4.

3.3 Dependence on SED Variations

In this Section we briefly explore the effects that varying the SED shape will have on our estimates of $T_{\text{bias}}$ presented in Sections 3.1 and 3.2. In regards to detecting LyC from a given galaxy above a specified limit, the key difference resulting from a change in SED shape will be a change in the flux ratio of the LyC and UV ($\lambda_{\text{rest}} \sim 1500$ Å) portions of the observed spectrum. $(F_{900}/F_{1500})_{\text{obs}}$, at a fixed $T_{\text{IGM}}$. The factor that will affect $(F_{900}/F_{1500})_{\text{obs}}$ (in addition to $T_{\text{IGM}}$) considered here is variation in the intrinsic ratio of LyC and UV emission, $(L_{900}/L_{1500})_{\text{int}}$.

To test the effect of altering $(L_{900}/L_{1500})_{\text{int}}$ on our results we rerun the analysis described in Section 2.3 for each age of our exponentially declining BPASS v2.1 models (with $\epsilon$-folding timescale of 0.1 Gyr) in the range $6.0 < \log(\text{age}) < 9.0$ in steps of $\Delta \log(\text{age}) = 0.1$. The models produced exhibit $(L_{900}/L_{1500})_{\text{int}}$ in the range $\sim 0.07$–$0.77$, with corresponding values of $\xi_{\text{ion}}$ from $\sim 25.4$–$26.0$. For each aged model we again create 100 mock spectra for each of the 10,000 IGM transmission functions produced at each redshift ($2.9 < z < 3.9, \Delta z = 0.1$) with 1500 Å fluxes sampled from an LBG-like distribution. We then repeat our measurements of LyC flux as in previous sections and adopt the flux limits of our fiducial model: $F_{\text{lim}}$ (spectroscopy) = 0.025 mJy (~27.9 mag) and $m_{\text{lim}}$ (F336W) = 30.24. The CFHT u comparison is not considered here as the relatively shallow nature of these observations results in prohibitively few detections at low $(L_{900}/L_{1500})_{\text{int}}$. For a similar reason, we also do not consider LAE-like samples in this section.

We show the resulting $(L_{900}/L_{1500})_{\text{int}}$ versus $T_{\text{bias}}$ for spectroscopic, LBG-like LyC detections in the left panel of Figure 13. Similar to the results for our test on detection limits we find only slight variation in $T_{\text{bias}}$ with redshift with a total spread in values of $\sim 0.03$ for all redshifts at a fixed $(L_{900}/L_{1500})_{\text{int}}$ above $(L_{900}/L_{1500})_{\text{int}}$ = 0.15 (again, a fractional definition of $T_{\text{bias}}$ will result in significant redshift variation). For reference, we show the location of the fiducial model presented in Section 3.1.1 with the dotted green line and shaded regions. Slight differences can be attributed to stochasticity as the analysis here represents an independent sample of 1500 Å fluxes and $f_{\text{esc}}$ values at the same $(L_{900}/L_{1500})_{\text{int}}$ value. Regardless, the results of Figure 13 are consistent with those of 3.1.1 within errors.

Results for F336W detections are shown similarly in the right panel of Figure 13. We show results at redshifts where F336W partially probes non-ionizing photons with dashed lines (i.e. $z < 3.2$). Qualitatively the curves are similar to those in the left panel, with the difference in $T_{\text{bias}}$ again attributed to the increased depth of the F336W observational comparison.

Finally, we note that none of the models presented to this point have considered the effects of dust attenuation on the observed LyC flux from mock galaxies. The effect that dust will have on LyC will vary considerably between $(f_{\text{esc}}$ and $T_{\text{IGM}}$. Given the low attenuation for LyC detections (e.g. S18), we ignore the effects of dust simply noting that detections should be biased towards galaxies with low dust attenuation (or even none in the case of LAEs, e.g. Fletcher et al. 2019, Nakajima et al. 2020).

4 DISCUSSION

4.1 Correlation between $T_{\text{IGM}}$(LyC) and $T_{\text{IGM}}$(Ly\u03ba)

One major difficulty in accurately measuring $f_{\text{esc}}$ from high redshift galaxies is the unknown value of $T_{\text{IGM}}$. So far, there is no clear observational indicator of $T_{\text{IGM}}$(LyC), which has necessitated statistical methods such as those explored in this paper. In the work of Inoue & Iwata (2008), however, it was argued that the $T_{\text{IGM}}$ at Ly$\alpha$ wavelengths may correlate with $T_{\text{IGM}}$(LyC) (their Section 4.4, Figure 10). This claim is in direct contrast with previous results of Shapley et al. (2006) who found no such correlation at $z = 3.06$. Inoue & Iwata (2008) suggest that the lack of correlation seen in
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Figure 13. $T_{\text{bias}}$ as a function of intrinsic ratio of LyC (at 900Å) to UV (at 1500Å) luminosities for spectroscopy (left) and photometry (right). Solid lines show results in each redshift bin as indicated in each legend while dotted lines in the right panel indicate redshifts at which the F336W filter contains contamination from Ly$\alpha$ forest photons as it has not passed fully into the LyC portion of the spectrum. The location corresponding to intrinsic ratios presented in Sections 3.1 and 3.2 are indicated with dotted green lines and shaded regions. The top axis of both panels indicates $\zeta_{\text{ion}}$ for the BPASSv2.1 model at a given ($L_{900}/L_{1500}$)$_{\text{int}}$.

Shapley et al. (2006) was due to those authors exploring $T_{\text{IGM}}$ at only one redshift. Here we test for a correlation between $T_{\text{IGM}}(\text{LyC})$ and $T_{\text{IGM}}(\text{Ly} \alpha)$ for our simulated IGM transmission functions, noting that our simulations differ from those of Shapley et al. (2006) and Inoue & Iwata (2008) in that we include a CGM component to our HI column density distributions following the work of S18 and Rudie et al. (2013).

To perform this test, we assess all one million IGM sightlines we have produced in Section 2.1 measuring $T_{\text{IGM}}$ for LyC at 880 < $\lambda_{\text{rest}}$ < 910 Å and for Ly$\alpha$ at 1050 < $\lambda_{\text{rest}}$ < 1170 Å following Shapley et al. (2006) and Inoue & Iwata (2008). We note, however, that the LyC and Ly$\alpha$ wavelength ranges used in these works are not probing the same redshift range. Thus, we also measure an alternative Ly$\alpha$ wavelength range 1173 < $\lambda_{\text{rest}}$ < 1213 Å, matched to the redshift of LyC in the specified range. In each redshift bin, we measure the spearman rank-order correlation coefficient between $T_{\text{IGM}}$(LyC) and $T_{\text{IGM}}$(Ly$\alpha$) in both wavelength ranges and also the correlation coefficient of the combined data from all redshift bins.

Figure 14 shows $T_{\text{IGM}}$(LyC) vs $T_{\text{IGM}}$(Ly$\alpha$) for all one million sightlines colored by their redshift. Overall there appears to be a correlation between the two values (albeit with large scatter), however at any individual redshift such a correlation is less apparent. For $T_{\text{IGM}}$(Ly$\alpha$) at 1050-1170 Å we measure correlation coefficients at individual redshifts finding values in the range 0.05-0.08 indicating no correlation with $T_{\text{IGM}}$(LyC) at fixed redshift consistent with Shapley et al. (2006). Considering all redshift bins together we find a drastic increase in the correlation coefficient to 0.34. This is still lower than the correlation of 0.86 quoted by Inoue & Iwata (2008), however, in this work the authors tested a much wider redshift range from 0.2 to 6.0. Our results combined with those of Inoue & Iwata (2008) suggest that any apparent correlation between $T_{\text{IGM}}$ at LyC and Ly$\alpha$ wavelengths is driven only by the fact that both values correlate similarly with redshift (e.g. Figure 1). For any individual galaxy (or sample) at a given redshift, however, $T_{\text{IGM}}$(Ly$\alpha$) provides no useful prediction for $T_{\text{IGM}}$(LyC). Indeed, this is apparent from the contours shown in Inoue & Iwata (2008) Figure 10.

As we have pointed out, however, the Ly$\alpha$ wavelength range considered in Shapley et al. (2006) and Inoue & Iwata (2008) is not well matched to the LyC wavelength range they considered. If we instead use our alternative Ly$\alpha$ range, 1173-1213 Å, we find a significant increase in the correlation coefficient at fixed redshift range to 0.32-0.37. Combining the values for all bins we find a modest increase to 0.45. Thus, we find a weak correlation between...
Comparison of $f_{\text{esc}}$ computed via Equation 9 (gold) and Equation 10 (cyan) compared to the true $f_{\text{esc}}$ at $z = 3.0$ (left) and $z = 3.1$ (right). Here we perform 5000 trials in which 15 LyC detected galaxies are selected at random (comparable to the number detected in S18) from among the one million mock galaxies produced at each redshift as described in Section 2.3. We calculate the average $\langle F_{\nu}/F_{\nu,\text{obs}} \rangle$ among the 15 galaxies and use this value to estimate $f_{\text{esc}}$ using Equations 9 and 10. The 1-to-1 relation is shown with the thick dotted line while the thin dotted lines represent the average 68 percentile spread of the 15 galaxies selected in individual trials (more description in text), which we find to decrease roughly linearly with increasing the mean $f_{\text{esc}}$ for a given trial.

$T_{\text{IGM}}$ for LyC and Lyα at fixed redshift where the wavelength ranges for these two are well matched. We note that a direct comparison to the results of House & Iwata (2008) and Shapley et al. (2006) may be slightly tenuous as the IGM transmission curves produced there do not include a CGM component while our models do. Indeed, this may be the reason that we find such a large increase in the correlation coefficient at fixed redshift when the wavelength ranges of LyC and Lyα are properly matched. Given the large scatter and the fact that $T_{\text{IGM}}$(LyC) is found to be 0 for a range of $T_{\text{IGM}}$(Lyα) at fixed redshift, however, we would be hesitant to try and estimate one from the other regardless of the apparent weak correlation.

4.2 Effects of $T_{\text{bias}}$ on $f_{\text{esc}}$ Estimates for Samples

The analysis presented in Section 4.1 was designed to predict the average bias for a sample of LyC detected galaxies, which in turn can be used to estimate the average $f_{\text{esc}}$ of the sample (e.g. S18, F19). Thus, it may not be appropriate to blindly apply values measured here to individual galaxies. Here we test the discrepancy between the average value of $f_{\text{esc}}$ for a sample of LyC detections estimated with and without including $T_{\text{bias}}$ when compared to the true average $f_{\text{esc}}$. This should be seen as a highly simplified test as all mock galaxies represent dust-free BPASSv2.1 models with a fixed $(L_{900}/L_{1500})_{\text{int}}$ of 0.18 ($\log_{10}(\xi_{\text{ion}}/\text{Hz erg}^{-1}) = 26.51$). Real galaxy samples are likely to exhibit a range of $(L_{900}/L_{1500})_{\text{int}}$, and will thus decrease the accuracy of $f_{\text{esc}}$ estimates when compared to this test.

The typical method of estimating $f_{\text{esc}}$ is to employ an equation of the form (or similar to):

$$f_{\text{esc}} = \frac{(F_{\nu}/F_{\nu,\text{obs}})_{\text{int}}}{(L_{900}/L_{1500})_{\text{int}}} \times \frac{1}{T_{\text{IGM}}}$$

noting that the effects of dust attenuation are ignored here. In order to estimate $f_{\text{esc}}$ for a given level of $T_{\text{bias}}$, Equation 9 must be modified in the following way:

$$f_{\text{esc}} = \frac{(F_{\nu}/F_{\nu,\text{obs}})_{\text{int}}}{(L_{900}/L_{1500})_{\text{int}}} \times \frac{1}{T_{\text{IGM}} + T_{\text{bias}}}$$

Our test of the recovery of $\langle f_{\text{esc}} \rangle$ for a sample of spectroscopically LyC detected galaxies is performed on the mock observations described in Section 2.3. We first select those mock galaxies with output $880 < A_{\text{test}} < 910$ Å fluxes above the detection limit of 0.025 $\mu$Jy. We then perform 5000 trials in which we randomly select 15 mock LyC detections (matched to the number of detections in S18) and measure $\langle (F_{\nu}/F_{\nu,\text{obs}}) \rangle$ of this subsample. For each trial we calculate the average $f_{\text{esc}}$ using Equations 9 and 10 and compare this with the true $f_{\text{esc}}$ for the 15 selected detections.

The results of this test at $z = 3.0$ and $z = 3.1$ for our $\eta = 0.5$ $f_{\text{esc}}$ PDF model are shown in Figure 15, though we find similar results for the flat $f_{\text{esc}}$ PDF of our fiducial model. Here we plot the true $f_{\text{esc}}$ versus two estimated values. Gold and cyan contours show the distribution for $f_{\text{esc}}$ estimated using Equations 9 and 10 respectively. The thick dotted green line shows the 1-to-1 relation. The thin green lines are meant to be representative of the average 68 percentile spread of the 15 galaxies from any individual trial. To produce these lines we measure the 68 percentile lower and upper bounds and the average values of $f_{\text{esc}}$ for the 15 galaxies from each of the 5000 trials. We find that the upper and lower bounds for a given trial decrease roughly linearly with increasing mean $f_{\text{esc}}$ (albeit with significant scatter), thus we fit each bound with a straight line as a function of mean $f_{\text{esc}}$. In this way, we are attempting to illustrate, roughly, the expected spread in $f_{\text{esc}}$ values for a random selection of 15 LyC detected galaxies having a given mean $f_{\text{esc}}$ value.

At both redshifts there is good agreement between $f_{\text{esc}}$ and the true value, while failing to account for $T_{\text{bias}}$ results in an overestimate of the average $f_{\text{esc}}$. The level of overestimation is lower at $z = 3.0$ due to the fact that $f_{\text{esc}}$ in Equations 9 and 10 depends on the reciprocal of $T_{\text{IGM}}$, which is decreasing with redshift towards 0. At $z = 3.1$, only ~1.4% of the estimated $f_{\text{esc}}$ values calculated using Equation 9 fall within the range of typical “true” $f_{\text{esc}}$ values for our detected sample (noting this percentage is stochastic). At higher redshifts this falls to 0%. Considering $f_{\text{esc}}$, we find that, typically, less than 1% of trials fall outside of the rough confidence intervals presented in Figure 15. This test illustrates that not accounting for $T_{\text{bias}}$ when estimating the stacked $f_{\text{esc}}$ for detected galaxies can result in a significant overestimate of the true value.

Of course, as has been repeated throughout this work, the absolute differences between $f_{\text{esc}}$ and $f_{\text{esc}}$ (as well as the fractional decrease) will have some dependence on the details of our method for producing IGM transmission curves (e.g. $N_{\text{HI}}$ distributions), the assumed value(s) of $(L_{900}/L_{1500})_{\text{int}}$, the assumed $f_{\text{esc}}$ PDF, the input distribution of 1500 Å fluxes, etc. In addition, the inclusion of dust, choice of dust curve, and any assumed dependence between E(B-V) and $f_{\text{esc}}$ will further affect these results. Although not shown, we also performed the test presented here with dust attenuation included following the method outlined in Section 4.1 (where E(B-V) values are sampled from a distribution characterised by the observed values from S18) and find similar results with a similar level of scatter. This of course assumes that both the average E(B-V) for detected galaxies as well as the exact form of the attenuation curve is precisely known. Inevitably, these values will be highly uncertain for real observations resulting in a higher level of scatter. Providing more realistic tests of the associated effects on our stacking, while possible, would be highly model dependent, thus not particularly useful.

The fact that $T_{\text{IGM}}$ for LyC detected galaxies is expected to be larger than $(T_{\text{IGM}})$ at a given redshift will be true regardless of the exact implementations, however. Thus, the purpose of the illustration presented here is simply to highlight the fact that the assumption that $(T_{\text{IGM}})$ is representative of IGM sightlines towards

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LyC detected galaxies will result in an overestimation of $f_{\text{esc}}$. Given that $t_{\text{bias}}$ increases with decreasing observational depth, the overestimation of $f_{\text{esc}}$ will be the higher for shallower LyC surveys.

### 4.3 Survey Detection Rate vs $f_{\text{esc}}$ PDF

As we have shown in Section 3.2, the value of ($f_{\text{esc}}$) inferred for stacked samples of LyC detections will depend on the PDF assumed for $f_{\text{esc}}$. It has been repeated throughout this work that, observationally, there appears to be a preference for low (or zero) $f_{\text{esc}}$ from high redshift galaxies (e.g. Japelj et al. 2017; Smith et al. 2018; Bian & Fan 2020). This creates a chain of circular reasoning, however, as accurate measurements of $f_{\text{esc}}$ thus requires knowledge of the PDF of $f_{\text{esc}}$, which seemingly requires accurate measurements of $f_{\text{esc}}$ to determine. The way forward is to determine an observational metric that can help to determine the PDF $f_{\text{esc}}$ that is independent of the individual values of $f_{\text{esc}}$.

In this Section we propose that the detection rates of LyC from dedicated surveys can be used to probe the parameters of a given $f_{\text{esc}}$ PDF. We construct two mock versions of the surveys of S18, F19, and M20, one with a flat $f_{\text{esc}}$ PDF and one with an exponentially declining $f_{\text{esc}}$ PDF. In the latter case we tune the value of $\eta$ (see Equation 8) to match the observed detection rate of a given survey (more description to follow). In each case, we again use the same fixed input BPASSv2.1 SED model as our fiducial model with $(L_{900}/L_{1500})_{\text{int}} = 0.18$. In all cases the input 1500 Å fluxes are sampled from a distribution matched to the fluxes reported by each of those surveys. Thus, in this case, the F19 sample, which is made up of LAEs, has a characteristic 1500 Å flux that is lower than that of the LBG sample of S18 at the same redshift resulting in a lower relative LyC flux (see Figure 4). This is important as the selection method of a given sample strongly influences the distribution of galaxy properties included (e.g. typical 1500 Å flux, $(L_{900}/L_{1500})_{\text{int}}$, among others), which ultimately determine the output LyC fluxes, and thus the detectability of a given galaxy. Therefore, the toy model presented here is primarily for illustrative purposes.

The set of inputs described above is combined with our $T_{\text{IGM}}$ sightlines to produce an output sample of LyC fluxes. In the case of S18 and F19 we simply use the $T_{\text{IGM}}$ functions already produced, noting that this requires all of our mock galaxies to be at discrete redshifts with $\Delta z = 0.1$. For S18 we match the observed redshift distribution in each bin from that work and for F19 all galaxies are simulated at $z = 3.1$. As M20 explores significantly higher redshifts we simply randomly sample values across the full redshift range (matched to the observed distribution from that work) and create new $T_{\text{IGM}}$ functions each time. For each survey we produce 10,000 mock observations. We then randomly draw subsamples from these mock observations with sizes matched to the observed sample sizes in each paper and measure the detection rates of LyC for each subsample with detection rates of 0.025 mJy ($\sim$27.9 mag), 30.24 mag, and 72.82 mag for S18, F19, and M20, respectively. We perform this test with a few different $\eta$ values for the exponential $f_{\text{esc}}$ PDF, and coarsely tune the model such that the average detection rate falls within the range quoted for each survey.

The results of our test for KLCS and LACES are shown in Figure 16. In each panel the detection rate distribution for the tuned, exponentially declining model is shown in cyan (with the tuned $\eta$ value in the legend) and the distribution for the flat model is shown in gold. For LACES the observed detection rate range is defined by either only considering their “gold” sample (low) or considering the “gold” plus “silver” samples (high) and for KLCS we take their detection rate of 15/124 ~ 0.12. In the case of KLCS, the flat $f_{\text{esc}}$ PDF model is seen to predict a detection rate that is too large to reproduce the survey in question. While the $\eta = 0.5$ model is well matched to the observed detection rate. In the case of LACES, however, though the average detection rate for the flat model is close to the upper limit for the detection rate of that survey, it is difficult to rule out a flat PDF. The coarsely matched exponential model requires a relatively high value of $\eta = 0.75$. From Figure 12 we expect that the inferred $f_{\text{esc}}$ values from this model will not differ significantly from a flat distribution. In the case of our unconnected M20 test, we were unable to reproduce the high detection rate reported in the paper, which falls in the range 0.02-0.11 (1-5 out of 44) depending on the reliability cut for the LyC emitting galaxy candidates from that work. For our mocks we find an overall detection rate from the flat $f_{\text{esc}}$ PDF (which will give the highest detection rate) of 0.005, thus only a small fraction of random selections of 44 galaxies will even contain one detection.

Taken together, this toy model test for our three comparison samples provides strong evidence that the underlying $f_{\text{esc}}$ PDFs will be sensitive to the selection bias of the galaxy sample in question. In the case of KLCS and LACES, the former probes the bright end of the UV luminosity function characterised by LBGs while the latter significantly fainter LAEs. The fact that the detection rate of KLCS requires the $f_{\text{esc}}$ PDF to be skewed towards 0 while LACES is not inconsistent with a flat $f_{\text{esc}}$ PDF points towards a scenario in which faint galaxies, on average, have a $f_{\text{esc}}$ PDF less biased towards 0 (similar to the results of Finkelstein et al. 2019). Our inability to reproduce the high detection rate of M20, even employing a flat $f_{\text{esc}}$ PDF, suggests that this sample may be biased towards high values of $f_{\text{esc}}$ (though we have not tested such a model here). Interestingly, the goal of M20 was to provide a methodology for preferentially selecting high $f_{\text{esc}}$ galaxies, consistent with the toy model presented here. The key point highlighted here is that we have shown the calculation of $f_{\text{esc}}$ to be sensitive to the underlying PDF (e.g. Figure 12), which is in turn appears to depend on sample selection. Thus,
a consideration of the $f_{\text{esc}}$ PDF should be considered in particular when comparing inferred $f_{\text{esc}}$ values between disparate samples (e.g. LAEs vs LGBs).

We reiterate that the exponentially declining $f_{\text{esc}}$ PDF favoured here is simply an ad-hoc solution chosen for its bias towards low $f_{\text{esc}}$ values and a preference for $f_{\text{esc}} = 0$. This selection was motivated by the low detection rate of such emission and the, generally, low estimates of the average $f_{\text{esc}}$ for large galaxy samples (e.g. Yanzella et al. 2010; Grazian et al. 2016; Smith et al. 2018). The true functional form of the PDF of $f_{\text{esc}}$ is very likely more complex and may include dependencies on galaxy properties such as, e.g., stellar mass (Finkelstein et al. 2019; Naidu et al. 2020). Further clarification of this issue will require larger samples of LyC detections at $z > 3$ which would be greatly aided by more sensitive instrumentation at $\lambda$-band wavelengths. It is also likely that inputs from high-resolution, hydrodynamics simulations of high redshift galaxies that include full radiative transfer can help greatly with the interpretation of detections (and non-detections), though running such simulations is computationally expensive. Regardless, we show here evidence that the most likely PDF for $f_{\text{esc}}$ for LGB like galaxies favours a model with a reasonable bias towards low $f_{\text{esc}}$.

### 4.4 Dust Attenuation

To this point, we have avoided one key topic in the study of optical and UV radiation from star-forming galaxies: dust attenuation. In general, the level of attenuation at fixed E(B-V) increases with decreasing $\lambda_{\text{test}}$ such that UV wavelengths experience the highest levels of attenuation (i.e. lowest transmission) irrespective of the functional form of the assumed attenuation curve (e.g. Gordon & Clayton 1998; Calzetti et al. 2000; Reddy et al. 2016 etc). This statement, of course, assumes that extending the chosen attenuation curve to short wavelengths ($\leq 1500$ Å) is reasonable. We acknowledge that Kruit et al. 2002 have investigated dust attenuation at 900 Å in a handful of local star-forming galaxies and Weingartner & Draine 2001 have explored theoretical models of dust attenuation in a similar regime (based on the Magellanic clouds), however there applicability to high redshift galaxies is also uncertain. Regardless, the expected high level of attenuation at LyC wavelengths may lead one to expect that galaxies with a high enough LyC flux to be detected in current surveys should be biased towards low attenuation. Indeed, LyC detections from KLCS all have $(E(B-V)) = 0.045$ (and 0.129 for full LBG parent sample, S18), and those of LACES all exhibit negligible attenuation $(E(B-V)) < 0.07$, $(E(B-V)) > 0.01-0.03$, F19, Nakajima et al. 2020.

Regardless, to expect all LyC emitting galaxies to contain negligible amounts of dust is likely too simplistic. Thus, some consideration of the effects of dust in the interpretive framework for $f_{\text{esc}}$ calculations outlined in this paper is warranted. We advocate a methodology similar to that outlined in F19. First, a determination of the stellar E(B-V) value should be computed based on the available photometric data for a given sample of objects. This can be achieved through full SED fitting or through calibrations such as those based on the UV slope, $\beta$ (e.g. Meurer et al. 1999). In the case of SED fitting, we advocate a method only incorporating bands redward of Ly$\alpha$, as shorter wavelengths are strongly affected by IGM attenuation (e.g. effects not intrinsic to the galaxy) that should be treated independently to avoid added degeneracy in the SED model. The effects of including or omitting flux with wavelengths shortward of Ly$\alpha$ during the SED fitting process will be tested in future work (Bassett et al., in prep). The computed E(B-V) is combined with a choice of dust attenuation curve, $k(\lambda)$, to correct the observed 1500 Å flux to the “intrinsic”, dust-free, value. Finally, the chosen input SED template for a given sample (either computed through SED fitting or simply selecting a template with a reasonable value of (L$_{900}$/L$_{1500}$)$_{\text{int}}$) is scaled to match the corrected 1500 Å flux. Through this process, the intrinsic LyC flux can be determined, noting this value will be dependent on the selection of the intrinsic SED.

From the intrinsic LyC flux calculated in this manner, one can then determine the expected value of $f_{\text{esc}}$ by comparing with the observed value. In this way, any attenuation of LyC flux due to dust is incorporated into the definition of $f_{\text{esc}}$, as pointed out by F19 (i.e. there is no distinction between dust attenuation and absorption of LyC by neutral hydrogen). We also follow the methodology of F19 who allow $f_{\text{esc}}$ for a given value of $E(B-V)$ to only be as large as the transmission allowed by the extrapolated dust attenuation curve. This is reasonable as, in the case of a galaxy with relatively large $E(B-V)$, a value of $f_{\text{esc}} = 1.0$ would imply zero dust attenuation for LyC and high attenuation at 1500 Å. We note, however, that such a case is not entirely impossible given LyC emission is often dominated by stellar populations with ages $< 10$ Myr while stellar populations as old as a few hundred Myr can provide significant flux at 1500 Å (e.g. Eldridge et al. 2017), thus the emission at each wavelength may originate from different locations within a given galaxy.

We do note, however, that this maximum $f_{\text{esc}}$ allowed by the assumed attenuation curve is highly model dependent. For example a Small Magellanic Cloud attenuation curve (e.g. Gordon & Clayton 1998) will have a much higher attenuation at LyC wavelengths when compared to either a Calzetti et al. (2000) or Reddy et al. (2016) attenuation curve with the same 1500 Å attenuation. This results from the fact that the extension of the functional form of either a Calzetti et al. (2000) or Reddy et al. (2016) curve is significantly flatter at $\lambda < 1500$ Å than that of Gordon & Clayton (1998). This caveat is important to keep in mind when considering the possible “maximum” $f_{\text{esc}}$ allowable for a given value of $E(B-V)$.

### 4.5 LyC Detections at Other Redshifts

The study of LyC escape from galaxies in ground-based studies is limited to redshifts $z \geq 2.8$ due to the low atmospheric transmission of UV photons. This limitation is not suffered by space-based instrumentation, thus, studies of LyC at lower redshifts can be performed at significantly lower redshifts with satellite instrumentation. In particular LyC has been detected at $z \sim 2.5$ by Bian et al. (2017) using the HST-WFC3 F275W filter, and recently at $z = 1.42$ by Saha et al. (2020) with the Ultra-Violet-Imaging Telescope (UVIT) on board AstroSat. We also note that there has been significant activity in spectroscopic detection of LyC from green pea galaxies at $z \sim 0.3 - 4$ with HST COS (e.g. Izotov et al. 2016, 2018). At such low redshifts, however, IGM transmission should be negligible, thus these studies are not of particular relevance to the study of $f_{\text{bias}}$.

Here we focus on providing predictions for detection of LyC within the Ultraviolet Imaging of the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey Fields (UVCANDELS; PI: Teplitz, PID 15647), a -430 arcmin$^2$, 164-orbit Cycle 26 UV HST program. UVCANDELS will provide 3-orbit depth of WFC3/F275W and parallel ACS/F435W in four CANDELS fields: GOODS-N, GOODS-S, EGS, and COSMOS.

For our predictions we follow a similar procedure outlined in Section 4.4; however here we have produced 10,000 IGM transmission curves at both $z = 2.4$ and $z = 4.4$ for the purpose of providing mock observations of LyC using the WFC3/F275W and
The IGM Transmission of LyC Detections

30 mag and beyond in small, targeted fields (i.e. similar to the $z = 3.1$ observations of Fletcher et al. 2019) is likely to be more fruitful than shallow searches over large areas such as UVCANDELS.

Given the expected faintness of LyC emission, wide area surveys such as UVCANDELS will likely rely on stacking analysis in order to estimate the average $f_{\text{esc}}$ for galaxy subsamples. In this scenario, prior information regarding the likelihood of escaping LyC emission (e.g. evidence of a hard ionizing spectrum or high Lyα escape, if available) will be useful. This is due to the fact that, although high LyC flux is more common for UV bright galaxies, galaxies with the same UV brightness are also commonly found with relatively low LyC flux (as shown in Figure 17). Similarly, we find galaxies with relatively faint non-ionizing UV flux with relatively high LyC flux. Thus, simply stacking the galaxies with the highest 1500 Å flux does not guarantee that the galaxies with the highest LyC flux have been chosen.

Finally, we note a few caveats to this analysis. First, this analysis has been performed using $T_{\text{IGM}}$ curves produced independently, while UVCANDELS covers 4 individual fields. In the event that there is strong correlation in $T_{\text{IGM}}$ across the field, the resulting LyC fluxes may be systematically higher (in the case of high $T_{\text{IGM}}$) or lower (in the case of low $T_{\text{IGM}}$) for one particular field. Consideration of the correlation of $T_{\text{IGM}}$ between sources in individual fields of a given area may require dedicated analysis of large scale simulations of the HI distributions and is beyond the scope of this work. And second, this analysis has ignored variation in $(L_{900}/L_{1500})_{\text{int}}$ (as noted), assumed no dust attenuation, and employed a flat $f_{\text{esc}}$ PDF, all three of which will affect our resulting LyC fluxes.

4.6 Observed vs True $f_{\text{esc}}$

Ultimately the ongoing search for LyC emission from high redshift galaxies is closely connected with our understanding what types of galaxies are responsible for reionizing the universe. Characterising the population of strong LyC emitters will be key to informing our picture of the topological evolution of ionized regions during the EoR (Seiler et al. 2018). There exists, however, an inherent difficulty regarding the interpretation of $f_{\text{esc}}$ values measured observationally due to the complex geometry of LyC escape from galaxies, independent of $T_{\text{IGM}}$. Indeed various models have been hypothesised that may provide slightly different interpretations of the detected LyC flux in the context of measuring $f_{\text{esc}}$. A detailed discussion of various LyC escape models can be found in Section 9.4 of S18.

Crucially, it has been pointed out (e.g. Bassett et al. 2019; Barrow et al. 2020) that the detection of LyC from any individual galaxy is reflective of only the fraction of LyC that is able to escape into our single line-of-sight. There is still no reliable way of inferring if the observed $f_{\text{esc}}$ value is reflective of $f_{\text{esc}}$ in all directions, i.e. the 3D $f_{\text{esc}}$ (though intriguing indirect measurement techniques for the 3D $f_{\text{esc}}$ have been proposed, which warrant further exploration within an anisotropic LyC escape scenario, e.g. Zackrisson et al. 2013; Yamanaka et al. 2020). Similarly, the lack of LyC emission from any individual galaxy is not evidence of $f_{\text{esc}} = 0.0$ as large quantities of LyC photons could be escaping in directions other than our line-of-sight. As we have shown, the value of $f_{\text{esc}}$ is dependent on the assumed underlying PDF and current detection rates may disfavour a flat distribution. One way to provide a theoretically sound basis for our assumptions on the PDF of $f_{\text{esc}}$ for galaxies or galaxy samples is through the careful consideration of high resolution hydrodynamical simulations.

LyC escape can be measured in such simulations by applying full radiative transfer, then measuring $f_{\text{esc}}$ from a large number of

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**Figure 17.** UV magnitudes of mock star-forming galaxies at $z = 2.4$ and $z = 4.4$ as observed by the UVCANDELS survey. Here 1500 Å fluxes are sampled from the $z = 2.5$ UV luminosity function of Moutard et al. (2020) and from the $z = 4.0$ UV luminosity function of Bouwens et al. (2015) with depths matched to UVCANDELS. **Top row:** LyC vs non-ionizing UV magnitudes of mock observations. **Bottom row:** histograms of magnitudes for LyC probing bands. In all panels the vertical dashed line indicates the depths of UVCANDELS observations. Here mock galaxies are produced as dust-free, exponentially declining SFR BPASSv2.1 SEDs with $(L_{900}/L_{1500})_{\text{int}} = 0.184$, and assuming a flat $f_{\text{esc}}$ PDF. We note that a larger value of $(L_{900}/L_{1500})_{\text{int}}$ can produce a handful of individual LyC detected galaxies.
sight lines towards the galaxy. This method provides the full three dimensional \( f_{\text{esc}} \) at a given time and has shown that even for individual galaxies \( f_{\text{esc}} \) is highly variable and can swing from 0 to 1 within 100 Myr (Paardekooper et al. 2015, Trebitsch et al. 2017, Rosdahl et al. 2018) though there may be some mass dependence on the 3D \( f_{\text{esc}} \) PDF. It has been shown, however, that for a galaxy with given 3D \( f_{\text{esc}} \) value the value of \( f_{\text{esc}} \) in any particular sightline may vary from 0 to values larger than the true 3D value (e.g. Paardekooper et al. 2015, Figure 13). Thus, to construct the underlying \( f_{\text{esc}} \) PDF for a given sample of galaxies may require the combination of the 3D \( f_{\text{esc}} \) of galaxies (with possible dependencies on mass or other properties) with the probability distribution of 2D \( f_{\text{esc}} \) (line-of-sight) for a given 3D \( f_{\text{esc}} \) value. Disentangling the various dependencies on these underlying PDFs will require suites of high resolution simulations with full radiative transfer, but is of utmost importance in interpreting the 2D \( f_{\text{esc}} \) values from observations with the true 3D \( f_{\text{esc}} \) distributions. Ultimately it is the full 3D \( f_{\text{esc}} \) values from galaxies that are of interest in the context of the EoR, which can only be connected to our 2D observational results through such a complex line of reasoning as is described here.

5 SUMMARY AND CONCLUSIONS

In this paper we have explored the level of bias in the IGM transmission, \( T_{\text{IGM}} \), for galaxies with LyC detections at \( z=3-4 \) under the observational limits imposed by current instruments and surveys. Our tests were performed by simulating one million IGM transmission functions in our redshift range of interest and applying these to empirically motivated mock galaxy spectra constructed from the BPASSv2.1 models (Eldridge et al. 2017). We have also tested how the level of IGM transmission bias, \( T_{\text{bias}} \), depends on both the assumed probability distribution function, PDF, of \( f_{\text{esc}} \) and SED shape (which controls \( \log(L_{910}/L_{1500})_{\text{int}} \) , a key value for measuring \( f_{\text{esc}} \)). Our analysis has included modeling designed to approximate both spectroscopic and photometric LyC detections from recent surveys of Steidel et al. (2018), Fletcher et al. (2019), and Meštrić et al. (2020).

Broadly, we find that, in all cases the average value of \( T_{\text{IGM}} \) at LyC wavelengths for galaxies with LyC detections is found to be larger than the average \( T_{\text{IGM}} \) for all simulated sightlines at the same redshift. This results from the fact that the underlying \( T_{\text{IGM}} \) distribution at 880 Å < \( \lambda_{\text{rest}} < 910 \) Å is bimodal with the stronger peak at \( T_{\text{IGM}} = 0 \), but the simple fact that the galaxy has been detected means that \( T_{\text{IGM}} \neq 0 \). Thus, the \( T_{\text{IGM}} \) distribution for LyC detected galaxies is unimodal with a peak at relatively high \( T_{\text{IGM}} \), while the mean for all sightlines falls below this due to the inclusion of the \( T_{\text{IGM}} = 0 \) peak. This is the result that is the assumption of a mean \( T_{\text{IGM}} \) for all sightlines when calculating \( f_{\text{esc}} \) for a sample of LyC detected galaxies results in an overestimate of the true value. This result is similar to the recent results of Byrohl & Gronke (2020) for Ly\( \alpha \) transmission. Thus, it is becoming clear that, while tempting, using a single statistic (e.g. median or mean) when considering \( T_{\text{IGM}} \) for individual objects provides misleading results for LyC detected samples. Considering samples which include (are composed entirely of) LyC non-detected galaxies, the use of \( T_{\text{IGM}} \) when calculating upper limits on \( f_{\text{esc}} \) is appropriate, however. The remainder of our conclusions can be summarised as follows:

- In the case of a UV flux distribution more characteristic of LAE sample (e.g. those of Fletcher et al. 2019) a higher \( T_{\text{bias}} \) should be expected. In this case, mock HST F336W observations similar to Fletcher et al. (2019), the minimum \( T_{\text{bias}} \) increases to ~0.21.
- We have shown in Section 3.2 that, although \( T_{\text{bias}} \) does not increase significantly assuming an \( f_{\text{esc}} \) PDF mildly biased towards 0, there may be a slight decrease in the recovered \( f_{\text{esc}} \) value in such a model.
- We have also demonstrated that the current detection rates of LyC radiation from surveys may reflect information regarding the underlying \( f_{\text{esc}} \) PDF. Our simplified model presented in Section 4.3 for example, appears to slightly disfavour a flat \( f_{\text{esc}} \) PDF for LAEs (e.g. Steidel et al. 2018), though this may not be the case for LAE samples (e.g. Fletcher et al. 2019).

This final point may suggest that fainter galaxies, represented by LAE samples, are more likely to exhibit a higher \( f_{\text{esc}} \) than bright galaxies, represented by LBGs. Such a scenario is in agreement with other recent studies (e.g. Finkelstein et al. 2019). Our comparisons in this context in Section 4.3 with the detection rates of Steidel et al. (2018) and Fletcher et al. (2019) are still in the realm of low statistical significance. Thus, confirmation of these results will require larger samples of LyC detected galaxies on which to perform a similar analysis.

Of course, all of our results will depend on the various input parameters of our models including the assumed distribution of 1500 Å (rest-frame) fluxes, our treatment (or lack thereof) of dust attenuation, our assumptions regarding the intrinsic luminosity ratio \( (L_{910}/L_{1500})_{\text{int}} \) of galaxies, and even the details of our methods for producing \( T_{\text{IGM}} \) functions (e.g. HI distribution functions). Thus, we do not claim that the absolute values of \( T_{\text{bias}} \) from this work to be in any way definitive. The purpose of this work is to highlight the ways in which different assumptions regarding the underlying distributions of \( T_{\text{IGM}} \) and \( f_{\text{esc}} \) affect our attempts to estimate \( f_{\text{esc}} \) from galaxies. It is clear that significant theoretical work is still required to better understand these PDFs that are critical to our interpretation of LyC detections from observations.

From an observational point of view, it is also clear that larger samples of LyC detections will be essential in disentangling the various dependencies on \( f_{\text{esc}} \) (e.g. stellar mass, SFR, etc.). It is possible that more efficient searches can be conducted in the near future with a focus on increasing both depth and field-of-view (FOV). Indeed, we find the highest detection rates among our mock surveys for our model galaxies which are more likely to exhibit a higher \( f_{\text{esc}} \) and thus offer a focus on increasing both depth and field-of-view (FOV).

DATA AVAILABILITY

Simulated data used in this work is produced primarily using publicly available codes found at https://github.com/robbassett as well as publicly available galaxy SED models from the BPASS collabora-
This paper has been typeset from a TeX/LaTeX file prepared by the author.