THE EFFECTS OF STELLAR POPULATION AND GAS COVERING FRACTION ON THE EMERGENT LY$\alpha$ EMISSION OF HIGH-REDSHIFT GALAXIES

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ABSTRACT

We perform joint modeling of the composite rest-frame far-UV (FUV) and optical spectra of redshift 1.85 ≤ z ≤ 3.49 star-forming galaxies to deduce key properties of the massive stars, ionized ISM, and neutral ISM, with the aim of investigating the principal factors affecting the production and escape of Ly$\alpha$ photons. Our sample consists of 136 galaxies with deep Keck/LRIS and MOSFIRE spectra covering, respectively, Ly$\beta$ through [C III] λλ1907, 1909, and [O II], [Ne III], H$\beta$, [O III], H$\alpha$, [N II], and [S II]. Spectral and photoionization modeling indicate that the galaxies are uniformly consistent with stellar population synthesis models that include the effects of stellar binarity. Over the dynamic range of our sample, there is little variation in stellar and nebular abundance with Ly$\alpha$ equivalent width, $W_\alpha$(Ly$\alpha$), and only a marginal anti-correlation between age and $W_\alpha$(Ly$\alpha$). The inferred range of ionizing spectral shapes is insufficient to solely account for the variation in $W_\alpha$(Ly$\alpha$). Rather, the covering fraction of optically-thick H I appears to be the principal factor modulating the escape of Ly$\alpha$, with most of the Ly$\alpha$ photons in down-the-barrel observations of galaxies escaping through low-column-density or ionized channels in the ISM. Our analysis shows that a high star-formation-rate surface density, $\Sigma_{SFR}$, particularly when coupled with a low galaxy potential (i.e., low stellar mass), can aid in reducing the covering fraction and ease the escape of Ly$\alpha$ photons. We conclude with a discussion of the implications of our results for the escape of ionizing radiation at high redshift.

Keywords: stars:abundances — ISM: abundances — ISM: HII regions — galaxies: high-redshift — galaxies: ISM — galaxies: star formation

1. INTRODUCTION

Ly$\alpha$ emission is often used as a signpost of ionizing radiation from star-forming galaxies [Partridge & Peebles 1967] due to the strength of the line and the cosmic abundance of hydrogen. Despite its widespread use, its large absorption cross-section means that a Ly$\alpha$ photon may traverse a complicated path through the interstellar medium (ISM) of a galaxy before being absorbed by dust or escaping [Spitzer 1978, Meier & Terlevich 1981]. The intensity of the line will be severely affected as a result. Ly$\alpha$ photons will scatter out of the line of sight by relatively small columns of H I, rendering a significant fraction of the flux undetectable in typical slit-spectroscopic observations of galaxies. The observed Ly$\alpha$ flux will be further diminished in the presence of dust, and its velocity profile will be shaped by bulk motions that cause the photons to shift out of resonance (e.g., Kunth et al. 1998).

While the resonant scattering of Ly$\alpha$ poses challenges for interpreting the nature of the ionizing sources and the subsequent transmission of those photons, it can be exploited to probe the spatial structure and kinematics of the ISM and circumgalactic medium (e.g., Steidel et al. 2011, Momose et al. 2014, Xue et al. 2017, Bacon et al. 2017, Wisotzki et al. 2018, Leclercq et al. 2020). Further, because Ly$\alpha$ photons are easily scattered, the residual flux that emerges along the observer’s sightline holds important clues on the porosity of the ISM, a key factor in the escape of ionizing ("Lyman Continuum", or LyC) photons (Zackrisson et al. 2013, Traor et al. 2015, Dijkstra et al. 2016, Reddy et al. 2016b, Steidel et al. 2018). It is thus not surprising that many efforts to investigate the sources of cosmic reionization have focused on galaxies with strong Ly$\alpha$ emission, or LyC emitters (LAEs)—see Ouchi et al. (2020) and references therein.

Radiative transfer simulations can be used to trace Ly$\alpha$ photons from the time they are produced to their escape or absorption by dust, a useful exercise for understanding how the strength and the velocity profile of the emerging photons is shaped by a clumpy, dusty, or non-static ISM (Dijkstra et al. 2006, Verhamme et al. 2006, 2008, Duval et al. 2014, Gronke et al. 2015, 2016). Nevertheless, one can gain significant insight into the key factors governing the production and escape of Ly$\alpha$ and LyC photons—namely the ionizing spectrum and the gas covering fraction—without resorting to computationally-expensive radiative transfer simulations. As discussed below, these two factors appear to successfully describe the variation in Ly$\alpha$ equivalent widths and escape fractions measured for the high-redshift galaxies analyzed here. The rest-frame far-UV (FUV) and rest-frame optical spectra of galaxies can be used to constrain the ionizing spectrum and the gas covering fraction.
The FUV (λ = 1000 – 2000 Å) galaxy spectrum contains a high density of emission and absorption lines well suited for investigating the production and transmission of Lyα photons. Aside from allowing a direct measurement of the emergent Lyα flux, this region of the spectrum contains numerous stellar photospheric absorption lines (e.g., Leitherer et al. 2001; Rix et al. 2004) and stellar wind lines (e.g., NV λ1240, Si IV λ1402, C IV λ1550, He II λ1640; Leitherer et al. 2001; Crowther et al. 2006; Brinchmann et al. 2008) sensitive to the stellar metallicity, age, and initial mass function—factors that are among those responsible for modulating the ionizing radiation field. Several studies have used specific features in the FUV, or full-spectrum fitting, to deduce stellar metallicities and ages of the massive stellar populations in high-redshift galaxies (e.g., Halliday et al. 2008; Sommariva et al. 2012; Steidel et al. 2016; Cullen et al. 2019, 2020; Topping et al. 2020b).

The FUV and optical nebular emission lines provide additional powerful constraints on the shape of the extreme-UV (EUV; λ < 912 Å) radiation field, which ultimately sets the intrinsic number of ionizing photons. Specifically, these lines allow one to distinguish between single star population synthesis models and those that include the effects of stellar multiplicity (binarity). While both flavors of models successfully match many of the stellar photospheric absorption and wind lines in the FUV for various assumptions of the stellar metallicity and age, only the binary models are able to reproduce the hard EUV spectrum required to generate the nebular line luminosities and line ratios measured from composite FUV and optical spectra of z ~ 2 galaxies (Steidel et al. 2016).

In addition to providing valuable constraints on the ionizing radiation field, the FUV spectrum includes a number of low- and high-ionization metal and H I absorption lines that may be used to infer gas covering fraction. Several studies have used the strong saturated metal transitions occurring in a predominantly neutral medium (e.g., Si II λ1260, Si II λ1527, C II λ1334, Al II λ1670) to infer the covering fraction of H I (e.g., Shapley et al. 2003; Heckman et al. 2011; Berry et al. 2012; Jones et al. 2013; Alexander et al. 2015; Trainor et al. 2015; Henry et al. 2015; Du et al. 2018; Harkane et al. 2020). Many of the same works and others have suggested a strong connection between the escape of Lyα (and LyC photons) and gas covering fraction as inferred from these same lines (e.g., Kornei et al. 2010; Hayes et al. 2011; Wofford et al. 2013; Borthakur et al. 2014; Rivera-Thorsen et al. 2015; Trainor et al. 2015; Reddy et al. 2016b; Steidel et al. 2018; Jaskot et al. 2019).

As noted elsewhere, however, the depths of saturated low-ionization metal absorption lines may underestimate the covering fraction of H I (Henry et al. 2015; Vasei et al. 2016; Reddy et al. 2016b; Gazagnes et al. 2018): these lines are not sensitive to metal-poor and possibly less dense gas. The H I absorption lines provide the most direct probe of the covering fraction if the lines are saturated. Large variations in Lyα forest blanketing along different sightlines renders it difficult to robustly model the interstellar H I lines for all but the highest-column-density individual (damped Lyα) systems at high redshift. Thus, one must average the FUV spectra across typically N ≥ 25 independent sightlines to reduce uncertainty in the mean foreground opacity to ≲ 10% (Reddy et al. 2016b; Steidel et al. 2018).

For the most part, analyses of composite spectra of high-redshift galaxies, as well as the spectra of individual Lyα-emitting (and LyC-leaking) local galaxies, imply a picture where Lyα and LyC photons that emerge along the line-of-sight (or down the barrel of the galaxy) do so after escaping the ISM through low-column-density channels in an otherwise optically-thick (ionization-bounded) medium (Trainor et al. 2015; Dijkstra et al. 2016; Reddy et al. 2016b; Gazagnes et al. 2018; Chisholm et al. 2018; Steidel et al. 2018; Trainor et al. 2019; Gazagnes et al. 2020). Other studies of local galaxies with high-equivalent-width optical emission lines (such as “Green Pea” galaxies) find a high covering fraction of H I with ~-unity optical depth, where the column density modulates Lyα escape (Henry et al. 2015; Jaskot et al. 2019). There are yet other studies that have suggested that density-bounded conditions indicated by very high [O III]/[O II] may favor the escape of LyC and Lyα photons (e.g., Nakajima et al. 2013; Nakajima & Ouchi 2014; Jaskot & Oey 2015; Tang et al. 2019).

In general, galaxies are likely better-visualized not as a single H II region, but as many overlapping regions, with a complicated ISM structure as a consequence. Thus, all of the aforementioned conditions could be present even in an individual galaxy: e.g., some sightlines through the galaxy may be ionization-bounded, others may density-bounded, while still others may be something in between (H I gas with ~-unity optical depth; see also Kakichi & Gronke 2021). If this is the case, averaging over many galaxies (and hence many sightlines) will result in an average (composite) spectrum that appears consistent with an ionization-bounded and porous ISM; i.e., a non-unity covering fraction of optically-thick gas (Reddy et al. 2016b). One also expects the visibility of Lyα (and LyC) emission to be highly dependent on the orientation of the galaxy relative to the line of sight (e.g., Ma et al. 2016). At any rate, modeling of FUV spectra can elucidate the predominant pathways by which Lyα and LyC photons escape the ISM of galaxies (e.g., Henry et al. 2015; Reddy et al. 2016b; Steidel et al. 2018; Gazagnes et al. 2018, 2020).

Galaxies at redshifts 2.0 ≤ z ≤ 2.6 are uniquely suited for studying the production and transmission of Lyα photons: the FUV is shifted to observed wavelengths where the sky background is extremely low and the throughput of blue-optimized ground-based spectrographs is high, typical star-forming galaxies are sufficiently bright to enable detailed studies of individual objects (Reddy & Steidel 2009), the relative transparency of the foreground IGM allows for constraints on the gas covering fraction for ensembles of objects (Reddy et al. 2016b), and the full suite of strong optical emission lines used to diagnose the state of the ISM are shifted to the near-IR windows of atmospheric transmission.

In this paper, we investigate the role of stellar population and gas covering fraction in the production and escape of Lyα (and LyC) photons using a sample of 136 typical star-forming galaxies at redshifts 1.85 ≤ z ≤ 3.49 with deep FUV and optical spectra from the MOSFIRE Deep Evolution Field (MOSDEF) survey (Kriek et al. 2015). Our analysis extends upon previous efforts (e.g., Steidel et al. 2016; Topping et al. 2020b; Cullen et al. 2020) by jointly modeling FUV and optical composite spectra—including the interstellar H I absorption lines—constructed in bins of Lyα equivalent width and star-formation-rate surface density. The galaxies were targeted for optical and subsequent FUV spectroscopy independent of FUV or optical emission-line strength and, as such, constitute a sample that is particularly advantageous in the current context. While targeted searches of LAEs and other high-equivalent-width optical line emitters provide a means...
of efficiently selecting galaxies that contribute significantly to cosmic reionization, they lack the dynamic range in galaxy properties to properly evaluate the physical factors modulating the emission lines and escape of Ly$\alpha$ and ionizing photons. To address the question of why certain galaxies have strong Ly$\alpha$ emission and others do not, one would clearly want to obtain spectroscopy in a controlled way for many galaxies spanning a range of Ly$\alpha$ strength. Moreover, the availability of deep Hubble Space Telescope (HST) imaging in the fields targeted by MOSDEF allow for an exploration of how the compactness of star formation impacts the porosity of the ISM and the escape of Ly$\alpha$ and ionizing photons (e.g., Heckman et al. 2011, Verhamme et al. 2017, Marchi et al. 2019; Naidu et al. 2020).

The outline of this paper is as follows. The MOSDEF survey, followup Keck/LRIS FUV spectroscopy and data reduction, individual galaxy measurements, and construction of composite spectra are described in Section 2. Section 3 presents the procedures for fitting the composite FUV spectra and optical emission line ratios with stellar population synthesis (SPS) and photoionization models, respectively; and the correlations between Ly$\alpha$ equivalent width and parameters relating to the ionizing spectrum (e.g., stellar metallicity, age), state of the ionized ISM (e.g., ionization parameter, gas-phase oxygen abundance), and the configuration of the neutral ISM (e.g., H I column density and covering fraction). The role of the shape of the ionizing spectrum and gas covering fraction on Ly$\alpha$ escape, as well as the impact of the star-formation-rate surface density and galaxy potential well on the escape of Ly$\alpha$ and the ionization parameter are discussed in Section 4. We summarize the analysis and our conclusions in Section 5. Unless indicated otherwise, quoted wavelength ranges (e.g., EUV, FUV, and optical) refer to the rest frame. All equivalent widths are expressed in the rest frame. A Chabrier (2003) initial mass function (IMF) is considered throughout the paper. Magnitudes are on the AB system (Oke & Gunn 1983). We adopt a cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.7$, and $\Omega_{\Lambda} = 0.3$.

2. SAMPLE SELECTION AND OBSERVATIONS

2.1. The MOSDEF Survey

Galaxies analyzed here were drawn from the MOSDEF survey. This survey obtained moderate resolution ($R \approx 3000$ – 3600) rest-frame optical spectroscopy of $\approx 1500$ $H$-band-selected galaxies and AGNs at redshifts $1.4 \lesssim z \lesssim 3.8$ in the CANDELS fields (Grogin et al. 2011, Koekemoer et al. 2011) using the MOSFIRE spectrometer (McLean et al. 2012) on the Keck telescope. MOSDEF galaxies were selected for spectroscopy based on pre-existing photometric, grism, or spectroscopic redshifts ($z_{\text{spec}}$)—$z = 1.37 - 1.70$, $z = 2.09 - 2.70$, and $z = 2.95 - 3.80$—that place the strong rest-frame optical emission lines (e.g., [O II], H$\beta$, [O III], H$\alpha$, [N II]) in the $YJHK$ atmospheric transmission windows. Details of the spectroscopic data reduction are provided in Kriek et al. (2015). The final spectroscopic sample spans ranges of star-formation rate ($1 \lesssim \text{SFR} \lesssim 200$ $M_{\odot}$ yr$^{-1}$) and stellar mass ($10^3 \lesssim M_\star \lesssim 10^11$ $M_{\odot}$) typical for galaxies at $z \approx 1.4$–3.8, with the majority of galaxies in the sample having detections of multiple rest-frame optical emission lines. Optical line luminosities were calculated using the methodology presented in Kriek et al. (2015).

2.2. MOSDEF-LRIS FUV Spectroscopy

Optical spectra from MOSDEF were complemented with FUV spectra obtained using the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995, Steidel et al. 2004) on the Keck telescope. Objects from the parent MOSDEF spectroscopic sample in the AEGIS, COSMOS, GOODS-N, and GOODS-S fields were prioritized for LRIS spectroscopy in the following manner. Objects with detections of H$\beta$, [O III], H$\alpha$, and [N II] were given the highest priority, and those with detections of the first three of these lines and an upper limit on [N II] were given the next-highest priority. We then included the following in order of priority: objects with MOSDEF redshifts $2.0 \lesssim z_{\text{spec}} \lesssim 2.7$, $1.4 \lesssim z_{\text{spec}} \lesssim 1.7$, or $3.0 \lesssim z_{\text{spec}} \lesssim 3.8$; those for which we were unable to obtain a redshift with MOSFIRE; and finally objects not observed with MOSFIRE, but which have photometric or grism redshifts from the 3D-HST survey that place them in the redshift ranges—and which meet the limit in $H$-band magnitude—targeted by MOSDEF.

Slit masks were milled with 1"-2-width slits and, to ensure proper background subtraction, a minimum slit length of 9". A total of 259 objects (217 of which have $z_{\text{spec}}$ from MOSFIRE) were observed using 9 slit masks in the AEGIS, COSMOS, GOODS-N, and GOODS-S fields. The observations were obtained over 10 nights in five separate observing runs during the period 2017 January to 2018 June. Spectra were obtained with the blue and red channels of LRIS (LRIS-B and LRIS-R, respectively), with the incoming beam split at $\approx 5000$ Å using the d500 dichroic. LRIS-B and LRIS-R were configured with the 400 line/mm grism and the 600 line/mm gratingblazed at 5000 Å, respectively. The red-side grating was tilted so that the combined LRIS-B and LRIS-R spectrum for each galaxy has continuous wavelength coverage from the atmospheric cut-off at $\approx 3100$ Å to $\gtrsim 7000$ Å, with the reddest covered wavelength depending on the position of the slit within the LRIS spectroscopic field of view. This setup yielded blue and red spectral resolutions of $R \approx 800$ and $R \approx 1400$, respectively, for a typical seeing of around 0.8. Total exposure times varied from 6 to 11 hours, with a median of 7.5 hours. In addition to internal flats on the red side, we obtained sky flats taken in twilight on the blue side as they provide better illumination than the internal flats at $\lambda \lesssim 4000$ Å. Arc spectra from Cd, Ar, Zn, He, and Hg internal lamps were acquired for wavelength calibration, and spectroscopic flux standards were observed at different airmasses on all observing runs to aid in flux calibration. LRIS data were reduced using the procedures described in Steidel et al. (2018) and Topping et al. (2020).

2.3. Individual Galaxy Measurements

2.3.1. Redshifts

The procedure used to derive redshifts for Ly$\alpha$ emission and each of the strongest interstellar low-ionization metal absorption lines in the LRIS spectra—Si II $\lambda\lambda$2600, O I $\lambda\lambda$1302+Si II $\lambda\lambda$1304, C II $\lambda$1334, S II $\lambda\lambda$1526, Fe II $\lambda$1608, and Al II $\lambda\lambda$1670—is described in Topping et al. (2020b). Briefly, the redshift of each line was calculated by fitting the local continuum and the line with a quadratic and Gaussian function, respectively, and taking the centroid of the Gaussian function as the observed wavelength of the line. These fits were manually inspected and only those lines with satisfactory fits were used to derive the final Ly$\alpha$ emission line and interstellar absorption line redshifts, $z_{\text{Ly} \alpha}$ and $z_{\text{IS}}$, respectively.
The spectra were shifted to the rest frame using systemic redshifts, \( z_{\text{sys}} \), which were measured from the highest signal-to-noise (S/N) optical nebular emission lines (i.e., typically [O III] \( \lambda 5008 \) or H\( \alpha \)) in the MOSFIRE spectra, as described in Kriek et al. (2015). For the 21 (of 259) objects in the sample that did not have a spectroscopic redshift from MOSFIRE—either because a robust redshift identification was not possible or because the object had not been previously targeted in the MOSDEF survey—\( z_{\text{sys}} \) was estimated from \( z_{\text{Ly}\alpha} \) and/or \( z_{\text{IS}} \) using the relationships between \( z_{\text{sys}} \), \( z_{\text{Ly}\alpha} \), and \( z_{\text{IS}} \) for those objects where both \( z_{\text{sys}} \) and at least one of \( z_{\text{Ly}\alpha} \) or \( z_{\text{IS}} \) were available (see Topping et al. 2020b). There were an additional three objects in the sample that did not have redshifts from MOSFIRE and for which we were unable to derive redshifts from the LRIS spectra, usually because the LRIS spectrum was either too noisy or contained irreparable artifacts that prevented a robust redshift identification. The redshift and near-IR magnitude distributions of the MOSDEF-LRIS sample, relative to those of the parent MOSDEF sample, are presented in the top panel of Figure 1. The few objects fainter than the \( H = 24.0, 24.5, \) and 25.0 magnitude limits imposed for MOSDEF target selection in the \( z = 1.37 - 1.70, z = 2.00 - 2.70, \) and \( z = 2.95 - 3.80 \) redshift windows, respectively, are serendipitous objects that happened to fall on MOSFIRE slits and for which we were able to derive robust redshifts.

2.3.2. \( \text{Ly} \alpha \) Equivalent Widths, \( W_{\lambda}(\text{Ly} \alpha) \)

One of the basic parameters in this study is the equivalent width of \( \text{Ly} \alpha, \ W_{\lambda}(\text{Ly} \alpha) \). This quantity scales with the escape fraction of \( \text{Ly} \alpha \) photons, and thus depends on the intrinsic ionizing photon production rate and gas covering fraction. \( W_{\lambda}(\text{Ly} \alpha) \) was measured for each galaxy following the procedures given in Kornei et al. (2010) and Du et al. (2018). Errors in \( W_{\lambda}(\text{Ly} \alpha) \) were calculated by remeasuring \( W_{\lambda}(\text{Ly} \alpha) \) for many realizations of each spectrum based on the corresponding error spectrum. Note that \( W_{\lambda}(\text{Ly} \alpha) \) only includes the emission measured within the spectroscopic aperture, adjusted for slit loss by assuming the emission is spatially coincident with the non-ionizing FUV continuum (Section 2.2). \( W_{\lambda}(\text{Ly} \alpha) \) does not include the fraction of \( \text{Ly} \alpha \) scattered out of the spectroscopic aperture (e.g., Steidel et al. 2011). As discussed in Section 3.3.2, the spectroscopically-determined \( W_{\lambda}(\text{Ly} \alpha) \) is the one most relevant for identifying ISM configurations that are amenable for the escape of \( \text{Ly} \alpha \) (and ionizing) photons. Throughout this work, \( W_{\lambda}(\text{Ly} \alpha) \) refers to the rest-frame value and is positive for \( \text{Ly} \alpha \) in emission. In Section 4.1, we consider an alternative method for computing \( \text{Ly} \alpha \) equivalent widths that accounts for underlying interstellar and stellar absorption.

2.3.3. Broadband SED Modeling

To aid in accounting for stellar Balmer absorption when measuring line luminosities, as well as determining SFRs (SFR(SED)), stellar masses (\( M_\star \)), ages, and continuum reddening (\( E(B-V)_{\text{cont}} \)), we fit the broadband photometry of galaxies in the sample with the Binary Population and Spectral Synthesis (BPASS) version 2.2.1 models (Eldridge et al. 2017, Stanway & Eldridge 2018). Our choice of these models is motivated by recent studies (e.g., Steidel et al. 2016) that jointly model FUV and optical spectra and find that the FUV and optical line luminosity ratios of typical star-forming galaxies at \( z \sim 2 \) are best reproduced when incorporating the physics of stellar binarity. The BPASS distribution conveniently includes model predictions both with and without the effects of stellar binarity, as well as for two different cutoffs of the high-mass end of the IMF, 100 and 300 \( M_\odot \). The resulting four variations of the BPASS models are considered in the present analysis: binarity with an upper mass cutoff of 100 \( M_\odot \) ("100bin"), binarity with an upper mass cutoff of 300 \( M_\odot \) ("300bin"), single star evolution with an upper mass cutoff of 100 \( M_\odot \) ("100sin"), and single star evolution with an upper mass cutoff of 300 \( M_\odot \) ("300sin"). We refer to these four flavors of models as the BPASS model "types."

The instantaneous burst models provided in the BPASS distribution were summed to produce constant star formation
models for $\log[\text{Age/yr}] = 7.0 - 10.0$ in 0.1 dex increments. The $Z_*$ = 0.001 metallicity models were considered in fitting the broadband photometry, based on the results obtained when directly fitting the BPASS models to the FUV spectra (Section 3.1). Nebular continuum emission was added to the SPS models as described in Section 3.1.1. Based on the analysis presented in Appendix A (see also Section 3.1), the SMC (Gordon et al. 2003) dust extinction curve was assumed for the reddening of the stellar continuum.

The broadband photometry for each galaxy (as compiled in Skelton et al. 2014) was first corrected for contributions from the optical emissions lines and Ly$\alpha$. The corrected photometry was then fit with the aforementioned models, limiting the age to be less than the age of the Universe at the redshift of each galaxy and greater than the minimum dynamical timescale of $\sim 10$ Myr inferred for the most compact galaxies in the sample (e.g., Reddy et al. 2016; Price et al. 2016, 2020). The model parameters that yielded the lowest $\chi^2$ relative to the photometry were taken to be the best-fit values. Errors in the parameters were determined from the standard deviation of parameter values obtained when fitting many perturbed realizations of the photometry based on the photometric errors. Unless indicated otherwise, the SED-fitting results obtained with the 100bin models and the SMC extinction curve are adopted by default (see Section 3.1.1 and Appendix A for further discussion on the choice of the stellar reddening curve).

### 2.4. Final Sample

Several criteria were applied to the targeted set of 259 objects in the MOSDEF-LRIS survey to arrive at the final sample for analysis. Any objects for which the LRIS spectra contained irreparable artifacts that prevented a robust redshift identification, or that were too noisy to yield a redshift ($z_{\text{Ly} \alpha}$ or $z_{\text{IS}}$), were removed. AGNs identified using the IR, X-ray, and optical line flux criteria described in Coil et al. (2015), Azadi et al. (2017, 2018), and Leung et al. (2019) were removed. Examination of the LRIS spectra of the remaining objects did not reveal the presence of any additional luminous AGN (e.g., such as those identified by broad Ly$\alpha$ emission or significant N V or C IV emission). Any objects for which the MOSFIRE or LRIS spectra indicate that the target may be blended with a foreground object were removed. The combined telescope and instrumental sensitivity of LRIS-B with the 400 line/mm grism falls below $\sim 20\%$ at $\lambda \lesssim 3300$ Å. As such, any objects for which Ly$\alpha$ falls at bluer wavelengths (i.e., $z_{\text{sys}} < 1.7$) were removed. These criteria result in a final sample of 136 galaxies whose redshift and $W_\lambda$(Ly$\alpha$) distributions are indicated in the bottom panel of Figure 1—of these, 79 galaxies have complete coverage of the strong optical nebular emission lines. The redshift distribution is statistically similar to that of the full MOSDEF-LRIS sample, while the $W_\lambda$(Ly$\alpha$) distribution is statistically similar to that of the Keck Baryonic Structure Survey (KBSS) sample distribution for UV-selected galaxies at similar redshifts (Reddy et al. 2008, Steidel et al. 2018). The percentage of galaxies with $W_\lambda$(Ly$\alpha$) > 20 Å, the criterion that defines a Ly$\alpha$ emitter (LAE), is 12.5% (17 of 136 galaxies). This percentage agrees well with the 12% found for star-forming galaxies selected by their FUV colors to lie at similar redshifts, i.e., “BX”-selected galaxies, with $R_\ast$ > 25.5 (Reddy et al. 2008).

### 2.5. FUV and Optical Composite Spectra

#### Table 1: Subsample Construction and Statistics

| Subsample | Criteria | N | $\langle z_{\text{sys}} \rangle$ | $\langle W_\lambda(\text{Ly} \alpha) \rangle$ (Å) |
|-----------|----------|---|-----------------|-----------------|
| A | All | 136 | 2.362 | 1.09 ± 0.46 |
| AL | All, Ly$\beta$ | 118 | 2.410 | -0.79 ± 0.37 |
| ALN | All, Ly$\beta$, neb | 73 | 2.285 | -3.42 ± 0.47 |
| WTI | $W_\lambda$(Ly$\alpha$), T1 | 45 | 2.258 | -15.88 ± 0.41 |
| WTI1 | $W_\lambda$(Ly$\alpha$), T1, Ly$\beta$ | 39 | 2.326 | -16.89 ± 0.76 |
| WTI1N | $W_\lambda$(Ly$\alpha$), T1, Ly$\beta$, neb | 24 | 2.311 | -19.13 ± 0.97 |
| WT2 | $W_\lambda$(Ly$\alpha$), T2 | 45 | 2.371 | -0.98 ± 0.38 |
| WT2L | $W_\lambda$(Ly$\alpha$), T2, Ly$\beta$ | 39 | 2.368 | -1.56 ± 0.38 |
| WT2LN | $W_\lambda$(Ly$\alpha$), T2, Ly$\beta$, neb | 24 | 2.284 | -4.72 ± 0.63 |
| WT3 | $W_\lambda$(Ly$\alpha$), T3 | 46 | 2.417 | 19.72 ± 1.12 |
| WT3L | $W_\lambda$(Ly$\alpha$), T3, Ly$\beta$ | 40 | 2.533 | 15.67 ± 0.72 |
| WT3LN | $W_\lambda$(Ly$\alpha$), T3, Ly$\beta$, neb | 25 | 2.260 | 12.92 ± 0.82 |

Annotations:
- $\text{SFR}(\lambda)$ line of a line ratio
- $\text{SFR}(\lambda)$ for galaxies contributing to the composite spectrum
- Average systematic redshift of galaxies in the subsample
- Average of individually-measured $W_\lambda$(Ly$\alpha$) for galaxies contributing to the subsample

Higher S/N measurements and inferences of mean spectral properties were obtained by averaging individual galaxy spectra to produce composite spectra. The procedures used for constructing composite FUV and optical spectra are specified in Reddy et al. (2016a) and Reddy et al. (2020), respectively, and are summarized here. Galaxies were first grouped together based on a certain property of interest (e.g., $W_\lambda$(Ly$\alpha$), star-formation-rate surface density). The FUV and optical spectra for all galaxies in a given grouping were shifted to the rest frame based on $z_{\text{sys}}$, converted to units of luminosity density, and spline-interpolated to a linear wavelength grid with a spacing $d\lambda_0 = 0.5$ Å. At each grid wavelength point, the luminosity densities were averaged after rejecting values that differ from the median luminosity density by more than 3$\sigma$.

No weighting was applied in the averaging to ensure that every galaxy contributes equally to the composite spectrum and that the predicted mean IGM+CGM opacity—which is computed assuming all sightlines contribute equally to the mean decrement shortward of Ly$\alpha$—can be confidently used to correct the composite spectrum (Steidel et al. 2018). The method of normalizing each individual galaxy spectrum by the luminosity of the most frequently detected (or highest S/N) line of a line ratio can be used to ensure that a line ratio measured from a composite spectrum...
The foreground IGM+CGM transmission curve appropriate for the mean redshift of the galaxies forming the composite spectrum was derived from the \(N(H\ I)\) distribution of intervening absorbers as a function of redshift given in Rudie et al. (2013) (e.g., Shapley et al. 2006, Reddy et al. 2016a, Steidel et al. 2018). The composite FUV spectrum was divided by this transmission curve to correct for the mean foreground IGM+CGM opacity.

The error in the mean luminosity density at each dispersion point (i.e., the composite error spectrum) reflects both measurement uncertainties (from the error spectra for individual objects) and the variance in luminosity densities of objects contributing to each dispersion point. The composite FUV and optical spectra for the entire sample are presented in Figure 2.

Table[1] lists the subsets of the sample for which composite spectra were constructed, along with the number of objects in each subset and their mean redshifts and \(W_{\lambda}(Ly\alpha)\). For reference, the latter were calculated by simply averaging the individual \(W_{\lambda}(Ly\alpha)\) measurements of the galaxies comprising the subsets (Section 2.3.2). The \(\langle W_{\lambda}(Ly\alpha)\rangle\) measured directly from the composite spectra using the procedure described in Kornei et al. (2010) are systematically lower by \(\simeq 7\) Å than those computed from the individual measurements owing to the presence of significantly-detected interstellar H I absorption underlying the Ly\(\alpha\) emission line in the composite spectra (e.g., as seen in Figure 2). Consequently, while \(\langle W_{\lambda}(Ly\alpha)\rangle\) is relatively straightforward to compute, differences in exactly how it is calculated can lead to some ambiguity in its relation to the production and escape of Ly\(\alpha\) photons. Thus, the \(W_{\lambda}(Ly\alpha)\) of the emission line itself, \(W_{\lambda}^{em}(Ly\alpha)\), and the escape fraction of Ly\(\alpha\) photons, \(f_{esc}(Ly\alpha)\), are also considered below (Section 3.1).

3. MODELING OF THE COMPOSITE FUV AND OPTICAL SPECTRA
A central focus of this analysis is to identify the primary factors in the production and transmission of Lyα (and LyC) photons. For the most part, these factors are constrained by fitting SPS and simplified ISM models to composite FUV spectra, and through photoionization modeling of nebular emission lines in the composite optical spectra. The fitting proceeded in three steps. In the first step, the BPASS models were fit to the composite FUV spectra to constrain stellar metallicities, ages, and continuum reddening of the stellar population dominating the FUV light. In the second step, photoionization modeling of the emission line ratios measured from the composite optical spectra was used to deduce ionization parameters, gas-phase oxygen abundances, and nebular reddening. Additionally, the residual He II λ1640 nebular emission in the composite FUV spectra was used to constrain the BPASS model type (i.e., the high-mass cutoff of the IMF and stellar binary). The parameters obtained in the first two fitting steps determine the shape of the ionizing spectrum. In the third step, models of the neutral ISM were fit to the composite FUV spectra to infer the line-of-sight reddening, H I column densities, and H I covering fractions. These three steps—and the correlations between W5(He I) and the aforementioned parameters—are described, respectively, in Sections 3.1, 3.2, and 3.3. The fitting results are summarized in Section 4. Readers who wish to skip the details of the fitting procedures can proceed to Section 5.

3.1. SPS Modeling and Results

3.1.1. SPS Modeling Procedure

Composite FUV spectra were fit with the BPASS 100bin, 300bin, 100sin, and 300sin SPS models (see Section 2.3.3), using a methodology similar to that presented in Steidel et al. (2016) and Topping et al. (2020b), with a few modifications described below. Similar to the aforementioned studies, we adopted a constant star-formation history (SFH). While there exist several different physically-relevant models for the SFHs of star-forming galaxies (e.g., Chisholm et al. 2019), we chose a constant SFH based on findings that such a SFH (or slowly-rising SFHs) provide a reasonable approximation of the mean SFH of ensembles of typical star-forming galaxies at z ≥ 1.5 (Papovich et al. 2011; Reddy et al. 2012b). We also considered ages of log(Age/Gyr) = 7.0, 7.5, 8.0, 8.5, and 9.0. The publicly available BPASS version 2.2.1 distribution includes model spectra computed at stellar metallicities Z = 10^{-5} to 0.04, expressed in terms of the mass fraction of metals where, for reference, the solar value is Z⊙ = 0.0142 (Asplund et al. 2009). The provided spectra were interpolated to construct a new grid of models with Z, that more finely sample (and bracket) the values expected for z ~ 2 galaxies (Steidel et al. 2016). Specifically, we considered stellar metallicities of Z = 10^{-4}, 3 × 10^{-4}, 5 × 10^{-4}, 7 × 10^{-4}, 9 × 10^{-4}, 0.0010, 0.0012, 0.0014, 0.0016, 0.0018, 0.0020, 0.0022, 0.0024, 0.0026, 0.0028, and 0.0030. Thus, we obtain a grid of SPS models with different stellar metallicities and ages. Nebular continuum emission was added to each SPS model in the grid (as described in Topping et al. 2020b) to produce an “SPSneb” model.

Finally, because of the lower resolution of the blue-side LRIS spectra relative to the red-side (Section 2.2), the SPSneb models were smoothed to match the resolution of the former at λ0 < 1500 Å, corresponding to the rest-frame wavelength of the dichroic cutoff for the mean redshift of the sample, ⟨z⟩ ~ 2.3. No smoothing was applied at wavelengths redder than 1500 Å.

Appendix A presents a comparison of the SFRs obtained with the different continuum attenuation curves, SFR(SED), and those derived from Hα, SFR(Hα). This comparison indicates that only the SMC extinction curve results in UV-based SFRs fully consistent with the Hα-based ones for the galaxy ensembles considered in this study, irrespective of the BPASS model type (100bin, 300bin, 100sin, 300sin models; see also Theios et al. 2019). Thus, the SMC extinction curve—updated in the wavelength range λ = 950 – 1250 Å based on the analysis of Reddy et al. (2016a) —was assumed in fitting the SPSneb models to the composite FUV spectra. Each SPSneb model was reddened assuming a range of stellar continuum reddening E(B − V)_{cont} = 0.00 – 0.40. The χ^2 of each model of a given Z, age, and reddening is

\[ \chi^2 = \sum_i \left[ \frac{l(i) - m(i)}{\sigma(i)} \right]^2 \]

where l(i) is the luminosity density of the composite FUV spectrum, m(i) is the luminosity density of the model spectrum, and σ(i) is the error in luminosity density, at wavelength point i. Wavelength points in the “Mask 1” windows given in Steidel et al. (2016) were used in computing the χ^2 statistic, and only for those windows for which all galaxies in the composite spectrum have coverage. Furthermore, the model spectrum was normalized to have the same median luminosity density as the composite FUV spectrum in the Mask 1 windows—the normalization of the model yields an estimate of the SFR. The best-fit values of Z, age, reddening, and SFR were set equal to the mean values obtained when fitting many realizations of the composite spectrum generated through random sampling of the galaxy spectra with replacement. Uncertainties in parameters were conservatively set equal to the standard deviation of the values obtained by fitting these realizations—which are larger than the standard errors in the mean values—and are thus effectively marginalized over the uncertainties of other fitted parameters. This method of deriving the uncertainties applies to all of the line measurements and model parameters obtained in this work.

3.1.2. Modeling Constraints on Z, and Age

Figures 3 and 4 show the 100bin SPSneb model fits to the composite FUV spectrum of all the galaxies in our sample. The best-fit continuum reddening, stellar metallicity, and age obtained with the 100bin model are ⟨E(B − V)⟩_{cont} = 0.099 ± 0.005, ⟨Z⟩ = 0.0011 ± 0.0003 (0.076 ± 0.018 Z⊙), and ⟨log(Age/Gyr)⟩ = 8.0 ± 0.2. This best-fit model is shown by the blue spectrum. The best-fit models of the same age, but with Z = 0.0020 and Z = 0.0080 are also shown.

While all the models provide an adequate fit to the N V λ1240 P-Cygni emission feature (Figure 2), comparison of these models clearly demonstrates the strong preference for lower stellar metallicities when fitting the entire composite FUV spectrum (see also Topping et al. 2020b). For in-
Figure 3. Comparison of the composite FUV spectrum of the entire sample (black, with the 1σ error in gray) and the 100bin SPSneb models for log[Age/yr] = 8.0 and different metallicities, focused on the wavelength regions around C IV λ1548, 1550 (top) and λrest = 1700 - 2000 Å (bottom). Line labeling is similar to Figure 2 where we include the fine structure emission line Si II* λ1533. Regions not included in the fitting are indicated by the light green shaded regions.

Figure 4. Comparison of the composite FUV spectrum of the entire sample (black, with the 1σ error in gray) and the 100bin SPSneb models for log[Age/yr] = 8.0 and different metallicities, focused on the wavelength region around N V λ1240. The models shown here do not include interstellar H I absorption. Line labeling is similar to Figure 3 where we include the fine structure emission line Si II* λ1265. Regions not included in the fitting are indicated by the light green shaded regions.

Simultaneously, the blend of Si, C, and Fe photospheric lines centered at ≃ 1425 Å (i.e., the 1425 index; Rix et al. 2004); the depths of S V λ1502 and N V λ1719; and the Fe III blend centered at ≃ 1978 Å (i.e., the 1978 index; Rix et al. 2004) are all significantly weaker than the predictions of models with Z* ≳ 0.002. Moreover, the weak photospheric absorption seen across the full FUV wavelength range (excluding regions affected by interstellar absorption or nebular emission) is most consistent with the Z* ≲ 0.002 models. Formally, the Z* = 0.008 (∼ 0.56 Z⊙) model is excluded with ≳ 8σ significance.

Similar fitting of the composite FUV spectrum of 30 star-forming galaxies at z ∼ 2.3 from the Keck Baryonic Structure Survey (KBSS) also indicates a low stellar metallicity, Z* ≃ 0.001 - 0.002 (Steidel et al. 2016) see also Cullen et al. 2019 and Topping et al. 2020b). Interestingly, the KBSS composite FUV spectrum exhibits very weak C IV P-Cygni emission, possibly because of blending with interstellar C IV absorption (Steidel et al. 2016). The strong C IV P-Cygni emission observed in the composite FUV spectrum of our sample—similar in strength to the predictions of the Z* ≲ 0.002 models which best reproduce the overall level of photospheric absorption—may suggest a narrower velocity distribution and/or lower covering fraction of the C IV-bearing gas in the ISM.

The preference for subsolar stellar metallicities persists irrespective of the age of the stellar population (e.g., Topping et al. 2020b). Additionally, the variations in Z* and age that are obtained with different BPASS model type are negligible compared to the random uncertainties in these parameters (Steidel et al. 2016). Furthermore, Z* and age are primarily determined by the overall level of photospheric line blanketing in the FUV and, as such, are relatively insensitive to the assumed continuum dust attenuation curve. Because the FUV spectrum is dominated by the light from the youngest stellar populations, the ages derived from the spectral fitting are a factor of ∼ 2 – 3 × lower than—but still correlate with—those derived from the broadband SED fitting (Section 2.3.3 see also Section 3.1.3). The former are most relevant for our analysis since the youngest stellar populations dictate the shape of
Table 2
SPSneb and ISM Model Fit Results

| Subsample | \(<E(B - V)_{\text{cont}}\)> | \(<Z_*/Z_\odot\>) | \(<\log[A/e]_\odot\>) | \(<E(B - V)_{\text{neb}}\>) | \(<Z_{\text{neb}}/Z_\odot\>) | \(<\log(U)\>) | \(<E(B - V)_{\text{los}}\>) | \(<f_{\text{cont}}(\text{H I})>\) | \(<\log[N(\text{H I})/\text{cm}^{-2}]\>) | \(<W_\lambda^{\text{em}}(\text{Ly}\alpha)>(\text{Å})>\) | \(<f_{\text{esc}}^{\text{Ly}\alpha}(\text{Ly}\alpha)>\) |
|------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| A          | 0.099 ± 0.005   | 0.076 ± 0.018   | 8.0 ± 0.2       | 0.966 ± 0.013   | 0.97 ± 0.02     | 20.7 ± 0.2      | 9.11 ± 1.67     | 0.014 ± 0.003   |
| AL         | 0.099 ± 0.005   | 0.075 ± 0.017   | 8.1 ± 0.2       | 0.969 ± 0.012   | 0.99 ± 0.01     | 20.7 ± 0.2      | 8.65 ± 1.36     |
| ALN        | 0.101 ± 0.006   | 0.082 ± 0.017   | 8.2 ± 0.3       | 0.33 ± 0.04     | 0.38 ± 0.09     | -2.93 ± 0.05    | 21.0 ± 0.2      | 0.00 ± 0.89     | 0.001 ± 0.02 |
| WT1        | 0.116 ± 0.009   | 0.082 ± 0.019   | 8.5 ± 0.2       | 0.104 ± 0.010   | 0.98 ± 0.02     | 21.1 ± 0.2      | 0.00 ± 0.97     | 0.001 ± 0.02 |
| WT1L       | 0.113 ± 0.011   | 0.097 ± 0.019   | 8.4 ± 0.3       | 0.29 ± 0.07     | 0.37 ± 0.11     | -3.01 ± 0.07    | 21.1 ± 0.2      | 0.00 ± 0.97     | 0.001 ± 0.02 |
| WT1LN      | 0.115 ± 0.011   | 0.080 ± 0.021   | 8.4 ± 0.3       | 0.41 ± 0.04     | 0.44 ± 0.08     | -2.74 ± 0.07    | 20.2 ± 0.4      | 0.035 ± 0.009   |
| WT2        | 0.095 ± 0.007   | 0.126 ± 0.022   | 8.2 ± 0.2       | 0.093 ± 0.012   | 0.96 ± 0.02     | 20.7 ± 0.2      | 4.89 ± 1.37     | 0.006 ± 0.003   |
| WT2L       | 0.119 ± 0.023   | 7.7 ± 0.3       | 0.48 ± 0.11     | 0.106 ± 0.014   | 0.97 ± 0.03     | 20.0 ± 0.7      | 5.78 ± 1.69     | 0.006 ± 0.003   |
| WT2LN      | 0.078 ± 0.009   | 0.079 ± 0.017   | 7.8 ± 0.7       | 0.093 ± 0.017   | 0.90 ± 0.03     | 20.2 ± 0.4      | 22.50 ± 2.64    | 0.035 ± 0.009   |
| ST1        | 0.091 ± 0.010   | 0.115 ± 0.042   | 8.2 ± 0.2       | 0.24 ± 0.13     | 0.28 ± 0.13     | -3.06 ± 0.07    | 20.8 ± 0.3      | 0.015 ± 0.005   |
| ST1L       | 0.095 ± 0.009   | 0.091 ± 0.032   | 8.2 ± 0.2       | 0.100 ± 0.022   | 0.95 ± 0.03     | 20.8 ± 0.3      | 5.49 ± 1.98     | 0.015 ± 0.005   |
| ST2        | 0.113 ± 0.011   | 0.117 ± 0.034   | 8.1 ± 0.3       | 0.45 ± 0.07     | 0.40 ± 0.03     | -3.10 ± 0.06    | 20.3 ± 0.7      | 6.36 ± 2.45     | 0.007 ± 0.003   |
| ST2L       | 0.092 ± 0.012   | 0.146 ± 0.059   | 8.2 ± 0.3       | 0.117 ± 0.006   | 0.98 ± 0.01     | 20.3 ± 0.7      | 6.36 ± 2.45     | 0.007 ± 0.003   |
| ST3        | 0.083 ± 0.007   | 0.111 ± 0.020   | 7.8 ± 0.2       | 0.38 ± 0.07     | 0.43 ± 0.08     | -2.70 ± 0.07    | 20.8 ± 0.2      | 10.55 ± 3.62    | 0.013 ± 0.003   |
| ST3L       | 0.086 ± 0.009   | 0.118 ± 0.028   | 8.0 ± 0.2       | 0.082 ± 0.017   | 0.92 ± 0.02     | 20.8 ± 0.2      | 10.55 ± 3.62    | 0.013 ± 0.003   |
| sST1       | 0.127 ± 0.012   | 0.079 ± 0.022   | 7.9 ± 0.2       | 0.39 ± 0.08     | 0.34 ± 0.14     | -3.16 ± 0.07    | 20.4 ± 0.2      | 6.28 ± 2.43     | 0.009 ± 0.003   |
| sST2       | 0.095 ± 0.010   | 0.163 ± 0.052   | 8.3 ± 0.3       | 0.40 ± 0.02     | -2.95 ± 0.07    | 20.9 ± 0.2      | 5.17 ± 2.34     | 0.007 ± 0.003   |
| sST3       | 0.076 ± 0.006   | 0.108 ± 0.018   | 8.1 ± 0.2       | 0.30 ± 0.06     | 0.41 ± 0.08     | -2.70 ± 0.04    | 20.4 ± 0.3      | 11.30 ± 3.90    | 0.020 ± 0.003   |
| sST3L      | 0.080 ± 0.007   | 0.115 ± 0.014   | 8.1 ± 0.2       | 0.067 ± 0.005   | 0.91 ± 0.02     | 20.4 ± 0.3      | 11.30 ± 3.90    | 0.020 ± 0.003   |

\(a\) Continuum reddening assuming the SMC extinction curve\(,\) \(Gordon\ et\ al.\ 2003)\.
\(b\) Stellar metallicity in solar units, assuming \(Z_\odot = 0.0142\) \(Asplund\ et\ al.\ 2009\).
\(c\) Age.
\(d\) Nebular reddening assuming the \(Cardelli\ et\ al.\ 1989\) extinction curve.
\(e\) Nebular oxygen abundance in solar units.
\(f\) Ionization parameter.
\(g\) Line-of-sight reddening of the gas covering the continuum in the clumpy ISM model, assuming the SMC extinction curve.
\(h\) \(H\ I\) covering fraction in the clumpy ISM model.
\(i\) \(H\ I\) column density in the clumpy ISM model.
\(j\) \(H\ I\) emission-line equivalent width.
\(k\) Line-of-sight escape fraction of \(\text{Ly}\alpha\) photons.
Figure 5. Variation of \(\langle E(B - V)_{\text{cont}} \rangle\) (top), \(\langle Z_e/Z_{\odot} \rangle\) (bottom left), and \(\langle \log(\text{Age}/\text{yr}) \rangle\) (bottom right) assuming the 100bin models, with \(\langle W_\lambda(\text{Ly}\alpha) \rangle\) for the A, WT1, WT2, and WT3 subsamples. The \(E(B - V)_{\text{cont}}\) and \(\log(\text{Age}/\text{yr})\) obtained from SED fitting: Section 2.3.3, for individual galaxies are denoted by the light green points in the top and bottom right panels, respectively. Also indicated are the Spearman \(\rho\) correlation coefficient (\(\rho_{\text{ind}}\)) and \(p\)-value (\(p_{\text{ind}}\)) between \(E(B - V)_{\text{cont}}\) and \(W_\lambda(\text{Ly}\alpha)\), and \(\log(\text{Age}/\text{yr})\) and \(W_\lambda(\text{Ly}\alpha)\), for individual galaxies. The inset panel on the top zooms in on the \(E(B - V)_{\text{cont}}\) and \(\langle W_\lambda(\text{Ly}\alpha) \rangle\) measurements obtained from the composite FUV spectra.

the ionizing spectrum.

3.1.3. Correlations between \(W_\lambda(\text{Ly}\alpha)\) and SPS Model Parameters

The procedure described in Section 3.1.1 was used to fit the composite FUV spectra for subsamples A, AL, ALN, and the nine subsamples constructed in bins of \(W_\lambda(\text{Ly}\alpha)\) (Table 1). The best-fit values of \(\langle E(B - V)_{\text{cont}} \rangle\), \(\langle Z_e/Z_{\odot} \rangle\), and \(\langle \log(\text{Age}/\text{yr}) \rangle\) obtained from fitting the 100bin SPSneb models are listed in Table 2. The variations in \(\langle W_\lambda(\text{Ly}\alpha) \rangle\) with the aforementioned parameters are presented in Figure 5.

The reddening of the stellar continuum, parameterized by \(\langle E(B - V)_{\text{cont}} \rangle\), clearly anti-correlates with \(\langle W_\lambda(\text{Ly}\alpha) \rangle\), such that objects with higher \(\langle W_\lambda(\text{Ly}\alpha) \rangle\) exhibit significantly bluer \(\langle E(B - V)_{\text{cont}} \rangle\). The composite FUV spectrum with \(\langle W_\lambda(\text{Ly}\alpha) \rangle \approx 20\,\text{Å}\) (subsample WT3) has \(\langle E(B - V)_{\text{cont}} \rangle = 0.073 \pm 0.007\), roughly 0.043 mag bluer than the composite with \(\langle W_\lambda(\text{Ly}\alpha) \rangle \approx -20\,\text{Å}\) (subsample WT1). Throughout the analysis, we focus on the significance of the difference in the measurements made on composite spectra that contain independent sets of galaxies, such as subsamples formed from the lower and upper third of the \(W_\lambda(\text{Ly}\alpha)\) distribution of individual galaxies (e.g., subsamples WT1 and WT3, subsamples WT1LN and WT3, and so on).

The top panel of Figure 5 also shows the \(E(B - V)_{\text{cont}}\) and \(W_\lambda(\text{Ly}\alpha)\) measured for individual galaxies in the sample, where the former were inferred from broadband SED fitting (Section 2.3.3). The averages of these individual \(E(B - V)_{\text{cont}}\) measurements in bins of \(W_\lambda(\text{Ly}\alpha)\) are similar within the uncertainties to the \(\langle E(B - V)_{\text{cont}} \rangle\) of the composite spectra. The Spearman rank correlation coefficient between \(E(B - V)_{\text{cont}}\) and \(W_\lambda(\text{Ly}\alpha)\) for individual galaxies is \(\rho_{\text{ind}} = -0.31\), with a probability of \(p_{\text{ind}} = 2.6 \times 10^{-4}\) that the two variables are uncorrelated.

As noted in Section 3.1.2, the modeling of the composite FUV spectra strongly prefers sub-solar stellar metallicities: these metallicities vary from \(\langle Z_e/Z_{\odot} \rangle \approx 0.07\) to 0.12 for the composites formed in bins of \(W_\lambda(\text{Ly}\alpha)\). However, there is no significant correlation between \(\langle Z_e/Z_{\odot} \rangle\) and \(\langle W_\lambda(\text{Ly}\alpha) \rangle\) for the ensembles analyzed here. For example, the two composites with the most extreme values of \(\langle W_\lambda(\text{Ly}\alpha) \rangle\), namely subsamples WT1LN and WT3, have \(\langle Z_e/Z_{\odot} \rangle = 0.80 \pm 0.021\) and \(0.079 \pm 0.015\), respectively.

On the other hand, the composite FUV spectra indicate a marginally significant anti-correlation between \(\langle \log(\text{Age}/\text{yr}) \rangle\) and \(\langle W_\lambda(\text{Ly}\alpha) \rangle\). Composites with \(\langle W_\lambda(\text{Ly}\alpha) \rangle > 0\) have \(\langle \log(\text{Age}/\text{yr}) \rangle \lesssim 8.0\), while those with \(\langle W_\lambda(\text{Ly}\alpha) \rangle < 0\) absorption have \(\langle \log(\text{Age}/\text{yr}) \rangle \gtrsim 8.3\). Formally, the number of degrees of freedom in the fit (determined by the number of wavelength points considered in the fitting, \(\nu = 1000\)) implies a difference in reduced \(\chi^2\), \(\Delta \chi^2_{\nu} \approx 0.0198\) for \(\Delta \nu = 1\). Thus, based on the variation in \(\chi^2\) with \(\langle \log(\text{Age}/\text{yr}) \rangle\), the difference in ages of the two composites with the largest difference in \(\langle W_\lambda(\text{Ly}\alpha) \rangle\) (corresponding to subsamples WT1LN and WT3) is significant at the \(2\sigma\) level.

For comparison, the distributions of SED-inferred \(\log(\text{Age}/\text{yr})\) (Section 2.3.3) and \(\langle W_\lambda(\text{Ly}\alpha) \rangle\) measured for individual galaxies are shown in the lower right panel of Figure 5. A Spearman rank correlation test indicates a marginal anti-correlation between \(\log(\text{Age}/\text{yr})\) and \(\langle W_\lambda(\text{Ly}\alpha) \rangle\) for individual galaxies, with a probability of 18% that the two are uncorrelated. As noted in Section 3.1.2, the strengths of the correlations summarized in Figure 5 are similar to those obtained with the 300bin, 100bin, and 500bin models. The ionizing spectrum assumed for the next step of the fitting process (photoionization modeling; Section 3.2.2) was determined by the SPStab model that best fits the composite FUV spectrum.

3.2. Photoionization Modeling and Results

3.2.1. Photoionization Modeling Procedure

The Cloudy version 17.02 radiative transfer code (Ferland et al. 2017) was used to predict the nebular continuum spectra and line intensities for the SPStab models that best fit the composite FUV spectra, following the same procedure described in Topping et al. (2020b). The photoionization modeling also assumed a plane-parallel geometry with an electron density \(n_e = 250\,\text{cm}^{-3}\), the average value inferred for MOSDEF galaxies (Sanders et al. 2016). All elemental abundances were updated to the values given in Asplund et al. (2009). Additionally, we assumed \(\log(N/O) = -2.21\) based on the N2O2 and N2S2 indices computed for the composites and using the calibrations of Steidel et al. (2016) and Strom et al. (2017). For the range of O abundances inferred for the composites using lines other than [N II], \(\log(N/O)\) is expected to vary by \(\approx 0.14\) dex according to the best-fit relation between \(\log(N/O)\) and \(12 + \log(O/H)\) provided in Pilyugin et al. (2012). Regardless, the best-fit \(\langle Z_{\text{neb}} \rangle\) does not change.

For the subsample containing all galaxies with coverage of the optical nebular emission lines (subsample ALN), \(n_e = 288 \pm 58\,\text{cm}^{-3}\) based on the ratio of the two lines of the [O II] doublet, consistent with the \(n_e = 250\,\text{cm}^{-3}\) assumed for the photoionization modeling.

13 The Pilyugin et al. (2012) relation between \(\log(N/O)\) and electron-temperature-corrected \(12 + \log(O/H)\) was shifted by \(\approx 0.25\) dex towards higher \(12 + \log(O/H)\) to account for the tendency of the latter to underestimate O abundances obtained from photoionization modeling (e.g.,
of emission lines are listed in Table 3. The optical nebular the subsamples with complete coverage of the optical nebular emission lines. Dust-corrected [Ne II] λ6583 luminosity relative to L(Hβ).

| Subsample | ⟨(L(Hβ))⟩ | ⟨(I([O II]))⟩ | ⟨(I([Ne III]))⟩ | ⟨(I([O III])4960)⟩ | ⟨(I([O III]5008))⟩ | ⟨(I(Hα))⟩ | ⟨(I([N II]))⟩ | ⟨(I([S III]))⟩ |
|------------|-----------|---------------|-----------------|-----------------|-----------------|-------------|-------------|-------------|
| ALN        | 277 ± 41  | 3.18 ± 0.37   | 0.29 ± 0.08     | 1.17 ± 0.10     | 3.56 ± 0.25     | 2.79 ± 0.01  | 0.35 ± 0.04  | 0.55 ± 0.06  |
| W11LN      | 287 ± 119 | 3.17 ± 1.03   | 0.29 ± 0.21     | 1.02 ± 0.25     | 3.37 ± 0.65     | 2.79 ± 0.01  | 0.33 ± 0.05  | 0.49 ± 0.11  |
| W2LN       | 368 ± 128 | 4.59 ± 1.01   | 0.03 ± 0.21     | 1.07 ± 0.21     | 2.66 ± 0.42     | 2.79 ± 0.01  | 0.48 ± 0.07  | 0.67 ± 0.13  |
| W3LN       | 314 ± 65  | 3.03 ± 0.54   | 0.41 ± 0.16     | 1.37 ± 0.19     | 4.50 ± 0.51     | 2.79 ± 0.01  | 0.29 ± 0.05  | 0.44 ± 0.07  |
| ST1        | 158 ± 47  | 3.43 ± 0.83   | 0.31 ± 0.28     | 0.94 ± 0.21     | 2.64 ± 0.49     | 2.80 ± 0.01  | 0.46 ± 0.08  | 0.56 ± 0.14  |
| ST1L       | 160 ± 56  | 3.41 ± 0.91   | 0.25 ± 0.29     | 1.00 ± 0.27     | 2.64 ± 0.59     | 2.80 ± 0.01  | 0.42 ± 0.07  | 0.54 ± 0.13  |
| ST2        | 400 ± 97  | 4.44 ± 0.93   | 0.28 ± 0.24     | 0.87 ± 0.19     | 3.04 ± 0.47     | 2.79 ± 0.01  | 0.42 ± 0.06  | 0.58 ± 0.08  |
| ST2L       | 426 ± 98  | 4.74 ± 0.88   | 0.30 ± 0.25     | 0.80 ± 0.18     | 3.00 ± 0.51     | 2.79 ± 0.01  | 0.44 ± 0.06  | 0.60 ± 0.09  |
| ST3        | 491 ± 137 | 2.91 ± 0.45   | 0.41 ± 0.10     | 1.53 ± 0.17     | 4.76 ± 0.41     | 2.79 ± 0.01  | 0.28 ± 0.05  | 0.39 ± 0.05  |
| ST3L       | 511 ± 173 | 2.94 ± 0.45   | 0.41 ± 0.16     | 1.48 ± 0.17     | 4.65 ± 0.43     | 2.79 ± 0.01  | 0.28 ± 0.05  | 0.39 ± 0.05  |
| sST1       | 269 ± 96  | 3.83 ± 0.92   | 0.23 ± 0.19     | 0.69 ± 0.17     | 2.30 ± 0.31     | 2.80 ± 0.01  | 0.53 ± 0.05  | 0.61 ± 0.09  |
| sST1L      | 303 ± 104 | 4.28 ± 1.16   | 0.19 ± 0.31     | 0.72 ± 0.20     | 2.52 ± 0.50     | 2.79 ± 0.01  | 0.51 ± 0.05  | 0.62 ± 0.10  |
| sST2       | 415 ± 136 | 4.12 ± 0.78   | 0.49 ± 0.21     | 1.15 ± 0.21     | 3.60 ± 0.60     | 2.79 ± 0.01  | 0.36 ± 0.06  | 0.50 ± 0.10  |
| sST2L      | 400 ± 117 | 3.95 ± 0.64   | 0.49 ± 0.20     | 1.10 ± 0.20     | 3.63 ± 0.63     | 2.79 ± 0.01  | 0.37 ± 0.06  | 0.49 ± 0.10  |
| sST3       | 298 ± 74  | 2.41 ± 0.42   | 0.33 ± 0.11     | 1.58 ± 0.17     | 4.88 ± 0.39     | 2.79 ± 0.01  | 0.23 ± 0.04  | 0.37 ± 0.07  |
| sST3L      | 323 ± 90  | 2.57 ± 0.51   | 0.58 ± 0.16     | 1.52 ± 0.16     | 4.68 ± 0.45     | 2.79 ± 0.01  | 0.25 ± 0.05  | 0.39 ± 0.08  |

a Dust-corrected Hα luminosity in units of 10^{40} erg s^{-1}, assuming the intrinsic Hα/Hβ ratio of the best-fit photoionization model and the Cardelli et al. [1989] extinction curve, for the subsamples with complete coverage of the optical nebular emission lines.

b Dust-corrected [O III] λλ3727, 3730 luminosity relative to L(Hβ).

c Dust-corrected [Ne II] λ3870 luminosity relative to L(Hβ).

d Dust-corrected [O III] λ4960 luminosity relative to L(Hβ).

e Dust-corrected [O III] λ5008 luminosity relative to L(Hβ).
f Dust-corrected Hα luminosity relative to L(Hβ).

g Dust-corrected [N II] λ6585 luminosity relative to L(Hβ).

significantly if log(N/O) is allowed to vary with O abundance in the photoionization modeling, or if [N II] is excluded altogether from the fitting.

The nebular oxygen abundance was varied from Z_{neb}/Z_{⊙} = 0.1 to 1.0 in steps of 0.1 Z_{⊙}. Additionally, the intensity of the ionizing radiation field at the illuminated face of the gas slab, expressed by the ionization parameter, U, where

\[ U = \frac{n_e}{n_H}, \]

was varied from log U = −3.5 to log U = −1.6 in steps of 0.1 dex. Here, U is the ratio of the number densities of hydrogen-ionizing photons and hydrogen atoms, where n_{e} \approx n_{H}.

Each photoionization model predicts the intrinsic ratio of Hα-to-Hβ which, in concert with the Cardelli et al. [1989] extinction curve, was used to calculate the nebular reddening, E(B-V)_{neb} (e.g., Reddy et al. 2015), and dust-correct all the nebular emission lines.14 The dust-corrected nebular emission line intensities relative to dust-corrected Hβ for all the subsamples with complete coverage of the optical nebular emission lines are listed in Table 3. The optical nebular emission line ratios predicted by each photoionization model were then compared to the dust-corrected emission line ratios measured from the composite optical spectra to deduce the best-fit combinations of Z_{neb} and log U.15 Table 4 lists a few of the line diagnostics discussed below and their definitions. In identifying the best-fit photoionization model, we considered all of the following lines: [O II] λλ3727, 3730, [Ne III] λ3870, Hβ, [O III] λλ4960, 5008, Hα, [N II] λ6585, and [S II] λλ6718, 6733. The photoionization modeling constraints on Z_{neb}, log U, and the BPASS model type are discussed below in Sections 3.2.2, 3.2.3 and 3.2.4 respectively.

3.2.2. Modeling Constraints on Oxygen Abundance

A few of the key line ratios used to constrain Z_{neb} are depicted in Figure 9, including the O32 versus R23 diagnostic plane—which provides a clean separation between models of different Z_{neb} (e.g., McGaugh 1991; Kobulnicky et al. 1999; Kewley & Dopita 2002) and the N2 and S2 BPT planes (Baldwin et al. 1981). In these diagrams, each colored curve represents the sequence of log U at a fixed Z_{neb} for a given BPASS model type. The widths of the curves indicate the range of line ratios expected given the range of (Z_{⊙}) and [log Age/yr] inferred from modeling the composite FUV spectra (Section 3.1). Specifically, the upper and lower edges of each curve indicates the model expectations for the ionizing spectrum of a stellar population with Z_{⊙} = 0.0010 and log[Age/yr] = 7.8, and Z_{⊙} = 0.0018 and
Figure 6. O32 versus R23 (left), O3 versus N2 (middle), and O3 versus S2 (right) diagnostic diagrams. The dark blue, cyan, orange, and red curves show the predicted line ratios for the 300bin, 100bin, 300sin, and 100sin BPASS models types, respectively, for $Z_{\text{neb}} = 0.4 Z_{\odot}$, while the thickness of the curves indicates the range of expected line ratios for a (1) $Z_*= 0.0010$ and $\log[\text{Age/yr}] = 7.8$, and (2) $Z_*= 0.0018$ and $\log[\text{Age/yr}] = 8.5$ stellar population. The set of four lighter curves are for the four BPASS model types assuming $Z_{\text{neb}} = 0.1 Z_{\odot}$. The modeling assumes $\log(N/O) = -1.20$ (Section 3.2.1). The points denote the line ratios for the ALN, WT1LN, WT2LN, and WT3LN subsamples which have complete coverage of the optical nebular emission lines.

Figure 7. Ne3O2 versus O32 (top left), O32 versus R23 (top right), O3 versus N2 (bottom left), and O3 versus S2 (bottom right) diagnostic diagrams for the ALN, WT1LN, WT2LN, and WT3LN subsamples which have complete coverage of the optical nebular emission lines, where the points are color coded according to $\langle W_{\lambda}(\text{Ly}\alpha) \rangle$. The $3\sigma$ upper limits in Ne3O2 are shown for composites where [Ne III] was not detected with $S/N > 3$. The thick black curves show the expected line ratios for a 100bin stellar population with $Z_*= 0.0012$ and $\log[\text{Age/yr}] = 8.0$, and $Z_{\text{neb}} = 0.4 Z_{\odot}$. The points along the curves indicate the labeled values of $\log U$. 
log [Age/yr] = 8.5, covering roughly the range of $Z_*$ and ages found in Section 3.1. The differences in the ionizing spectra of the best-fit SPSneb models are discussed further in Section 4.2, but for the moment we note that these variations in the ionizing spectrum do little to alter the nebular line ratios predicted from the photoionization modeling (e.g., see also Runco et al. 2021).

Figure 6 clearly demonstrates the preference for oxygen abundances of $\langle Z_{\text{neb}} \rangle \approx 0.4 Z_\odot \sim (12 + \log (O/H)) \approx 8.29$ averaged across the ALN and WT subsamples with complete coverage of the optical nebular emission lines. The $\langle Z_{\text{neb}} \rangle$ obtained from the photoionization modeling vary in the range $\langle Z_{\text{neb}} \rangle \approx (0.3 - 0.5) Z_\odot$ (see also Topping et al. 2020b, Runco et al. 2021). As noted earlier, we adopted log(N/O) = −1.20 based on the N202 and N282 indices. This choice yields N2 that are consistent with the predictions of the photoionization modeling (with $Z_{\text{neb}} \approx 0.4 Z_\odot$) that reproduces all of the other line ratios under consideration. The inferred $\langle Z_{\text{neb}} \rangle$ are similar between the different BPASS model types given the typical uncertainties in the nebular line ratios. Photoionization models with $Z_{\text{neb}}$, comparable to the stellar metallicities obtained from fitting the composite FUV spectra (Zs, $\approx 0.01$; Section 3.1) are ruled out at the $3 - 4 \sigma$ level, depending on the subsample (e.g., see also Steidel et al. 2010). Appendix B discusses the O abundances derived from the “direct” metallicity method: these direct-method abundances agree with those obtained from the photoionization modeling.

3.2.3. Modeling Constraints on Ionization Parameter

The line diagnostic diagrams in Figure 6, in addition to Ne3O2 versus O32 (e.g., Nagao et al. 2006, Pérez-Montero et al. 2007, Levesque & Richardson 2014, Steidel et al. 2016, Strom et al. 2017, Jeong et al. 2020), may be used to constrain the ionization parameter, $U$. These diagrams are presented in Figure 4 zoomed in on the regions of line diagnostic space that encompass the measurements for the ALN and WT subsamples with complete coverage of the optical nebular emission lines. For simplicity, we only show the expected line ratios for a 100bin stellar population with $Z_*$ = 0.0012, log[Age/yr] = 8.0, and with $Z_{\text{neb}}$ = 0.4 Z_\odot (thick black curve), where points indicate the labeled values of log $U$. The photoionization modeling points to best-fit values of (log $U$) $\approx$ −3.1 to −2.8. As per the discussion in Section 3.2.2 and Figure 6, the best-fit values of (log $U$) are insensitive to the BPASS model type and the range of ionizing spectra corresponding to the best-fit SPSneb models.

3.2.4. Constraints on the BPASS Model Type (or Binarity)

The ratio of nebular He II $\lambda$1640 and H$\beta$ is one of the most sensitive discriminators of the BPASS model type (Steidel et al. 2016). In single-star models, He II emission arises from the stellar winds of very high mass and short-lived Wolf-Rayet stars (e.g., Shirazi & Brinchmann 2012, Crowther et al. 2016). On the other hand, the higher effective temperatures of massive binaries, their harder ionizing spectra, and the increased main-sequence lifetimes of such stars, result in significant production of He II-ionizing photons for a longer duration compared to single-star models (Eldridge et al. 2017). In the context of a continuous star-formation history, binary stellar evolution results in significant stellar He II emission, while this emission is absent in the single-star models for ages comparable to those that best fit the composite FUV spectra, as shown in Figure 8. As alluded to in Section 4, the (non-ionizing) FUV spectrum is insufficient to discriminate between single and binary star population synthesis models. On the other hand, binarity results in both a harder and more intense ionizing (EUV) spectrum whose signature can be probed with FUV and optical nebular emission line ratios (e.g., Steidel et al. 2014, 2016, Schaerer et al. 2019, Nanayakkara et al. 2019, Chisholm et al. 2019). Along these lines, the BPASS model type (i.e., single versus binary star evolution) can be evaluated by comparing the inferred nebular He II luminosity with that predicted by the best-fit photoionization model.

Following Steidel et al. 2016), we measured the residual He II luminosity from the composite FUV spectrum after subtracting the best-fit SPSneb model to that composite spectrum. Because the SPSneb model includes stellar He II emission, the residual He II luminosity is assumed to be nebular in nature. The inferred nebular He II luminosity was corrected for dust obscuration assuming ($E(B-V)_{\text{neb}}$) and the Cardelli et al. 1989 extinction curve. These residual values are listed in Table 5 for the 100bin model type. Figure 9 shows the relative intensity of nebular He II to H$\beta$, compared to (He II/H$\beta$) predicted by the best-fit photoionization models for the ALN and WT subsamples with complete coverage of the optical nebular emission lines. The errors, reflected by the length of the bars in this figure, include measurement uncertainties (and thus uncertainties in the best-fit SPSneb model and uncertainties in the best-fit photoionization model). A majority of the subsamples has residual nebular He II emission that is formally “undetected” for the binary models, for the reasons explained below.

Recall that the photoionization modeling assumes the best-fit SPSneb model as the ionizing source (Section 3.2.1). Hence, the inferred stellar He II emission and the nebular He II emission predicted by the best-fit photoionization model both assume the same SPSneb model, providing internal consistency in the way that He II is modeled. The inferred nebular He II emission is much larger in the single-star models because of the weaker inferred stellar emission, and in fact
that nebular emission is significantly larger than that predicted by the best-fit photoionization models when considering the same single-star (100sin and 300sin) models. In other words, the ionizing spectra associated with single-star models are unable to account for the level of nebular He II emission inferred based on the weak stellar He II predicted by the same models.

On the other hand, the binary models yield a residual He II intensity that is comparable within the uncertainties to that predicted by the photoionization models. Based on comparing the offsets between the predicted and residual nebular He II emission from subsample to subsample, it may be tempting to conclude that the binary models also tend to underestimate the nebular He II emission. However, it is important to keep in mind that many of the subsamples have galaxies in common, and therefore the offsets observed for a given subsample are not necessarily independent of the offsets for a different subsample. When considering all galaxies in our subsample with complete coverage of the optical nebular emission lines (i.e., subsample ALN), the inferred offset between the predicted and residual nebular He II emission for the binary models is consistent with zero, while it at least 1 d for the single-star models.

In conclusion, we find that the binary models produce internally-consistent inferences of the nebular He II emission for the composites, while the single-star models do not. Similar conclusions were reached by Steidel et al. (2016) in their analysis of the KBSS composite spectrum. Here, we have shown that the binary models appear consistent with the composite spectra irrespective of \( \langle W_\lambda (\text{Ly} \alpha) \rangle \) (see Section 3.2.5 for further discussion). In the present context, the most pertinent impact of the BPASS model type is on the intrinsic production of H-ionizing photons, which is addressed in Section 4.2. As per the discussion in Sections 3.1.2, 3.2.2 and 3.2.5, the BPASS model type has little effect on the derived \( Z_c, \log[\text{Age/yr}], Z_{\text{neb}}, \) and \( \log U. \)

### 3.2.5. Correlations between \( W_\lambda (\text{Ly} \alpha) \) and Photoionization Model Parameters

Table 5 summarizes the correlations between the best-fit photoionization model parameters (Table 2) and \( \langle W_\lambda (\text{Ly} \alpha) \rangle \). For comparison, the \( E(B-V)_{\text{neb}} \) calculated for individual galaxies with significant \((S/N \geq 3)\) detections of H\(\alpha\) and H\(\beta\) are also shown in the left panel of the figure. These individual \( E(B-V)_{\text{neb}} \) were calculated using the same method to calculate \( E(B-V)_{\text{neb}} \) for the ensembles. In calculating \( E(B-V)_{\text{neb}} \) for individual galaxies, we assumed \( \langle H\alpha/H\beta \rangle_{\text{int}} = 2.79 \) based on the results of the photoionization modeling (Section 3.2.1). Over the dynamic range probed by our sample, we do not find a significant trend between \( E(B-V)_{\text{neb}} \) and \( \langle W_\lambda (\text{Ly} \alpha) \rangle \). Furthermore, while the averages of individual \( E(B-V)_{\text{neb}} \) measurements in bins of \( W_\lambda (\text{Ly} \alpha) \) are consistent with the \( E(B-V)_{\text{neb}} \) measured from the composite spectra, a Spearman correlation test indicates a high probability \( (p_{\text{null}} = 0.56) \) of a null correlation between \( E(B-V)_{\text{neb}} \) and \( W_\lambda (\text{Ly} \alpha) \) for individual galaxies (c.f., Scarlata et al. [2009]), perhaps as a result of the larger uncertainties on the individual \( E(B-V)_{\text{neb}} \) measurements.

The best-fit \( \langle Z_{\text{neb}} \rangle \) also do not appear to correlate strongly with \( W_\lambda (\text{Ly} \alpha) \), in the sense that galaxies with high \( W_\lambda (\text{Ly} \alpha) \gtrsim 10 \lambda \) have \( Z_{\text{neb}} \) consistent within the uncertainties with that of galaxies with lower \( W_\lambda (\text{Ly} \alpha) \). The ostensible lack of correlation between \( Z_{\text{neb}} \) and \( W_\lambda (\text{Ly} \alpha) \) can be appreciated from Figures 6 and 7, where all compositions irrespective of \( W_\lambda (\text{Ly} \alpha) \) have optical nebular line ratios that are generally consistent with photoionization models where \( Z_{\text{neb}} \approx 0.4 Z_\odot \).

The only significant difference found among the photoionization modeling parameters for galaxies with low and high \( W_\lambda (\text{Ly} \alpha) \) is \( \log U. \) Composites formed from the lower and upper third of the \( W_\lambda (\text{Ly} \alpha) \) distribution (i.e., WT1LN and WT3LN) indicate \( \langle \log U \rangle \approx -3.01 \pm 0.07 \) and \( -2.74 \pm 0.07 \), respectively, a difference significant at the \( \approx 3\sigma \) level (see also Figure 7).

### 3.3. Neutral ISM Modeling and Results

#### 3.3.1. Neutral ISM Modeling Procedure

The third and last step of the spectral modeling involved modifying the SPNeb models to include interstellar H I absorption with varying column density and line-of-sight reddening. The method employed here is identical to that of Reddy et al. (2016) and Steidel et al. (2018), where the observed spectrum consists of two components: (a) the intrinsic spectrum and (b) the spectrum that emerges after pass-

| Subsample | \( \langle f (\text{O III}) \rangle^a \) | \( \langle f (\text{C III}) \rangle^b \) | \( \langle W_\lambda (\text{C III}) \rangle^c \) | \( \langle f (\text{He II}) \rangle^d \) |
|-----------|----------------|----------------|----------------|----------------|
| ALN       | 0.112 ± 0.034  | 0.393 ± 0.120  | 1.330 ± 0.244  | 0.012 ± 0.029  |
| WT1LN     | 0.093 ± 0.052  | 0.280 ± 0.245  | 1.052 ± 0.361  | 0.094 ± 0.195  |
| WT2LN     | 0.147 ± 0.072  | 0.847 ± 0.531  | 1.278 ± 0.554  | 0.023 ± 0.107  |
| WT3LN     | 0.149 ± 0.096  | 0.478 ± 0.201  | 1.790 ± 0.637  | 0.015 ± 0.042  |
| ST1       | 0.132 ± 0.062  | 0.286 ± 0.183  | 1.138 ± 0.509  | 0.069 ± 0.061  |
| ST1L      | 0.103 ± 0.072  | 0.305 ± 0.289  | 1.053 ± 0.474  | 0.010 ± 0.058  |
| ST1R      | 0.122 ± 0.085  | 0.774 ± 0.403  | 1.660 ± 0.605  | 0.022 ± 0.090  |
| ST2       | 0.102 ± 0.042  | 0.861 ± 0.372  | 1.759 ± 0.639  | 0.029 ± 0.082  |
| ST3       | 0.133 ± 0.079  | 0.459 ± 0.196  | 1.546 ± 0.503  | 0.038 ± 0.076  |
| ST3L      | 0.133 ± 0.099  | 0.423 ± 0.230  | 1.349 ± 0.520  | 0.026 ± 0.061  |

\(^{a}\text{Dust-corrected O III} \lambda \lambda 5007, 5016 \text{ luminosity relative to } L(\text{H}\beta).\)
\(^{b}\text{Dust-corrected C III} \lambda \lambda 4650, 4658 \text{ luminosity relative to } L(\text{H}\beta).\)
\(^{c}\text{Equivalent width of C III} \lambda \lambda 1907, 1909.\)
\(^{d}\text{Dust-corrected He II} \lambda \lambda 1640 \text{ luminosity relative to } L(\text{H}\beta).\)
ing through foreground H I and dust. These two components are then weighted according to the H I gas covering fraction, $f_{\text{cov}}(\text{H} I)$, to model a non-unity covering fraction of optically-thick H I. This model of the neutral ISM, referred to as the “clumpy” model (also called the “holes” model in Steidel et al. 2018) can be expressed as:

$$m_{\text{final}} = f_{\text{cov}}(\text{H} I) \times m_{\text{H} I} \times 10^{-0.4E(B-V)_{\text{los}}k(\lambda)} + [1 - f_{\text{cov}}(\text{H} I)] \times m_0. \quad (3)$$

Here, $m_0$ is the intrinsic (unreddened) stellar spectrum determined from fitting the composite FUV spectrum with the SPSneb models (Section 3.1.1). $E(B-V)_{\text{los}}$ is the line-of-sight reddening (i.e., the reddening of the covered portion of the continuum), where a range $E(B-V)_{\text{los}} = 0.000 - 0.300$ and the SMC extinction curve, $k(\lambda)$, was assumed. Lyman series absorption lines were added to the intrinsic (unreddened) stellar spectrum with a Doppler parameter of $b = 125$ km s$^{-1}$ and column densities in the range $\log[N(\text{H} I)/\text{cm}^{-2}] = 18.0 - 23.0$. $N(\text{H} I)$ is primarily constrained by the H I damping wings and is therefore insensitive to the particular choice of $b$.

Furthermore, the assumed range of $\log[N(\text{H} I)/\text{cm}^{-2}]$ is motivated by the results of Reddy et al. (2016b) (e.g., see their Figure 2) that show that it is not possible to fit the red damping wings of the H I lines, particularly that of Ly$\alpha$, unless $\log[N(\text{H} I)/\text{cm}^{-2}] \gtrsim 19$. The resulting H I-absorbed spectrum is denoted by $m_{\text{H} I}$ in Equation 5. Accordingly, we obtained a grid of neutral ISM models with varying $E(B-V)_{\text{los}}$, $\log[N(\text{H} I)/\text{cm}^{-2}]$, and $f_{\text{cov}}(\text{H} I)$.

The clumpy model makes the physically-motivated assumption that the mechanisms that establish low-column-density channels in the ISM also result in negligible dust attenuation along those channels, such that only the light passing through the high-column-density H I is reddened by dust (c.f., Borthakur et al. 2014). However, because we cannot rule out the possibility of non-negligible columns of dust in these channels, we also consider the more extreme possibility of a “screen” model where all light is attenuated by a foreground screen of dust (e.g., Steidel et al. 2018; Gazagnes et al. 2018). In this case, the ISM model can be expressed as:

$$m_{\text{final}} = f_{\text{cov}}(\text{H} I) \times m_{\text{H} I} + (1 - f_{\text{cov}}(\text{H} I)) \times m_0 \times 10^{-0.4E(B-V)_{\text{cont}}k(\lambda)}. \quad (4)$$

Covering fractions derived from the screen model are systematically lower than those derived from the clumpy model (see Section 3.3.2 for further discussion). Throughout the subsequent discussion, we assume by default the clumpy model (see Section 3.1.1) and discuss the results from the screen model where relevant.

The best-fit values of $E(B-V)_{\text{los}}$, $\log[N(\text{H} I)/\text{cm}^{-2}]$, and $f_{\text{cov}}(\text{H} I)$ are determined by the neutral ISM (clumpy) model with the minimum $\chi^2$ relative to the composite FUV spectrum in the wavelength windows specified in Steidel et al. (2018)—slightly modified from the windows used in Reddy et al. (2016b)—where only those windows with $\lambda_0 \gtrsim 1000$ Å were considered, for the following reason. While the best constraints on $f_{\text{cov}}(\text{H} I)$ come from fitting multiple Lyman series absorption lines, doing so would require us to only consider galaxies for which those lines are redshifted above the atmospheric cutoff at $\lambda \approx 3100$ Å. All of these lines, and the LyC continuum region at $\lambda \approx 900$ Å, can be observed from the ground at $z > 2.7$, a limit that excludes the bulk of our sample which lies at lower redshifts (Figure 1). Alternatively, adopting a redshift cutoff of $z > 2.12$ ensures coverage of at least Ly$\beta$ while still retaining sufficient numbers of galaxies in the smallest subsamples to reduce uncertainties in the foreground IGM+CGM opacity to $\lesssim 10\%$ (Steidel et al. 2018). For this reason, the neutral ISM models are com-
pared to the composite spectra in wavelength windows lying above $\lambda_0 \gtrsim 1000$ Å. Consequently, $f_{\text{cov}}(\text{H} \beta)$ is primarily determined by the depth of $\text{Ly}\alpha$, while $\log[N(\text{H} \beta)/\text{cm}^{-2}]$ is constrained by the damping wings of $\text{Ly}\alpha$ and $\text{Ly}\beta$. Note that the depths of the Lyman series lines are sensitive to the H I gas covering fraction only if the lines are saturated. Below, we present evidence that this is the case for galaxies in our sample.

3.3.2. Correlations between $W_\lambda(\text{Ly}\alpha)$ and Neutral ISM Model Parameters

The procedure described in Section 3.3.1 was used to determine the best-fit $(E(B-V)_{\text{int}})$, $\log[N(\text{H} \beta)/\text{cm}^{-2}]$, and $f_{\text{cov}}(\text{H} \beta)$ for the ALN, WT1LN, and WT3LN subsamples with coverage of $\text{Ly}\beta$ (Table 1). These best-fit values are listed in Table 2, and their correlations with $W_\lambda(\text{Ly}\alpha)$ are shown in Figure 11. Figure 12 demonstrates the neutral ISM model fits to the composite FUV spectra for subsamples WT1LN and WT3LN. Although the gas covering fraction is primarily constrained by the depth of $\text{Ly}\beta$, the inferred gas covering fractions provide a good match to the depth of $\text{Ly}\gamma$, for which only the subset of galaxies with $z \gtrsim 2.3$ has coverage.

The neutral ISM model fitting indicates no significant correlation between $(E(B-V)_{\text{int}})$ and $W_\lambda(\text{Ly}\alpha)$. There are marginal differences in the H I column densities for galaxies with low and high $W_\lambda(\text{Ly}\alpha)$ (middle panel of Figure 11), such that galaxies with high $W_\lambda(\text{Ly}\alpha)$ appear to have somewhat lower $\log[N(\text{H} \beta)/\text{cm}^{-2}]$. However, the uncertainties in the latter are sufficiently large to prevent us from coming to any strong conclusions regarding any correlation between $W_\lambda(\text{Ly}\alpha)$ and $\log[N(\text{H} \beta)/\text{cm}^{-2}]$. Regardless, the column densities even for composites with the highest $W_\lambda(\text{Ly}\alpha)$ (i.e., those containing the strongest $\text{Ly}\alpha$ emitters) indicate gas that is optically-thick in all the Lyman series lines and the Lyman continuum. Thus, the presence of significant $\text{Ly} \beta$ emission spatially coincident with the stellar continuum (i.e., $\text{Ly} \beta$ emission that is detected within the spectroscopic aperture) suggests that the $\text{Ly} \alpha$ photons must be escaping the galaxies through optically-thin (i.e., ionized or low-column-density) channels in the ISM, or are scattered off of gas with sufficient velocity to be redshifted out of resonance and pass unimpeded through foreground H I.

Evidence for a non-unity covering fraction of optically-thick gas is illustrated in the comparison of the neutral ISM model fits to subsamples WT1LN and WT3LN (Figure 12), consisting of galaxies in the lower and upper third of the $W_\lambda(\text{Ly}\alpha)$ distribution, respectively (Table 1). In the former case, there is little residual flux under the $\text{Ly} \beta$ line—and $\text{Ly} \gamma$ for the subset of higher redshift galaxies where this line is covered in the spectra, while the damping wings of $\text{Ly} \alpha$ imply high-column-density gas. Thus, the model fit to subsample WT1LN suggests a very high covering fraction of high-column-density H I. The neutral ISM model fit for subsample WT3LN suggests somewhat lower (but still high) column densities of $\log[N(\text{H} \beta)/\text{cm}^{-2}] = 20.2 \pm 0.4$, with significant residual flux detected under the $\text{Ly} \beta$ core, and $\text{Ly} \gamma$ for the subset of galaxies where this line is covered. This residual flux is a principal signature of the non-unity covering fraction of optically-thick H I gas (e.g., Reddy et al. 2016).

More generally, galaxies with $W_\lambda(\text{Ly}\alpha) < 0$ Å have $f_{\text{cov}}(\text{H} \beta) \gtrsim 0.96$, while those with $W_\lambda(\text{Ly}\alpha) > 0$ Å have $f_{\text{cov}}(\text{H} \beta) \lesssim 0.93$. This difference in $f_{\text{cov}}(\text{H} \beta)$ is significant at the $\simeq 2.5\sigma$ level. However, the constraints on $f_{\text{cov}}(\text{H} \beta)$ are sufficient to rule out (to $\gtrsim 3\sigma$) unity covering fraction for galaxies with high $W_\lambda(\text{Ly}\alpha)$. A more significant anti-correlation between $f_{\text{cov}}(\text{H} \beta)$ and $W_\lambda(\text{Ly}\alpha)$ was found for UV-selected galaxies at $z \sim 3$ (Reddy et al. 2016b), where multiple Lyman series lines were used to constrain $f_{\text{cov}}(\text{H} \beta)$. The right panel of Figure 11 also shows $f_{\text{cov}}(\text{H} \beta)$ inferred from the screen model (red circles), which are for the most part systematically lower than $f_{\text{cov}}(\text{H} \beta)$ derived from the clumpy model, but still correlate with $W_\lambda(\text{Ly}\alpha)$. At any rate, the inference of high-column-density H I, $\text{Ly} \beta$ that is not black at line center, and a similar level of residual flux under the $\text{Ly} \beta$ and $\text{Ly} \gamma$ lines suggest that the Lyman series lines are saturated and that their depths are sensitive to the covering fraction of high-column-density H I.

It is worth noting that for some of the composites considered in this study, a screen model implies high escape fractions of ionizing photons that lead to suppressed Balmer line luminosities. Accounting for the fraction of ionizing photons that escapes results in $\text{H} \alpha$-inferred SFRs (SFR(\text{H} \alpha)) that exceed the UV-inferred SFRs (SFR(\text{UV})) if the UV-inferred SFRs are up to a factor of $\simeq 2$ lower than the values implied by the clumpy model. Such low covering fractions imply high escape fractions of ionizing photons that lead to suppressed Balmer line luminosities.

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16 $\text{Ly} \alpha$ absorption provides little constraint on $f_{\text{cov}}(\text{H} \beta)$ owing to emission-filling.
Figure 11. Variation of \((E(B-V))_{los}\) (left), \(\log[N(H I)/cm^{-2}]\) (middle), and \(f_{cov}(H I)\) (right) assuming the 100bin models, with \((W_3(Ly\alpha))\) for the AL, WT1L, WT2L, and WT3L subsamples with coverage of \(L_\beta\). The blue and red points in the right panel denote covering fractions derived in the clumpy and screen models, respectively.

![Composite FUV spectra for subsamples WT1L (top) and WT3L (bottom) shown in black (1σ error in gray), along with the best-fit neutral ISM model fits in red (top) and blue (bottom). These neutral ISM models assume the best-fit \(Z_\star\) and \(\log[Age/yr]\) obtained from the 100bin SPSneb model fitting (Section 3.1.1). Indicated in each panel are the \(Z_\star\) and \(\log[Age/yr]\) for the models shown. Line labeling is similar to Figure 2.](image)

There are a few salient points to keep in mind regarding the inferences of gas covering fractions. First, foreground contamination [Vanzella et al. 2010, 2012; Nestor et al. 2011; Mostardi et al. 2015; Siana et al. 2015] can in principle lead to residual flux under the Lyman series lines in the spectra of the targets of interest. However, as discussed in Reddy et al. (2016b), FUV spectra of the typical depth at-
tained in this study have proven to be quite effective in identifying and removing spectroscopic blends of target and foreground galaxies, particularly when coupled to deep optical (i.e., MOSFIRE) spectra than enable the identification of low-redshift contaminants over a broader range of redshifts via a second set of (typically strong) optical nebular lines. The final sample for this work excludes galaxies for which either the MOSFIRE or LRIS spectrum indicated there may be foreground contamination in the spectroscopic aperture (Section 2.3). The purity of these samples has been confirmed with spatially-resolved deep HST observed optical and near-infrared imaging where foreground contaminants can be identified through photometric redshifts of galaxy subcomponents (Mostardi et al. 2013; Pahl et al. 2021).

Second, redshift uncertainties can artificially broaden and weaken the Lyman series absorption lines, resulting in a larger uncertainty in the systemic redshifts—which were derived from combining absorption line and Lyα emission redshifts in a manner similar to that discussed in Section 2.3.1—cannot explain the level of residual flux observed in composite FUV spectra, particularly for inferred N(H I) \( \geq 10^{19.5} \text{ cm}^{-2} \). Relative to the previous work of Reddy et al. (2016b), our analysis has the advantage of direct measurements of \( z_{\text{sys}} \) from the strong optical nebular emission lines, resulting in a factor of \( \sim 2 \) lower uncertainties in \( z_{\text{sys}} \). Thus, based on the precise \( z_{\text{sys}} \) and the large column densities inferred from the damping wings of Lyα, the residual flux observed in the FUV composite spectra cannot be due to redshift uncertainties.

Third, there are a few reasons why the covering fraction inferred from the H I lines may be a lower limit on the true covering fraction of high-column-density H I. First, limited spectral resolution will mask the presence of narrow (\( \Delta v \sim 300 \text{ km s}^{-1} \)) absorption components that may be opaque to LyC (and Lyα) radiation but not detectable because of the lack of prominent damping wings, corresponding to column densities of \( 18 \leq \log N(\text{H I})/\text{cm}^{-2} \leq 20 \). Section 4.2 argues that the presence of this moderate column density and unresolved gas is likely correlated with the covering fraction of optically-thick H I. Second, if different velocity components of the H I gas are not spatially-coincident, then the derived covering fraction will underestimate the true covering fraction (e.g., Vasei et al. 2016; Reddy et al. 2016b). Finally, independent of the H I column density, Lyα and LyC photons may be further attenuated if there is significant dust in the low-column-density channels of the ISM (e.g., Borthakur et al. 2014), as is assumed in the screen model of the ISM. Consequently, the line-of-sight escape fraction of LyC photons may be viewed as a more direct indicator of the effective gas and dust covering fractions (Section 4.2).

### 3.3.3. Gas Covering Fractions from Saturated Low-Ionization Interstellar Absorption Lines

As discussed in Section 1, saturated line transitions of metal ions—in particular, low-ionization interstellar absorption lines—have been widely-used to infer H I covering fractions given their relative ease of detection. As noted elsewhere (Henry et al. 2015; Rivera-Thorsen et al. 2015; Reddy et al. 2016b; Vasei et al. 2016; Steidel et al. 2018; Gazagnes et al. 2018; Chisholm et al. 2018; Du et al. 2021), covering fractions derived from the low-ionization metal lines may significantly underpredict the H I covering fraction if, for example, the metal-bearing gas traces only the regions with highest gas densities, the H I gas is metal poor, or partially-ionized H I provides significant LyC opacity and where metal ions are primarily ionized in the doubly-ionized state. Additionally, there may be some degree of emission filling of the absorption from line photons scattered along the line of sight (e.g., Prochaska et al. 2011; Scarlata & Panagia 2015), though adjacent fine-structure transitions can mitigate this effect (e.g., Steidel et al. 2016). Nevertheless, several studies have found that covering fractions deduced from the low-ionization metal lines correlate significantly with those derived directly from the H I lines (Reddy et al. 2016b; Gazagnes et al. 2018), and thus the former could potentially be used as a proxy for the H I gas covering fraction (e.g., Gazagnes et al. 2018; Chisholm et al. 2018).

With that in mind, we explored how the depths of three saturated low-ionization metal lines in the composite FUV spectra—Si II \( \lambda 1260 \), Si II \( \lambda 1527 \), and C II \( \lambda 1334 \)—correlate with \( W_\lambda(\text{LyC}) \) and \( f_{\text{cov}}(\text{H I}) \). In the optically-thin limit, the ratio of the equivalent widths of the two Si II transitions is \( W_{1260}/W_{1527} \sim 6 \). However, the observed ratio is \( W_{1260}/W_{1527} \sim 1 \), indicating that the lines are saturated and their depths are sensitive to the covering fraction of Si II enriched gas. The similarity in velocity width and depth of the low-ionization transition C II \( \lambda 1334 \) to those of the saturated Si II transitions implies that the former arises from the same gas, and that its depth is also sensitive to the covering fraction. To measure these lines, we divided the composite FUV spectra by their corresponding best-fit SPSneb models, and

| Subsample | \( R(\text{Si II} \lambda 1260) \) | \( R(\text{Si II} \lambda 1527) \) | \( R(\text{C II} \lambda 1334) \) |
|-----------|-----------------|-----------------|-----------------|
| A         | 0.46 ± 0.04     | 0.53 ± 0.04     | 0.52 ± 0.04     |
| AL        | 0.43 ± 0.04     | 0.53 ± 0.04     | 0.51 ± 0.05     |
| ALN       | 0.40 ± 0.05     | 0.48 ± 0.04     | 0.48 ± 0.04     |
| WT1       | 0.30 ± 0.07     | 0.40 ± 0.06     | 0.40 ± 0.06     |
| WT1L      | 0.32 ± 0.09     | 0.38 ± 0.07     | 0.38 ± 0.07     |
| WT1LN     | 0.24 ± 0.10     | 0.47 ± 0.07     | 0.31 ± 0.11     |
| WT2       | 0.43 ± 0.06     | 0.47 ± 0.06     | 0.46 ± 0.05     |
| WT2L      | 0.40 ± 0.07     | 0.44 ± 0.05     | 0.45 ± 0.07     |
| WT2LN     | 0.30 ± 0.07     | 0.42 ± 0.07     | 0.43 ± 0.09     |
| WT3       | 0.51 ± 0.07     | 0.64 ± 0.08     | 0.71 ± 0.05     |
| WT3L      | 0.47 ± 0.07     | 0.64 ± 0.09     | 0.65 ± 0.07     |
| WT3LN     | 0.52 ± 0.06     | 0.53 ± 0.06     | 0.55 ± 0.07     |
| ST1       | 0.36 ± 0.09     | 0.35 ± 0.09     | 0.45 ± 0.09     |
| ST1L      | 0.35 ± 0.10     | 0.37 ± 0.09     | 0.47 ± 0.09     |
| ST2       | 0.33 ± 0.08     | 0.40 ± 0.07     | 0.49 ± 0.09     |
| ST2L      | 0.29 ± 0.07     | 0.39 ± 0.06     | 0.39 ± 0.08     |
| ST3       | 0.46 ± 0.06     | 0.49 ± 0.07     | 0.48 ± 0.07     |
| ST3L      | 0.43 ± 0.07     | 0.48 ± 0.07     | 0.47 ± 0.09     |
| sST1      | 0.34 ± 0.11     | 0.41 ± 0.06     | 0.47 ± 0.08     |
| sST1L     | 0.33 ± 0.10     | 0.42 ± 0.06     | 0.46 ± 0.07     |
| sST2      | 0.40 ± 0.10     | 0.37 ± 0.10     | 0.39 ± 0.13     |
| sST2L     | 0.35 ± 0.10     | 0.36 ± 0.09     | 0.35 ± 0.13     |
| sST3      | 0.45 ± 0.05     | 0.50 ± 0.07     | 0.53 ± 0.05     |
| sST3L     | 0.41 ± 0.06     | 0.48 ± 0.07     | 0.52 ± 0.06     |

a Residual flux at line center of Si II \( \lambda 1260 \) relative to the continuum.
b Residual flux at line center of Si II \( \lambda 1527 \) relative to the continuum.
c Residual flux at line center of C II \( \lambda 1334 \) relative to the continuum.
thus allowing us to both normalize the line absorption relative to the continuum and remove any stellar absorption components (e.g., C II λ1334). The residual fluxes, \( \langle f_{\text{cov}}(\text{metal}) \rangle \), at the absorption line centers were then measured from the continuum-normalized composite FUV spectra. These values are listed in Table[5].

These residual fluxes were converted to covering fractions based on assuming the two-component model discussed in Section [3.3.1] (see also Gazagnes et al. 2018). The variations in the metal-line covering fractions, \( \langle f_{\text{cov}}(\text{metal}) \rangle \) with \( \langle W_{\alpha}(\text{Ly}\alpha) \rangle \) and \( \langle f_{\text{cov}}(\text{HI}) \rangle \) are shown in Figure [13]. These results show that galaxies with higher \( \langle W_{\alpha}(\text{Ly}\alpha) \rangle \) have lower covering fractions of metal-bearing gas. The direct comparison between the metal and HI covering fractions suggests the former is systematically smaller than the latter (see discussion above), indicating that some portion of the optically-thick HI may be metal-poor. Because of its potential utility, we provide the following empirical calibration between \( \langle f_{\text{cov}}(\text{metal}) \rangle \) and \( \langle f_{\text{cov}}(\text{HI}) \rangle \) for the independent WTL subsamples analyzed here:

\[
\langle f_{\text{cov}}(\text{metal}) \rangle = 1.50 \langle f_{\text{cov}}(\text{HI}) \rangle - 0.62,
\]

for \( 0.90 \lesssim \langle f_{\text{cov}}(\text{HI}) \rangle \lesssim 1.00 \) (shown as a thick green line in the bottom right panel of Figure [13]). We have not formally calculated errors on the slope and intercept of the relation as the subsamples are not independent of each other. In any case, while direct inferences of \( f_{\text{cov}}(\text{metal}) \) are useful, they do require a priori knowledge of \( f_{\text{cov}}(\text{HI}) \) and \( E(B-V)_{\text{los}} \) for the clumpy model of the ISM discussed above. For the screen model of the ISM, both \( \langle f_{\text{cov}}(\text{HI}) \rangle \) and \( \langle f_{\text{cov}}(\text{metal}) \rangle \) are systematically lower than the corresponding values for the clumpy model, while \( \langle f_{\text{cov}}(\text{HI}) \rangle \) is still systematically larger than \( \langle f_{\text{cov}}(\text{metal}) \rangle \). At any rate, for the same reasons given in Section [3.3.2], the limited resolution of the spectra implies that the derived \( f_{\text{cov}}(\text{metal}) \) may be a lower limit on the true covering fraction of the metal-bearing gas.

### 3.4. Summary of Composite-Fitting Results and Comparisons to Previous Works

We performed comprehensive modeling of composite FUV and optical spectra of galaxies in the MOSDEF-LRIS survey to deduce key properties of the massive stars (Section [3.1]), ionized ISM (Section [3.2]), and neutral ISM (Section [3.3]) of star-forming galaxies at redshifts \( 1.85 \leq z \leq 3.49 \); and determined how these properties vary with \( W_{\alpha}(\text{Ly}\alpha) \). The results of the spectral modeling are summarized below.

#### 3.4.1. Reddening Measures

We find a significant anti-correlation between \( \langle W_{\alpha}(\text{Ly}\alpha) \rangle \) and \( E(B-V)_{\text{cont}} \), similar to results from other studies (e.g., Shapley et al. 2003; Gawiser et al. 2006; Atek et al. 2008, 2009; Pentericci et al. 2009, 2010; Finkelstein et al. 2011, Guaita et al. 2011, Jones et al. 2012; Atek et al. 2014, Hathi et al., Du et al. 2018, 2021). Generally, this trend has been interpreted in a framework where \( \text{Ly}\alpha \) photons are preferentially attenuated (owing to their resonant scattering) compared to continuum photons, resulting in lower \( W_{\alpha}(\text{Ly}\alpha) \) with increasing \( E(B-V)_{\text{cont}} \). Alternatively, Reddy et al. (2016b) find that \( E(B-V)_{\text{cont}} \) correlates with \( f_{\text{cov}}(\text{HI}) \). This correlation arises because a galaxy with higher \( f_{\text{cov}}(\text{HI}) \) has a larger fraction of sightlines with non-negligible dust content, translating to a higher \( E(B-V)_{\text{cont}} \); i.e., the reddening measured in the case of a foreground screen of dust, namely \( E(B-V)_{\text{cont}} \), is effectively the line-of-sight reddening, \( E(B-V)_{\text{los}} \), weighted by the gas covering fraction. In this framework, the decrease in \( W_{\alpha}(\text{Ly}\alpha) \) with increasing \( E(B-V)_{\text{cont}} \) may be more directly tied to the larger fraction of \( \text{Ly}\alpha \) photons scattering out of the line of sight with increasing \( f_{\text{cov}}(\text{HI}) \) (see Section [4.2]).

We do not find a significant correlation between \( \langle W_{\alpha}(\text{Ly}\alpha) \rangle \) and \( E(B-V)_{\text{los}} \). This lack of correlation is perhaps not unexpected if the majority of \( \text{Ly}\alpha \) photons are escaping through low-column-density (and low-reddening) channels in the ISM, in which case \( W_{\alpha}(\text{Ly}\alpha) \) would be insensitive to the reddening of the (high-column-density) covered portion of the continuum, \( E(B-V)_{\text{los}} \).

Finally, \( E(B-V)_{\text{neb}} \) does not appear to correlate significantly with \( \langle W_{\alpha}(\text{Ly}\alpha) \rangle \), at least on an individual galaxy basis, with only a marginal correlation present for the composite measurements. At face value, these results run counter to those reported by Scarlata et al. (2009), who found lower \( \text{Ly}\alpha/\text{H}\alpha \) ratios (i.e., roughly translating to lower \( W_{\alpha}(\text{Ly}\alpha) \)) with increasing \( \text{H}\alpha/\text{H}\beta \), or nebular reddening (see also Trainor et al. 2016). However, this study was based exclusively on strong \( \text{Ly}\alpha \) emitters at \( z = 0.3 \), and it is possible that the inclusion of similarly strong LAEs in our \( z \approx 2 \) sample would reveal a trend that is otherwise difficult to discern based on the small fraction of LAEs in our sample.

For all the relevant subsamples presented here, \( E(B-V)_{\text{neb}} > E(B-V)_{\text{cont}} \). Other studies report a similar offset in the reddening of the nebular emission lines relative to the stellar continuum (e.g., Panelli et al. 1988, Calzetti et al. 1994, 2000; Förster Schreiber et al. 2009; Kashino et al., Reddy et al. 2010; Kreckel et al. 2013; Price et al. 2014; Reddy et al. 2015; Battistelli et al. 2016; Theios et al. 2019; Shivaei et al. 2020; Reddy et al. 2020), though the extent of the difference depends on the attenuation curves assumed for the two (e.g., Shivaei et al. 2020; Reddy et al. 2020). As noted in many of these same studies, this difference in nebular and stellar reddening may arise from the higher column densities of dust along the sightlines to the youngest stellar populations that dominate the emission line luminosities.

#### 3.4.2. Ages

Subsamples with \( \langle W_{\alpha}(\text{Ly}\alpha) \rangle > 10 \text{\AA} \) have best-fit ages a factor of \( \approx 3 - 4 \times \) younger (less than \( \approx 100 \) Myr) than those of subsamples with \( \langle W_{\alpha}(\text{Ly}\alpha) \rangle < 0 \text{\AA} (\approx 300 \) Myr). There is a marginal correlation between age and \( W_{\alpha}(\text{Ly}\alpha) \) when...
examined on an individual galaxy basis, such that galaxies with stronger Lyα emission are younger. The relative youth of galaxies with strong Lyα emission has been suggested in many previous studies (e.g., Gawiser et al. 2006; Pentericci et al. 2007; Finkelstein et al. 2007; Guaita et al. 2011; Hagen et al. 2014), though there appears to be a fairly large scatter in the relationship between Lyα strength and age (e.g., Pentericci et al. 2009; Finkelstein et al. 2009; Kornei et al. 2010). The implication for these age differences on the shape of the ionizing spectrum is discussed further in Section 4.2.4.

3.4.3. Stellar and Gas-Phase Metallicities

There is no apparent significant variation of \( \langle Z_X \rangle \) and \( \langle Z_{\text{neb}} \rangle \) with \( \langle W_X(\text{Ly} \alpha) \rangle \). The typical stellar metallicity across the subsamples is \( \langle Z_X \rangle \approx 0.08 \, Z_\odot \), and the typical nebular abundance inferred from photoionization modeling is \( \langle Z_{\text{neb}} \rangle \approx 0.4 \, Z_\odot \). The direct-method \( T_e \)-based estimates from O III \( \lambda \lambda 1660, 1666 \) point to \( \langle Z_{\text{neb}} \rangle \) consistent with those obtained from the photoionization modeling of all the strong optical nebular emission lines (Appendix B). The lack of any significant correlation between \( W_X(\text{Ly} \alpha) \) and either the stellar or gas-phase metallicity may be related to the limited dynamic range of metallicity probed by the MOSDEF-LRIS sample. In particular, Topping et al. (2020a) find a range of \( Z_{\text{neb}} \approx 0.3 - 1.0 \, Z_\odot \) for individual objects in the MOSDEF-LRIS sample, while strong LAEs at similar redshifts (\( z \approx 2 - 3 \)) are found to have lower \( Z_{\text{neb}} \approx 0.2 \, Z_\odot \) (Trainor et al. 2016). Similarly, the broader stellar mass and \( W_X(\text{Ly} \alpha) \) ranges probed by Cullen et al. (2020) for a large spectroscopic sample of \( 3 \leq z \leq 5 \) galaxies drawn from the VANDELS survey (McLure et al. 2018; Pentericci et al. 2018) allowed these authors to uncover a trend between \( W_X(\text{Ly} \alpha) \) and \( Z_\star \).

Regardless, the apparent insensitivity of \( W_X(\text{Ly} \alpha) \) to \( Z_\star \) for MOSDEF-LRIS galaxies strongly suggests that the observed variation in \( W_X(\text{Ly} \alpha) \) within the sample may be tied to factors unrelated to the intrinsic stellar population. We revisit this issue in Section 4.4.2. For the time being, we note that the offset in the sample-averaged values of \( \langle Z/X \rangle \approx 0.08 \) and \( \langle Z_{\text{neb}}/Z_\odot \rangle \approx 0.40 \) implies a ratio of (O/Fe) that is roughly \( 5 \times \) the solar ratio, placing these galaxies at the theoretical upper limit for (O/Fe) from core-collapse (Type II) supernovae (SNe) enrichment (Nomoto et al. 2006). The apparent \( \alpha \)-enhancement inferred for these galaxies is consistent with their spectrally-derived stellar population ages of less than a few hundred Myr (Section 3.4.1), placing them at a stage prior to the onset of significant Fe enrichment from Type Ia SNe (e.g., see also Steidel et al. 2016; Cullen et al. 2019; Topping et al. 2020b; Mattei & Schaye 2018).

3.4.4. Ionization Parameter, \( \log U \)

The ionization parameter, \( U \), exhibits significant variation with \( W_X(\text{Ly} \alpha) \): subsamples of galaxies with \( \langle W_X(\text{Ly} \alpha) \rangle < 0 \, \text{Å} \) have low average ionization parameters of \( \langle \log U \rangle \lesssim -2.9 \) (and as low as \( \langle \log U \rangle \approx -3.2 \)), while those with \( \langle W_X(\text{Ly} \alpha) \rangle > 0 \, \text{Å} \) have high average ionization parameters of \( \langle \log U \rangle \gtrsim -2.8 \). Additional evidence for this increase in ionization parameter with \( W_X(\text{Ly} \alpha) \) comes from the correlation between the latter and C III \( \lambda \lambda 1907, 1909 \), one which cannot be explained by abundance variations (Appendix C). These results concur with previous studies that have suggested high ionization parameters for LAEs relative to galaxies with weaker Ly\( \alpha \) emission at similar redshifts (e.g., Trainor et al. 2016). A possible physical interpretation of the trend between \( \langle W_X(\text{Ly} \alpha) \rangle \) and \( \langle \log U \rangle \) is discussed in Section 4.3.3.

3.4.5. Evidence of Binary Stellar Populations

SPS models that include the effects of binary stellar evolution (and with a high-mass cutoff of the IMF of 100 and 300 \( M_\odot \)) predict significant stellar He II \( \lambda 1640 \) emission which, when subtracted from the observed He II emission in the composite FUV spectra, yields residual (nebular) He II emission consistent with the predictions from photoionization modeling. On the other hand, SPS models that do not include the effects of binary stellar evolution, regardless of the high-mass cutoff of the IMF, lead to inferences of nebular He II emission that are significantly higher than the predictions of the photoionization models (see also Steidel et al. 2016). Only the SPS models that include stellar binarity can self-consistently explain the observed He II \( \lambda 1640 \) emission, a conclusion that applies to all of the subsamples considered in this work, irrespective of \( W_X(\text{Ly} \alpha) \).

3.4.6. Column Densities and Gas Covering Fractions

There is marginal evidence that the mean gas column density decreases with increasing \( \langle W_X(\text{Ly} \alpha) \rangle \), where the former varies from \( \langle \log [N(\text{H} I)/\text{cm}^{-2}] \rangle \approx 21.1 \) for subsamples with the lowest \( \langle W_X(\text{Ly} \alpha) \rangle \) to \( \langle \log [N(\text{H} I)/\text{cm}^{-2}] \rangle \approx 19.5 \) for subsamples with the highest \( \langle W_X(\text{Ly} \alpha) \rangle \). In all cases, however, the best-fit \( \log [N(\text{H} I)/\text{cm}^{-2}] \) imply gas that is optically thick in all the Lyman series lines and the Lyman continuum. As a result, Ly\( \alpha \) photons spatially coincident with the stellar continuum are likely escaping through optically-thin (i.e., ionized or low-column-density) channels in the ISM, or shifted out of resonance by gas with non-zero velocity.

For both the clumpy and screen geometries of the ISM considered above, we find that subsamples with \( \langle W_X(\text{Ly} \alpha) \rangle < 0 \, \text{Å} \) have mean H I covering fractions, \( \langle f_{\text{cov}}(\text{H} I) \rangle \), that are close to unity, while the modeling of subsamples with \( \langle W_X(\text{Ly} \alpha) \rangle > 0 \, \text{Å} \) rules out unity covering fractions at the \( \gtrsim 3\sigma \) level. Additional constraints on the covering fraction of metal-bearing neutral H I, \( f_{\text{cov}}(\text{metal}) \), comes from an examination of saturated low-ionization interstellar absorption lines. Covering fractions inferred from these lines are strongly anti-correlated with \( W_X(\text{Ly} \alpha) \), where subsamples with the lowest \( \langle W_X(\text{Ly} \alpha) \rangle \) have \( \langle f_{\text{cov}}(\text{metal}) \rangle \approx 0.91 \) while those with the highest \( \langle W_X(\text{Ly} \alpha) \rangle \) have \( \langle f_{\text{cov}}(\text{metal}) \rangle \approx 0.78 \). This strong anti-correlation between \( W_X(\text{Ly} \alpha) \) and the depths of the low-ionization interstellar absorption lines (or their equivalent widths) has been noted in a large number of previous studies (e.g., Shapley et al. 2003; Pentericci et al. 2007, 2009; Erb et al. 2010; Berry et al. 2012; Jones et al. 2012; Du et al. 2018; Marchi et al. 2019; Pahl et al. 2020; Du et al. 2021), and implies a lower covering fraction of metal-bearing gas with increasing \( W_X(\text{Ly} \alpha) \).

4. DISCUSSION

With the modeling results of Section 3 in hand, we are in a position to evaluate the primary mechanisms responsible for the escape of Ly\( \alpha \) photons for galaxies in our sample. The escape fraction of Ly\( \alpha \) photons is discussed in Section 4.1. Section 4.2 focuses on the role of massive stars and the gas covering fraction on the escape of Ly\( \alpha \) photons. The relations between gas covering fraction and the distribution of star formation and galaxy potential is discussed in Section 4.3.
with the connection between star-formation-rate surface density and ionization parameter. Section 4.4 briefly addresses the scatter between \( W_\lambda (\text{Ly} \alpha) \) and several other parameters examined in this work. We then conclude with a discussion of the implications of our analysis for the escape of ionizing radiation at high redshift (Section 4.5).

4.1. Ly\( \alpha \) Emission Equivalent Width and Escape Fraction

The correlations presented up to this point have been cast in terms of \( W_\lambda (\text{Ly} \alpha) \), as this quantity can be easily measured for individual galaxies and ensembles of galaxies. However, as noted in Section 3.1.3, the connection between the production/escape of Ly\( \alpha \) photons and \( W_\lambda (\text{Ly} \alpha) \) is complicated by virtue of the method used to compute \( W_\lambda (\text{Ly} \alpha) \). \( W_\lambda (\text{Ly} \alpha) \) computed using the procedures of [Kornei et al. (2010)] will not only depend on the level of Ly\( \alpha \) emission relative to the continuum, but also on the underlying absorption. This absorption is detected in some individual galaxies (typically the brighter ones), ubiquitous in composite FUV spectra (e.g., Figures 2 and 12) and, as per the discussion of Section 3.1.3 due primarily to absorption from interstellar H I. Though the net \( W_\lambda (\text{Ly} \alpha) \) for a given subsample (or individual galaxy) may be negative, there may be some residual leakage of Ly\( \alpha \) photons. Hence, to more directly connect the production and escape of Ly\( \alpha \) photons to many of the galaxy properties discussed up to this point, we calculated two additional quantities: the emission-line \( W_\lambda (\text{Ly} \alpha) \) as

\[
W_\lambda^{\text{em}} (\text{Ly} \alpha) = \frac{L(\text{Ly} \alpha)_{\text{obs}}}{L_\lambda^{\text{red}}},
\]

and the “escape” fraction of Ly\( \alpha \) photons as

\[
f_{\text{esc}}^{\text{spec}} (\text{Ly} \alpha) = \frac{L(\text{Ly} \alpha)_{\text{obs}}}{L(\text{Ly} \alpha)_{\text{int}}},
\]

where \( L(\text{Ly} \alpha)_{\text{obs}} \) and \( L(\text{Ly} \alpha)_{\text{int}} \) are the observed and intrinsic Ly\( \alpha \) emission luminosities, respectively, and \( L_\lambda^{\text{red}} \) is the mean luminosity density of the continuum just redward of Ly\( \alpha \) (see [Kornei et al. 2010]). Note that \( f_{\text{esc}}^{\text{spec}} (\text{Ly} \alpha) \) only refers to the fraction of Ly\( \alpha \) photons transiting the sightline, and does not account for photons resonantly scattered out of the spectroscopic aperture. As discussed in [Steidel et al. 2011], the total escape fraction of Ly\( \alpha \) when summing over all sightlines will typically be \( \lesssim 3 \times \) larger than \( f_{\text{esc}}^{\text{spec}} (\text{Ly} \alpha) \).

The observed Ly\( \alpha \) emission luminosity was computed as follows. First, the best-fit neutral ISM model (Section 3.3.1) was subtracted from the composite FUV spectrum, effectively removing both stellar and interstellar H I absorption. The resulting model-subtracted spectrum was integrated between the wavelength points where the Ly\( \alpha \) emission line intersects the absorption trough in the original composite FUV spectrum, yielding \( \langle L(\text{Ly} \alpha)_{\text{obs}} \rangle \). The intrinsic Ly\( \alpha \) luminosity was computed by multiplying the dust-corrected H\( \alpha \) luminosity, \( L(\text{H} \alpha) \) (see Section 3.2.1), by the intrinsic Ly\( \alpha / \text{H} \alpha \) ratio predicted by the best-fit photoionization model. This intrinsic ratio varies in the range \( (\text{Ly} \alpha / \text{H} \alpha)_{\text{int}} = 8.99 - 9.58 \) depending on the specific SPSneb model, photoionization model, and BPASS model type, and is slightly larger than the canonically-assumed value of \( (\text{Ly} \alpha / \text{H} \alpha)_{\text{int}} = 8.7 \) for an H II region temperature of \( T_e = 10,000 \text{ K} \). While \( L(\text{Ly} \alpha)_{\text{int}} \) can also be computed from the best-fit SPSneb model (i.e., integrating the model to obtain the ionizing photon production rate, \( N(\text{H}^0) \); Section 4.2, the adopted method of computing

![Figure 14. Left: Emission-line \( W_\lambda (\text{Ly} \alpha) \), denoted by \( W_\lambda^{\text{em}} (\text{Ly} \alpha) \), versus \( W_\lambda^{\text{em}} (\text{Ly} \beta) \) for the 14 subsamples with complete coverage of Ly\( \beta \) (Table 1). The solid line indicates the one-to-one relation. Right: Escape fraction of Ly\( \alpha \), denoted by \( f_{\text{esc}}^{\text{spec}} (\text{Ly} \alpha) \), versus \( W_\lambda (\text{Ly} \alpha) \) for the 10 subsamples with complete coverage of the optical nebular emission lines and Ly\( \beta \) (Table 1). The values shown assume the 100-bin SPShb models.](image-url)
The ionizing spectrum may affect the HI gas covering fraction: e.g., a harder ionizing spectrum may lead to a larger fraction of ionized sightlines through which Lyα and LyC leakage can occur (i.e., a lower HI gas covering fraction; e.g., Erb et al. 2016; Tramor et al. 2016). Additionally, there is evidence that the dust column density, or reddening, correlates with HI covering fraction (e.g., Reddy et al. 2016b). These points are addressed below.

4.2.1. Quantifying the Shape of the Ionizing Spectrum

The shape of the ionizing spectrum of massive stars is determined by the BPASS model type (binary versus single star evolution and IMF slope), $Z_*$, $\log\text{[Age/yr]}$, and the star-formation history (e.g., Stanway et al. 2016; Bouwens et al. 2016a; Steidel et al. 2016; Shivaei et al. 2018; Chevallard et al. 2018; Chisholm et al. 2019; Topping et al. 2020a). In Section 3.1.3, we motivated the choice of a constant star formation model in fitting the average FUV spectrum of an ensemble of $z \sim 2$ galaxies. Further, Section 3.2.4 presents evidence that SPS models including the effects of stellar binarity (100bin and 300bin models) are able to self-consistently explain the observed level of He II $\lambda 1640$ emission in the composite FUV spectra, while the single star models cannot. Section 3.1.3 noted a marginal correlation between $\log\text{[Age/yr]}$ and $\langle W_{\lambda}(\text{Ly}\alpha) \rangle$, while $(Z_*/Z_{\odot})$ appears to be uncorrelated with $\langle W_{\lambda}(\text{Ly}\alpha) \rangle$ (e.g., Figure 5). Based on these constraints, we can more directly examine the connection between the escape of Lyα photons and the shape (or hardness) of the ionizing spectrum by computing a commonly-used proxy for the ionizing spectrum by computing a commonly-used proxy for the ionization rate, $\xi_{\text{ion}}$, (e.g., Robertson et al. 2013; Bouwens et al. 2016a; Shivaei et al. 2018; Theios et al. 2019):

$$\xi_{\text{ion}} = \frac{N(H^0)}{L_{\text{FUV}}} \text{[s}^{-1} \text{erg s}^{-1} \text{Hz}^{-1}], \tag{8}$$

where $N(H^0)$ is the ionizing photon rate in s$^{-1}$ and $L_{\text{FUV}}$ is the luminosity density at 1500 Å in erg s$^{-1}$ Hz$^{-1}$. $\xi_{\text{ion}}$ is typically constrained by combining dust-corrected Hα and FUV luminosities (e.g., Bouwens et al. 2016a; Matthee et al. 2017; Shivaei et al. 2018; Emami et al. 2020). In this work, $\xi_{\text{ion}}$ was computed directly from the best-fit intrinsic SPSneb models, a route that obviates the need to apply potentially uncertain dust corrections to Hα and FUV luminosities (Shivaei et al. 2018), account for LyC photons that may escape the ISM or be absorbed by dust (Inoue 2001), or implement conversions between Hα luminosity and $N(H^0)$ that may not apply to the galaxies in question (e.g., Reddy et al. 2016b; Theios et al. 2019). The ionizing photon rate was obtained by integrating the best-fit intrinsic SPSneb model:

$$N(H^0) = \int_0^{912} \frac{W_{\lambda}}{hc} d\lambda, \tag{9}$$

where $\lambda$ is in Å, and $l_{\lambda}$ is the luminosity density of the best-fit intrinsic SPSneb model in erg s$^{-1}$ Å$^{-1}$. Notwithstanding the aforementioned uncertainties in computing $\xi_{\text{ion}}$ from dust-corrected Hα and FUV luminosities, such estimates (Shivaei et al. 2018) are consistent with those derived directly from the SPSneb models for fixed assumptions of the nebular and stellar dust attenuation curves.

4.2.2. Relationships between Lyα Escape, $\xi_{\text{ion}}$, and Gas Covering Fraction

The relationships between $\langle W_{\lambda}^{\text{em}}(\text{Ly}\alpha) \rangle$ and $\langle \log[\xi_{\text{ion}}/s^{-1}/\text{erg s}^{-1} \text{Hz}^{-1}] \rangle$, and between $\langle f_{\text{esc}}^{\text{spec}}(\text{Ly}\alpha) \rangle$ and $\langle \log[\xi_{\text{ion}}/s^{-1}/\text{erg s}^{-1} \text{Hz}^{-1}] \rangle$, are shown in Figure 15. The scatter in $\langle \log[\xi_{\text{ion}}/s^{-1}/\text{erg s}^{-1} \text{Hz}^{-1}] \rangle$ at a fixed $\langle W_{\lambda}^{\text{em}}(\text{Ly}\alpha) \rangle$ (or $\langle f_{\text{esc}}^{\text{spec}}(\text{Ly}\alpha) \rangle$) appears to be driven by differences in age of the stellar population, as demonstrated by the age color coding of the points shown in Figure 15. Subsamples with the youngest ages, $\log[\text{Age/yr}] \lesssim 8$, tend to have higher $\langle W_{\lambda}^{\text{em}}(\text{Ly}\alpha) \rangle$ and $\langle f_{\text{esc}}^{\text{spec}}(\text{Ly}\alpha) \rangle$ on average, and also have $\log[\xi_{\text{ion}}/s^{-1}/\text{erg s}^{-1} \text{Hz}^{-1}]$ that are marginally ($\sim 0.1$ dex) larger than those of subsamples with the oldest ages, $\log[\text{Age/yr}] \simeq 8.5$. A similar increase in $\xi_{\text{ion}}$ for strong LAEs relative to continuum-selected galaxies has also been reported at $z \sim 3$ (Nakajima et al. 2018a). At any rate, the lack of a significant correlation between $\langle W_{\lambda}^{\text{em}}(\text{Ly}\alpha) \rangle$ and $\langle \log[\xi_{\text{ion}}/s^{-1}/\text{erg s}^{-1} \text{Hz}^{-1}] \rangle$, or between $\langle f_{\text{esc}}^{\text{spec}}(\text{Ly}\alpha) \rangle$
Since the latter is solely dependent on the uncovered portion of the continuum, \( f_{\text{cov}}(\text{HI}) \) is likely a principal factor modulating \( f_{\text{esc}}(\text{Ly} \alpha) \). This is perhaps not surprising given that even very small changes in \( f_{\text{cov}}(\text{HI}) \) can lead to large variations in \( W_{\text{em}}^{\text{Ly} \alpha} \); e.g., for a fixed ionizing spectral shape, an \( \approx 3\% \) decrease in \( f_{\text{cov}}(\text{HI}) \) from 0.97 to 0.94 results in a factor of 2 increase in \( W_{\text{em}}^{\text{Ly} \alpha} \) and \( f_{\text{esc}}(\text{Ly} \alpha) \), assuming \( f_{\text{esc}}(\text{Ly} \alpha) = 1 - f_{\text{cov}}(\text{HI}) \). In other words, it is precisely because of the very large gas covering fraction that a small change in this fraction can lead to a dramatic variation in the line-of-sight (or down-the-barrel) Ly\( \alpha \) luminosity. The bottom panel of Figure 16 demonstrates that our finding that a vast majority (\( \gtrsim 95\% \)) of Ly\( \alpha \) photons are scattered out of (or removed from) the line of sight is consistent with the high covering fraction of optically-thick gas inferred from the depths of the Lyman series absorption lines (Section 3.3.2).

Moreover, there are a number of subsamples where \( 1 - f_{\text{cov}}(\text{HI}) \) actually overpredicts \( f_{\text{esc}}(\text{Ly} \alpha) \), i.e., \( f_{\text{esc}}(\text{Ly} \alpha) \lesssim 1 - f_{\text{cov}}(\text{HI}) \), implying that \( f_{\text{cov}}(\text{HI}) \) is a lower limit to the true covering fraction for the reasons discussed in Section 3.3.2. For example, the presence of unresolved moderate column density gas may further scatter Ly\( \alpha \) photons out of the line of sight. Figure 16 shows that \( f_{\text{esc}}(\text{Ly} \alpha) \) still correlates with \( 1 - f_{\text{cov}}(\text{HI}) \), and that the (additional) opacity provided by moderate column density gas (or dust) increases with decreasing \( f_{\text{cov}}(\text{HI}) \) (e.g., see also Gazagnes et al. 2020; Kakiichi & Gronke 2021).18

Several previous investigations have also emphasized the role of gas covering fraction in the escape of Ly\( \alpha \) and LyC photons (e.g., Rivera-Thorsen et al. 2015; Trairno et al. 2015; Dijkstra et al. 2016; Reddy et al. 2016b; Gazagnes et al. 2018; Chisholm et al. 2018; Steidel et al. 2018; Jaskot et al. 2019; Gazagnes et al. 2020; Matthee et al. 2021). We also highlight the recent study of Cullen et al. (2020), which finds that the

18 Reddy et al. (2016b) examined the relationship between \( f_{\text{esc}}(\text{Ly} \alpha) \) and \( f_{\text{cov}}(\text{HI}) \) for composites constructed in bins of \( E(B - V)_{\text{cont}} \) for \( L^* \) UV-selected galaxies at \( z \sim 2 \). They found a range of \( f_{\text{esc}}(\text{Ly} \alpha) \approx 0.61 - 0.18 \) and \( f_{\text{esc}}(\text{Ly} \alpha) \approx 1 - f_{\text{cov}}(\text{HI}) \) for all \( E(B - V)_{\text{cont}} \) bins except the bluest one for which \( f_{\text{esc}}(\text{Ly} \alpha) > 1 - f_{\text{cov}}(\text{HI}) \). In general, the \( f_{\text{esc}}(\text{Ly} \alpha) \) derived here are lower than those obtained by Reddy et al. (2016b) at a fixed \( f_{\text{cov}}(\text{HI}) \), as the intrinsic \( L(\text{H} \alpha) \) is larger at a fixed SFR when assuming the binary BPASS models.
variation in $Z_*$ among the galaxies in their sample is insufficient to account for the range of observed $W_\lambda^\text{H I}$, and that some other factor (i.e., gas covering fraction) likely dominates the escape of Ly\text{\textsc{o}}. Our analysis points to a similar conclusion for typical star-forming galaxies at $z \sim 2$, based on the direct modeling of the interstellar H I absorption lines and the depths of saturated interstellar metal absorption lines in the composite FUV spectra.

Finally, we briefly comment here on the large scatter in $\langle f_{\text{cov}}(\text{H I}) \rangle$ and $\langle f_{\text{cov}}(\text{metal}) \rangle$ at a given $\langle \log[\xi_{\text{ion}}/s^{-1}/\text{erg s}^{-1}\text{Hz}^{-1}] \rangle$ (e.g., Figure 17). In particular, subsamples with the highest H I (near unity) or metal covering fractions have $\langle \log[\xi_{\text{ion}}/s^{-1}/\text{erg s}^{-1}\text{Hz}^{-1}] \rangle$ that are consistent within the sampling errors with the values obtained for galaxies with lower $\langle f_{\text{cov}}(\text{H I}) \rangle$. These results suggest that the shape of the ionizing spectrum is not the sole determinative factor in the covering fraction. Section 4.3 presents evidence that another factor, namely the compactness of star formation, likely plays an important role in determining the covering fraction.

In summary, the preference for binary stellar evolution models irrespective of $\langle W_\lambda^{\text{Ly}\alpha} \rangle$ (Section 3.2.4), the absence of any significant variation of $\langle Z_* \rangle$ with $\langle W_\lambda^{\text{Ly}\alpha} \rangle$ (Section 3.1.3), and the modest anti-correlation between $\langle \log[\text{Age}/\text{yr}] \rangle$ and $\langle W_\lambda^{\text{Ly}\alpha} \rangle$ (Section 3.1.3) together imply a narrow range of $\langle \log[\xi_{\text{ion}}/s^{-1}/\text{erg s}^{-1}\text{Hz}^{-1}] \rangle \simeq 25.30 - 25.40$. This range is insufficient to account for the large variation in $\langle W_\lambda^\text{Ly}\alpha \rangle$ observed for galaxies in our sample. On the other hand, the inferred range of $\langle f_{\text{cov}}(\text{H I}) \rangle$ (Section 3.3.2) is more than sufficient to account for the variation in $\langle W_\lambda^\text{Ly}\alpha \rangle$ observed for galaxies in our sample. Furthermore, $\langle f_{\text{esc}}^{\text{Ly}\alpha} \rangle$ correlates with $1 - \langle f_{\text{cov}}(\text{H I}) \rangle$ in the manner one would expect if most of the Ly\text{\textsc{o}} opacity is due to foreground optically-thick H I (or dust, in the case of the screen model). Accordingly, the covering fraction of optically-thick H I (or dust) is the dominant factor in modulating Ly\text{\textsc{o}} emission within the spectroscopic aperture, while the shape of the ionizing spectrum—parameterized by $\xi_{\text{ion}}$—plays a minor role in modulating the emergent Ly\text{\textsc{o}} emission of the galaxies analyzed here.

### 4.3. Impact of the SFR Surface Density and Gravitational Potential on the Escape of Ly\text{\textsc{o}} and the Ionization Parameter

Section 4.2 presents evidence that the covering fraction of optically-thick H I is the dominant factor in modulating $\langle W_\lambda^\text{Ly}\alpha \rangle$ and $\langle f_{\text{esc}}^{\text{Ly}\alpha} \rangle$ among the galaxies in our sample. The question remains as to the properties of galaxies that regulate the H I covering fraction. The radiative, thermal, and mechanical feedback from star formation, stellar winds, and/or supernovae can promote the formation of ionized and/or low-column-density channels in the ISM (and CGM), providing pathways through which H I and LyC photons can escape galaxies (e.g., Gnedin et al. 2008; Ma et al. 2016; Kimm et al. 2019; Ma et al. 2020; Cen 2020; Kakuchi & Gronke 2021). Both theoretical and observational work suggest the impact of these “feedback” effects on the surrounding ISM, and the subsequent escape of Ly\text{\textsc{o}} and LyC photons, can be enhanced in regions of compact star formation (e.g., Ma et al. 2016; Sharma et al. 2016; Verhamme et al. 2017; Marchi et al. 2019; Cen 2020; Nadu et al. 2020), typically expressed by the SFR surface density, $\Sigma_{\text{SFR}}$, in units of $M_\odot\text{yr}^{-1}\text{kpc}^{-2}$. The deep CANDELS imaging in the MOSDEF survey fields allows us to examine the connection between Ly\text{\textsc{o}} escape and $\Sigma_{\text{SFR}}$ through the measurement of galaxy sizes. In addition, while previous analyses have focused almost exclusively on the impact of $\Sigma_{\text{SFR}}$ on the escape of Ly\text{\textsc{o}} and LyC photons, the galaxy potential may also play an important role (e.g., Kim et al. 2020). For example, the feedback associated with a fixed $\Sigma_{\text{SFR}}$ may be more efficient in clearing sightlines in the ISM of a low-mass (low-escape-velocity) galaxy relative to a high-mass (high-escape velocity) galaxy. This possibility is explored below by also considering $\Sigma_{\text{SFR}}$ normalized by stellar mass, $M_*$, Section 4.3.1 describes the calculation of $\Sigma_{\text{SFR}}$ and its normalization by $M_*$, while the correlation between Ly\text{\textsc{o}} escape and these quantities is discussed in Section 4.3.2. Section 4.3.3 concludes with a discussion of the correlation between the compactness of star formation and ionization parameter.

#### 4.3.1. Parameterization of the Distribution of SFR and Galaxy Potential

The distribution, or compactness, of star formation is typically parameterized by the SFR surface density, $\Sigma_{\text{SFR}}$:

$$\Sigma_{\text{SFR}} = \frac{\text{SFR}(\text{H} \alpha)}{2\pi R_c^2},$$

where $R_c$ is the effective radius within which half the total light of the galaxy is contained. These half-light radii were obtained from the single- component Sérsic fits to the HST/IF160W images of the MOSDEF-LRIS galaxies, as compiled in van der Wel et al. (2014). Note that $\Sigma_{\text{SFR}}$ was computed assuming SFR(H\alpha). Adopting the SFR(SED) inferred from broadband SED modeling (Section 2.3.3) does not significantly affect any of our conclusions.

For individual galaxies for which H\alpha and H\beta are both detected with $S/N \geq 3$, SFR(H\alpha) was computed by multiplying the dust-corrected $L(\text{H} \alpha)$ for each galaxy (Section 3.2.1) by the factor $2.12 \times 10^{-42} M_\odot\text{yr}^{-1}\text{erg}^{-1}\text{s}$, appropriate for the $Z_* = 0.001$ 100bin SPPhib models—i.e., the same

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig17.pdf}
\caption{$\langle f_{\text{cov}}(\text{H I}) \rangle$ versus $\langle \log[\xi_{\text{ion}}/s^{-1}/\text{erg s}^{-1}\text{Hz}^{-1}] \rangle$ (blue), and $\langle f_{\text{cov}}(\text{metal}) \rangle$ versus $\langle \log[\xi_{\text{ion}}/s^{-1}/\text{erg s}^{-1}\text{Hz}^{-1}] \rangle$ (red), for the ALN, WT1LN, WT2LN, and WT3LN subsamples which have coverage of Ly\beta and the optical nebular emission lines.}
\end{figure}
models assumed in fitting the broadband photometry (Section 3.3). For ensembles containing galaxies with complete coverage of the optical nebular emission lines, (SFR(Hα)) was computed by multiplying the dust-corrected (L(Hα)) by the factor derived from the best-fitting SPS-neb model. This factor is similar to the one used for individual galaxies, and depends on the exact age and metallicity of the SPS-neb model that best fits the composite FUV spectrum. Furthermore, these values of (SFR(Hα)) were divided by (f_{cov}(H\alpha)) inferred from the clumpy ISM model (Section 3.3.1) to account for the fraction of ionizing photons that escapes, and is therefore unavailable for generating Balmer recombination photons. Σ_{sSFR(H\alpha)} for individual galaxies and ensembles were then computed from the SFR(Hα), assuming the individual and mean R_e, respectively.

To examine the dependence of Lyα escape on gravitational potential, we computed Σ_{sSFR(H\alpha)} normalized by stellar mass:

$$\Sigma_{sSFR} = \frac{\Sigma_{SFR}}{M_*} = \frac{\text{SFR}(H\alpha)}{2\pi R_*^2 M_*},$$  \hspace{1cm} (11)

where the subscript “sSFR” refers to the specific SFR based on Hα, and M_* is used as a proxy for the galaxy potential. For simplicity, we assume a choice that does not affect any of the relative trends examined in this work—as the impact of feedback on the ISM is likely to be sensitive to the entire galaxy mass, not just that contained within the half-light radius.

Galaxies were grouped together based on their individually-measured Σ_{SFR} and Σ_{sSFR} to form subsamples ST1 through ST3 and sST1 through sST3, respectively (Table 1). The best-fit parameters obtained from fitting the composite spectra of these subsamples are listed in Table 2, and the average sizes, stellar masses, SFR(Hα), Σ_{SFR}, and Σ_{sSFR} for all the relevant subsamples (i.e., those with coverage of Lyα and the optical nebular emission lines) are given in Table 7.

Galaxy potentials based on dynamical and baryonic masses will be considered elsewhere. For the time being, we note that Price et al., 2020 find a highly significant correlation between dynamical and stellar mass for z ∼ 2 galaxies in the MOSDEF sample: a Spearman test of the correlation between these two variables yields $\rho = 0.67$ with a probability of $p = 5.19 \times 10^{-44}$ of a null correlation. Thus, we use $M_*$ as a proxy for galaxy potential, given that this parameter is available for every galaxy in the sample.

The grouping of galaxies based on their Σ_{SFR} and Σ_{sSFR} requires that they have detected Hα and Hβ emission lines. However, we note that grouping galaxies based on Σ_{SFR(full)} and Σ_{sSFR(full)} (which do not require individual Hα and Hβ detections) yields results similar to those presented here.

Figure 18. Dependence of H I (blue) and metal covering fraction (red) on Σ_{SFR} (left) and Σ_{sSFR} (right) for, respectively, the ST and sST subsamples with coverage of Lyβ, assuming the clumpy ISM model. The thick purple line in the top right panel denotes a linear fit to the independent subsamples constructed in bins of Σ_{sSFR}, indicating $f_{cov}(H\alpha) \propto -0.056 \log[(\Sigma_{sSFR})/Gyr^{-1} kpc^{-2}]$ (see Equation 15).

Figure 19. Correlation of $f_{cov}(H\alpha)$ (blue points) and $f_{cov}(metal)$ (red points) with average stellar mass, $\langle M_* \rangle$, for subsamples sST1L, sST2L, and sST3L.

4.3.2. Connection between Lyα Escape and the SFR Distribution and Galaxy Potential

The correlations between $W_\alpha$(Lyα) and $R_e$, SFR, and $M_*$ for individual galaxies are presented in Appendix D. Here, we focus on the individual and composite measurements of Σ_{SFR} and Σ_{sSFR} and their impact on Lyα escape. If concentrated star formation and a shallower galaxy potential lead to conditions favorable for the formation of ionized or low-column-density channels in the ISM, then we expect the gas covering fraction to correlate with Σ_{SFR} and Σ_{sSFR}. Figure 18 shows the variation of $f_{cov}(H\alpha)$ and $f_{cov}(metal)$ with Σ_{sSFR}.

The left panel of Figure 18 shows that there is no significant difference in $f_{cov}(H\alpha)$ for galaxies in the lowest and highest Σ_{SFR} bins. There is a marginally significant difference ($\approx 2\sigma$) in $f_{cov}(metal)$ for the same two bins: galaxies in the upper third of the Σ_{SFR} distribution have lower $f_{cov}(metal)$ than galaxies in the lower third of the Σ_{SFR} distribution. There does not appear to be a clear monotonic relation between either $f_{cov}(H\alpha)$ or $f_{cov}(metal)$ and Σ_{sSFR} over the dynamic range probed by the MOSDEF-LIRIS sample.

In contrast to their lack of obvious correlation with Σ_{SFR}, $f_{cov}(H\alpha)$ and $f_{cov}(metal)$ appear to be significantly anti-correlated with Σ_{sSFR}. For example, galaxies in the upper third of the Σ_{sSFR} distribution have $f_{cov}(H\alpha) = 0.91 \pm 0.02$, while those in the lower third have $f_{cov}(H\alpha) = 0.99 \pm 0.02$, a difference that is significant at the $\approx 3\sigma$ level. Similarly, there is a large and significant difference in $f_{cov}(metal)$ for galaxies in the upper and lower third of Σ_{sSFR}. Similar conclusions are reached if we consider $f_{cov}(H\alpha)$ and $f_{cov}(metal)$ from the screen model.

The difference in $f_{cov}(H\alpha)$ and $f_{cov}(metal)$ between the upper and lower third of the Σ_{sSFR} distribution is both larger and more significant that the difference in the covering fraction in the upper and lower third of the Σ_{SFR} distribution. Additionally, there is a clear monotonic trend between covering fraction and Σ_{SFR} while no such trend is apparent between covering fraction and Σ_{sSFR}. These results point to a tighter anti-correlation between $f_{cov}(H\alpha)$ and Σ_{sSFR} than between $f_{cov}(H\alpha)$ and Σ_{SFR}, in accordance with the...
Figure 20. There is a high probability (anti-correlation between covering fraction and porosity). Higher \( \langle \text{cov} \rangle \) (Å) and both \( \Sigma_{\text{SFR}} \) and \( \Sigma_{\text{SFR}}^{\text{fr}} \) are all expected to increase in such cases.

The correlations between \( W_\lambda (\lambda_{Ly}) \lambda_0 \) and both \( \Sigma_{\text{SFR}} \) and \( \Sigma_{\text{SFR}}^{\text{fr}} \) are shown for individual objects and subsamples in Figure 20. There is a high probability (\( \rho_{\text{ind}} = 0.28 \)) of a null correlation between \( W_\lambda (\lambda_{Ly}) \lambda_0 \) and both \( \Sigma_{\text{SFR}} \) and \( \Sigma_{\text{SFR}}^{\text{fr}} \) for individual galaxies, though we do find more significant differences in the average values computed for the subsamples. For example, the subsample with the highest \( \langle \Sigma_{\text{SFR}} \rangle \) has \( \langle W_\lambda (\lambda_{Ly}) \lambda_0 \rangle \geq -1.5 \AA \), while the one with the lowest \( \langle \Sigma_{\text{SFR}} \rangle \) has \( \langle W_\lambda (\lambda_{Ly}) \lambda_0 \rangle \simeq -5 \AA \), a difference in \( \langle W_\lambda (\lambda_{Ly}) \lambda_0 \rangle \) that is significant at the \( \simeq 3.5 \sigma \) level. Individual galaxies exhibit a correlation between \( W_\lambda (\lambda_{Ly}) \lambda_0 \) and \( \Sigma_{\text{SFR}} \) that is more significant than the one between \( W_\lambda (\lambda_{Ly}) \lambda_0 \) and \( \Sigma_{\text{SFR}}^{\text{fr}} \). Furthermore, the subsample with the highest \( \langle \Sigma_{\text{SFR}} \rangle \) has \( \langle W_\lambda (\lambda_{Ly}) \lambda_0 \rangle \simeq 1 \AA \) compared to \( \langle W_\lambda (\lambda_{Ly}) \lambda_0 \rangle \simeq -4 \text{ to } -7 \AA \) for subsamples with lower \( \langle \Sigma_{\text{SFR}} \rangle \), a difference that is significant at the \( \simeq 4 \sigma \) level. Interestingly, we do not find a monotonic trend between \( \langle W_\lambda (\lambda_{Ly}) \lambda_0 \rangle \) and \( \langle \Sigma_{\text{SFR}} \rangle \) for the composite measurements, suggesting a large scatter in the relationship between these two quantities (see discussion in Section 4.4).

Figure 21 shows the variation of \( \langle f_{\text{esc}}^{\text{spec}}(\lambda_{Ly}) \rangle \) with \( \langle \Sigma_{\text{SFR}} \rangle \) and \( \langle \Sigma_{\text{SFR}}^{\text{fr}} \rangle \). The difference in \( \langle f_{\text{esc}}^{\text{spec}}(\lambda_{Ly}) \rangle \) between the
Figure 21. \( f_{\text{esc}}^{\text{spec}}(\text{Ly} \alpha) \) as a function of \( \langle \Sigma_{\text{sSFR}} \rangle \) (left) and \( \langle \Sigma_{\text{sSFR}} \rangle \) (right) for subsamples constructed in bins of \( \langle \Sigma_{\text{sSFR}} \rangle \) and \( \langle \Sigma_{\text{sSFR}} \rangle \), respectively, and with coverage of Ly\( \beta \).

The shaded region in Figure 22 depicts the 95% confidence interval on the predicted relationship between \( \log U \) and \( \log[\Sigma_{\text{sSFR}}/M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}] \) given in Equation [10] normalized to pass through the point \((\Sigma_{\text{sSFR}})_0, (\log U)_0\) = \((0.5 \, M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}), -3.0\).

The SFR density within a sphere of radius \( R \) can be written as

\[
\dot{n}_{\text{SFR}} \propto \frac{\Sigma_{\text{sSFR}}}{R} \propto \Sigma_{\text{sSFR}}^{1-1/S_R}, \tag{14}
\]

where \( S_R = -2.82 \pm 0.16 \) based on fitting the relationship between \( \log[\Sigma_{\text{sSFR}}/M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}] \) and \( \log[R/\text{kpc}] \) for the independent bins of \( \Sigma_{\text{sSFR}} \). The number density of ionizing photons is proportional to the product of \( n_{\text{sSFR}} \) and \( \xi_{\text{ion}} \):

\[
n_{\gamma} \propto n_{\text{sSFR}} \xi_{\text{ion}}; \tag{15}
\]

i.e., such that an increase in \( n_{\text{sSFR}} \) by some factor results in a similar factor increase in \( n_{\gamma} \) at a fixed \( \xi_{\text{ion}} \) and, likewise, an increase in \( \xi_{\text{ion}} \) by some factor results in a similar factor increase in \( n_{\gamma} \) at a fixed \( n_{\text{sSFR}} \). We do not find a significant correlation between \( \xi_{\text{ion}} \) and \( \Sigma_{\text{sSFR}} \), and therefore assume

\[
n_{\gamma} \propto \Sigma_{\text{sSFR}}^{1-1/S_R}; \tag{16}
\]

based on Equation [14].

Combining Equations [13] and [16] with the definition of the ionization parameter as \( U \equiv n_{\gamma}/n_e \) yields the following relationship:

\[
\log U \propto \left[\frac{1}{S_R} - \frac{1}{S_{n_e}}\right] \log[\Sigma_{\text{sSFR}}/M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}]. \tag{17}
\]

The shaded region in Figure 22 depicts the 95% confidence interval on the slope of Equation [17] where the relationship has been normalized to pass through the point \((\Sigma_{\text{sSFR}})_0, (\log U)_0\) = \((0.5 \, M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}), -3.0\).

The relationship between \( \log U \) and \( \Sigma_{\text{sSFR}} \) is undoubtedly more complicated than what we have approximated here given the large differences in physical scales associated with the ionized and cold gas, and ambiguity in the physical interpretation of \( \log U \) for geometries that depart from the simple ones (plane-parallel or spherical) assumed in the photoionization modeling (Section 3.2.1). In spite of these complications,

upper and lower third of the \( \Sigma_{\text{sSFR}} \) distribution is not as pronounced as it is between the upper and lower third of the \( \Sigma_{\text{sSFR}} \) distribution. The significance of the difference in \( \langle W_\lambda(\text{Ly} \alpha) \rangle \) and \( \langle f_{\text{esc}}^{\text{spec}}(\text{Ly} \alpha) \rangle \) for galaxies in the upper and lower thirds of the \( \Sigma_{\text{sSFR}} \) distribution relative to that obtained for the upper and lower thirds of the \( \Sigma_{\text{sSFR}} \) distribution suggest that the gravitational potential may be a relevant factor in the escape of Ly\( \alpha \) photons (see also Kim et al. 2020), consistent with a framework in which compact star formation in a shallow potential results in lower gas covering fractions (Figure 18 and associated discussion). Datasets spanning a larger dynamic range in \( W_\lambda(\text{Ly} \alpha) \), \( f_{\text{cov}}(\text{H} I) \), \( f_{\text{cov}}(\text{metal}) \), \( \Sigma_{\text{sSFR}} \), and \( \Sigma_{\text{sSFR}} \) will be needed to confirm these preliminary results regarding the role of the gravitational potential in modulating \( f_{\text{cov}}(\text{H} I) \) and, as a consequence, \( f_{\text{esc}}^{\text{spec}}(\text{Ly} \alpha) \).

4.3.3. Impact of the SFR Distribution on Ionization Parameter

One significant difference between subsamples with high and low \( \langle W_\lambda(\text{Ly} \alpha) \rangle \) is in their ionization parameters (Section 3.2.5), where subsamples with higher \( \langle W_\lambda(\text{Ly} \alpha) \rangle \) also have higher \( \langle \log U \rangle \) (e.g., Figure 10). As per the discussion in Sections 3.2.2 and 3.2.3 and Figures 6 and 7, \( \langle \log U \rangle \) is insensitive to the BPASS model type and the range of ionizing spectra indicated by the best-fit SPSneb models. The question then remains as to the physical cause of the change in \( \langle \log U \rangle \) with \( \langle W_\lambda(\text{Ly} \alpha) \rangle \). Section 3.2.2 presents evidence that compact star formation in a shallow potential conditions (i.e., lower gas covering fractions) favorable for the escape of Ly\( \alpha \) photons. Here, we suggest that changes in the compactness of star formation may also be responsible for the observed variation in \( \langle \log U \rangle \).

In particular, Shimakawa et al. (2015) find a significant correlation between \( \Sigma_{\text{sSFR}} \) and \( n_e \) for \( z = 2.5 \) galaxies, such that

\[
n_e \propto \Sigma_{\text{sSFR}}^{1/S_{n_e}}, \tag{13}
\]

where \( S_{n_e} = 1.7 \pm 0.3 \). This correlation may be a consequence of the relationship between star formation activity and interstellar pressure in H II regions (Shimakawa et al. 2015), and may further imply a connection between the electron and cold gas densities, even though the two are sensitive to gas on different physical scales (i.e., 50 – 100 pc scales for the densities of H II regions versus \( \sim 1 \) kpc scales for the density of cold gas; e.g., Shirazi et al. 2014; Shimakawa et al. 2015; Jiang et al. 2019; Davies et al. 2021). 21

21 The \( n_e \) derived in bins of \( \Sigma_{\text{sSFR}} \) for the present sample are too uncertain to independently confirm a trend between \( \Sigma_{\text{sSFR}} \) and \( n_e \).
the simplified assumptions adopted here predict a relationship between $\log U$ and $\Sigma_{\text{SFR}}$ that lies within a factor of $\lesssim 2$ of the measurements for most of the subsamples considered in this work (Figure 22).22 Thus, the apparent super-linear dependence of $\Sigma_{\text{SFR}}$ on $n_e$ (Equation [13]) could plausibly explain at least part of the dependence of $\log U$ on $\Sigma_{\text{SFR}}$.

4.4. Scatter between Proxies for Ly$\alpha$ Escape and Other Galaxy Properties

A principal consequence of the dependence of $W_\lambda$(Ly$\alpha$) on covering fraction (Section 4.2) is that Ly$\alpha$ visibility is a highly stochastic function of viewing angle, and that a high $W_\lambda$(Ly$\alpha$) may signal the fortuitous alignment of a low-column-density and/or ionized channel in the ISM with the observer’s line of sight as has been suggested by radiative transfer simulations (e.g., see also Verhamme et al. 2012 [Behrens & Braun 2014, Behrens et al. 2019, Smith et al. 2019, Mauerhofer et al. 2021]. This stochasticity may be responsible for much of the scatter between $W_\lambda$(Ly$\alpha$) and other galaxy properties noted in previous studies. Examples of this scatter are shown in Figure 23 which in some cases only becomes apparent when binning galaxies by properties independent of those on the abscissa and ordinate. For instance, the top two panels show the relationship between $W_\lambda$(Ly$\alpha$) and $E(B - V)_{\text{cont}}$, including subsamples that were not constructed in bins of either $W_\lambda$(Ly$\alpha$) or $E(B - V)_{\text{cont}}$ (i.e., the ST and sST subsamples). Similarly, the bottom two panels show the relationship between $W_\lambda$(Ly$\alpha$) and $\Sigma_{\text{SFR}}$, including those subsamples not constructed in bins of either $W_\lambda$(Ly$\alpha$) or $\Sigma_{\text{SFR}}$ (i.e., the sST subsamples). These results suggest that the spread in $W_\lambda$(Ly$\alpha$) at a fixed $E(B - V)_{\text{cont}}, \log U$, or $\Sigma_{\text{SFR}}$ may in part be driven by changes in $\text{H} I$/metal covering fraction, as demonstrated by the color coding of the points in Figure 23. For instance, subsamples W1GLN and W3LN have a relatively small separation in both $\log U$ and $\Sigma_{\text{SFR}}$, yet they contain galaxies at the extreme ends of the $W_\lambda$(Ly$\alpha$) distribution. In this case, the difference in $W_\lambda$(Ly$\alpha$) between the two samples is likely due to changes in gas covering fraction.

It is worth noting that several of the correlations investigated here are not expected to be monotonic, such as that between $W_\lambda$(Ly$\alpha$) and $f_{\text{cov}}$(H I), and between $W_\lambda$(Ly$\alpha$) and other parameters that influence $f_{\text{cov}}$(H I) (e.g., $\Sigma_{\text{SFR}}, \Sigma_{\text{SFR}}$, for galaxies with lower covering fractions. A low covering fraction implies a significant escape of LyC photons that will result in a corresponding reduction in H I recombination line (e.g., Ly$\alpha$, H$\alpha$, H$\beta$, etc.) strengths. If $f_{\text{esc}}$(Ly$\alpha$) = $f_{\text{esc}}$(LyC), then one may expect $W_\lambda$(Ly$\alpha$) $\propto f_{\text{cov}}$(H I)($1 - f_{\text{cov}}$(H I)), where the first term reflects the fraction of LyC photons that photoionize hydrogen. While this function reaches a maximum value at $f_{\text{cov}}$(H I) = 0.56, additional scattering/attenuation of Ly$\alpha$ photons from moderate-column-density gas/dust—such that $f_{\text{spec}}$(Ly$\alpha$) < $f_{\text{esc}}$(Ly$\alpha$) (LyC)—may result in a turnover of the function at higher $f_{\text{cov}}$(H I). On the other hand, if $f_{\text{spec}}$(Ly$\alpha$) > $f_{\text{esc}}$(Ly$\alpha$) (e.g., Dijkstra et al. 2010 [Izotov et al. 2021]—as might be expected if a significant fraction of the LyC flux observed within the spectroscopic aperture has resonantly scattered through many mean free paths (e.g., Figure 16)—then the turnover in the relation between $W_\lambda$(Ly$\alpha$) and $f_{\text{cov}}$(H I) may occur at lower $f_{\text{cov}}$(H I). The non-monotonic dependence of $W_\lambda$(Ly$\alpha$) on $f_{\text{cov}}$(H I) and variations in the turnover of this function from galaxy to galaxy would naturally contribute additional scatter in the relations between $W_\lambda$(Ly$\alpha$) and other properties that correlate with $f_{\text{cov}}$(H I).

4.5. Implications for LyC Escape at High Redshift

While our analysis has focused primarily on the production and escape of Ly$\alpha$, it has obvious implications for LyC production and escape as well. The small variation in $\langle \xi_{\text{ion}} \rangle$ with $W_\lambda$(Ly$\alpha$) (Section 4.2) implies a narrow range of ionizing photon production efficiencies across the sample. The variation in $W_\lambda$(Ly$\alpha$) is most directly explained by the covering fraction of H I (Section 4.2). From a physical standpoint, the low-column-density and ionized channels that facilitate the escape of Ly$\alpha$ provide avenues for LyC leakage. This scenario is supported empirically by the strong connection between $W_\lambda$(Ly$\alpha$) and the ionizing-to-non-ionizing flux density ratio measured for $z \sim 3$ star-forming galaxies (Steidel et al. 2018), as well as correlations between $f_{\text{esc}}$(Ly$\alpha$) and $1 - f_{\text{cov}}$(H I) (Reddy et al. 2016B [Gazagnes et al. 2020]) (see also Section 4.2) and between $f_{\text{esc}}$(LyC) and $1 - f_{\text{cov}}$(H I).
The variation in $f_{	ext{cov}}$ (H I) alone is sufficient to account for the range of $W_{\lambda}(\text{Ly}\alpha)$ measured in our sample (Section 4.2). However, there is evidence that the hardness of the ionizing radiation field may play a more important role in the escape of Ly$\alpha$ and LyC radiation at higher redshifts ($z \gtrsim 4$) and for galaxies with fainter continuum luminosities and stronger Ly$\alpha$ emission (e.g., Trainor et al. 2016; Maseda et al. 2020). For instance, Pahl et al. (2020) report higher C IV P-Cygni emission and Ly$\alpha$ equivalent width for $z \sim 5$ galaxies compared to lower-redshift galaxies at a fixed interstellar absorption line equivalent width, suggestive of a harder ionizing spectrum on average for the former. Similarly, Atek et al. (submitted) suggest an evolution of higher $\xi_{\text{ion}}$ with redshift for galaxies of similar mass based on a compilation of $\xi_{\text{ion}}$ measurements at different redshifts. The strong correlation between $\xi_{\text{ion}}$ and the equivalent widths of optical nebular emission lines (e.g., Chevallard et al. 2018; Fang et al. 2019; Reddy et al. 2018b; Atek et al., submitted) and the evolution towards higher equivalent widths with redshift at a fixed stellar mass (e.g., Fumagalli et al. 2012; Sobral et al. 2014; Khoshtavan et al. 2016; Faisst et al. 2016; Reddy et al. 2018b) imply an increase in the average hardness of the ionizing spectrum with redshift. This increase in $\xi_{\text{ion}}$ with redshift (e.g., for galaxies of a fixed mass) may also be accompanied by a decrease in the gas covering fraction. The well-studied size evolution of galaxies (e.g., Ribeiro et al. 2016; Allen et al. 2017) points to more compact sizes with redshift at a fixed stellar mass. This size evolution combined with the increase in SFR with redshift at a fixed stellar mass (e.g., Noeske et al. 2007; Whitaker et al. 2014; Schreiber et al. 2015) together imply a more compact configuration of star formation (i.e., higher $\Sigma_{\text{SFR}}$) at higher redshifts that may favor the formation of low-column-density and/or ionized channels through which Ly$\alpha$ and LyC photons can escape.

Regardless of these evolutionary trends that may favor the escape of ionizing radiation, it is worth noting that the SPSt nebular modeling described in Section 3.1 implies that even typical star-forming galaxies at $z \sim 2$ are quite metal poor in terms of their stellar abundances: $5\%$–10\% of solar. If the escape of LyC radiation at higher redshifts ($z \gtrsim 3$) is aided by an increase in $\xi_{\text{ion}}$, then it would ostensibly point to even younger ($\lesssim 10^7$ yr) or more metal-deficient ($Z_{\odot} \lesssim 0.05 Z_{\odot}$) stellar populations at these redshifts. However, for the 100bin SPSt neb model with an age of $10^7$ yr, $\log(N_{\text{ion}}/\text{s}^{-1}/\text{erg s}^{-1} \text{Hz}^{-1}) = 25.58$ and $25.66$ for $Z = 0.001$ and $Z = 0.0001$ (i.e., $Z_{\odot}/Z_{\odot} = 0.07$ and 0.007), respectively, implying a relatively modest change of $\Delta \log(N_{\text{ion}}/\text{s}^{-1}/\text{erg s}^{-1} \text{Hz}^{-1}) \approx 0.08$ dex. The same numbers for the 300bin SPSt neb model are $\log(N_{\text{ion}}/\text{s}^{-1}/\text{erg s}^{-1} \text{Hz}^{-1}) = 25.65$ and 25.71, again implying a modest change of $\Delta \log(N_{\text{ion}}/\text{s}^{-1}/\text{erg s}^{-1} \text{Hz}^{-1}) \approx 0.06$.

Thus, it appears that changes in stellar metallicity alone are insufficient to cause significant increases in $\xi_{\text{ion}}$ relative to the values found for typical star-forming galaxies at $z \sim 2$. The analysis described in Section 4.3.2 suggests that $\Sigma_{\text{SFR}}$ and, in particular, $\Sigma_{\text{SFR}}$, may have more influence on LyC escape than the actual properties of the massive stars (e.g., stellar metallicity and age). Alternatively, strong bursts of star formation can both temporarily elevate $\xi_{\text{ion}}$ (e.g., Emami et al. 2019, 2020; Nanayakkara et al. 2020) and reduce the covering fraction. Additionally, a harder ionizing spectrum than that predicted by the BPASS models at a fixed metallicity may allow for significant production (and escape) of LyC radiation without the need for invoking extremely metal-poor stellar populations. Further insight into the relevant factors for LyC escape may be achieved by extending the joint FUV and optical spectral modeling discussed here to galaxies with stronger Ly$\alpha$ emission and/or at higher redshifts where at least most of the salient measurements are still possible, particularly at $2.7 \lesssim z \lesssim 4.0$ where the IGM is still relatively transparent and the LyC region is accessible using ground-based facilities.

5. CONCLUSIONS

We used spectral fitting and photoionization modeling of typical star-forming galaxies at redshifts $1.85 \lesssim z \lesssim 4.9$ to deduce several important characteristics of the massive stellar populations, and neutral and ionized ISM, and explore how the emergent Ly$\alpha$ line luminosity varies with these characteristics. The sample consists of 136 galaxies with deep FUV and optical spectra obtained with the Keck/LRIS and MOSFIRE spectrographs, respectively. The galaxies were binned according to $W_{\lambda}(\text{Ly}\alpha)$, $\Sigma_{\text{SFR}}$, and $\Sigma_{\text{SFR}}$, and composite FUV and optical spectra were constructed for these bins. Stellar population synthesis model fits to the composite FUV spectra were used to infer stellar metallicity, age, and continuum reddening of the massive stars. Simultaneous fits to the interstellar H I absorption lines including Ly$\alpha$ and Ly$\beta$ were used to infer line-of-sight reddening, column density, and gas-covering fraction. Photoionization modeling of the composite optical spectra of the same sets of galaxies was used to infer the nebular reddening, gas-phase oxygen abundance, and ionization parameter. The joint FUV and optical spectral modeling is also used to distinguish between single and binary stellar evolution models. Section 3.4 summarizes most of the findings from the spectral fitting, including confirmation of several previously found (anti-)correlations, such as those between $W_{\lambda}(\text{Ly}\alpha)$ and $E(B-V)_{\text{cont}}$, and between $W_{\lambda}(\text{Ly}\alpha)$ and age. Here, we summarize the key new results from our analysis.

- Based on a comparison of the inferred He II nebular emission from the FUV composite spectra and the predictions from photoionization modeling, we find that the galaxies in our sample are uniformly consistent with stellar population models that include the effects of stellar binarity, independent of $W_{\lambda}(\text{Ly}\alpha)$ (Section 3.2.4, Figure 9). Furthermore, we find little variation in the stellar and nebular metallicity with $W_{\lambda}(\text{Ly}\alpha)$ over the dynamic range probed by our sample, with $\langle Z_{\odot} \rangle \approx 0.08 Z_{\odot}$ (Section 3.1.3, Figure 3) and $\langle Z_{\text{neb}} \rangle \approx 0.40 Z_{\odot}$ (Section 3.2.5, Figure 10, Appendix B). The offset in stellar and nebular metallicity implies that the stars and gas have $(O/Fe) \approx 5 \times (O/Fe)_{\odot}$ irrespective of $W_{\lambda}(\text{Ly}\alpha)$, consistent with primary enrichment from Type II (core-collapse) SNe (Section 3.4). This conclusion is corroborated by the spectrally-derived ages that vary from $\lesssim 100$ Myr for galaxies with net positive $W_{\lambda}(\text{Ly}\alpha)$ to $\approx 300$ Myr for those with net negative age.
\langle W_{\lambda}(\text{Ly}\alpha) \rangle$ (Section 3.1.3), implying that the galaxies are observed prior to the onset of significant Fe enrichment from Type Ia SNe.

- The preference for binary stellar evolution models, the absence of any significant correlation between $\langle \xi_{\text{ion}} \rangle$ and $\langle W_{\lambda}(\text{Ly}\alpha) \rangle$, and the modest anti-correlation between $\langle \log[\text{Age}/\text{Myr}] \rangle$ and $\langle W_{\lambda}(\text{Ly}\alpha) \rangle$ together imply a relatively narrow range of ionizing spectral shapes ($\langle \log[\xi_{\text{ion}}/\text{s}^{-1}/\text{erg s}^{-1}/\text{Hz}^{-1}] \rangle \approx 25.30 \pm 25.40$, Section 4.2, Figure 15), that alone cannot account for the variation in $\langle W_{\lambda}(\text{Ly}\alpha) \rangle$ observed within the sample. On the other hand, modeling of the Lyman series absorption lines and the depths of saturated low-ionization interstellar absorption lines suggests H I and metal-bearing gas covering fractions that are correlated with $W_{\lambda}(\text{Ly}\alpha)$. The covering fractions vary from $\langle f_{\text{cov}}(\text{H} I) \rangle \approx 0.90$ and $\langle f_{\text{cov}}(\text{metal}) \rangle \approx 0.75$ for galaxies with the highest $\langle W_{\lambda}(\text{Ly}\alpha) \rangle$, to $\langle f_{\text{cov}}(\text{H} I) \rangle \approx 1.00$ and $\langle f_{\text{cov}}(\text{metal}) \rangle \approx 0.92$ for galaxies with the lowest $\langle W_{\lambda}(\text{Ly}\alpha) \rangle$ (Section 3.3.2, Figures 11 and 13).

- These inferred covering fractions are sufficient to account for the variation in $\langle W_{\lambda}(\text{Ly}\alpha) \rangle$ observed within the sample (Section 4.2). Thus, the gas covering fraction plays a more important role in modulating $W_{\lambda}(\text{Ly}\alpha)$ than the ionizing stellar spectrum for galaxies in our sample. Furthermore, we find that the fraction of Ly\$\alpha$ photons that escapes along the line of sight, $\langle f_{\text{pec}}(\text{Ly}\alpha) \rangle$, correlates with $1 - \langle f_{\text{cov}}(\text{H} I) \rangle$, suggesting that the majority of Ly\$\alpha$ photons in down-the-barrel observations of galaxies escapes through low-column-density or ionized channels in the ISM (Section 4.2, Figure 16). The dependence of $\langle W_{\lambda}(\text{Ly}\alpha) \rangle$ on $f_{\text{cov}}(\text{HT})$ implies that Ly\$\alpha$ visibility may be a highly stochastic function of viewing angle, consequently contributing to the scatter between $\langle W_{\lambda}(\text{Ly}\alpha) \rangle$ and several other galaxy properties, such as $E(B - V)_{\text{cont}}$, log $U$, and $\Sigma_{\text{SFR}}$ (Section 4.3, Figure 23).

- The apparent large scatter in $\langle f_{\text{cov}} \rangle$ at a fixed $\xi_{\text{ion}}$ (Figure 17) implies that there are factors other than the shape of ionizing spectrum that affects $f_{\text{cov}}$. In particular, we investigate the effects of compact star formation and galaxy potential on gas covering fraction. We do not observe a clear monotonic relationship between $\langle f_{\text{cov}}(\text{H} I) \rangle$ and $\langle \Sigma_{\text{SFR}} \rangle$, and we only find a significant difference in $\langle f_{\text{cov}}(\text{metal}) \rangle$ between galaxies in the lower and upper third of the $\Sigma_{\text{SFR}}$ distribution (Section 4.3.2, Figure 18). On the other hand, both $\langle f_{\text{cov}}(\text{H} I) \rangle$ and $\langle f_{\text{cov}}(\text{metal}) \rangle$ are significantly lower in galaxies with higher $\Sigma_{\text{SFR}}$. Similarly, the difference in $\langle f_{\text{pec}}(\text{Ly}\alpha) \rangle$ for galaxies in the lower and upper third of the $\Sigma_{\text{SFR}}$ distribution is larger than that of galaxies in the lower and upper third of the $\Sigma_{\text{SFR}}$ distribution (Figure 21). These results suggest that the galaxy potential may play an important role in the escape of Ly\$\alpha$ (and LyC) photons: compact star formation in a low potential may yield conditions (i.e., lower gas covering fractions) that aid the escape of these photons. Furthermore, we suggest that the correlation between ionization parameter and $\Sigma_{\text{SFR}}$ may be connected to the superlinear dependence of the latter on electron density, or interstellar pressure (Section 4.3.3, Figure 22).

This paper presents a comprehensive analysis of the composite FUV and optical spectra of a sample of typical star-forming galaxies at $z \sim 2$, focusing on how Ly\$\alpha$ escape depends on key properties of the massive stars, and neutral and ionized ISM. To conclude, we suggest a few investigations to further elucidate the mechanisms of Ly\$\alpha$ and LyC escape in high-redshift galaxies. As noted in Section 3.3, direct inferences of H I gas covering fractions at high-redshift are limited to ensembles of galaxies given the large line-of-sight opacity variations of the Ly\$\alpha$ forest. Nonetheless, several of the correlations presented here, and the dependence of the scatter in these correlations on other galaxy properties (e.g., such as those between $W_{\lambda}(\text{Ly}\alpha)$, $Z_*$, and spectrally-derived ages; between $W_{\lambda}(\text{Ly}\alpha)$, $Z_{\text{metal}}$, and log $U$; between $W_{\lambda}(\text{Ly}\alpha)$ and $\xi_{\text{ion}}$; between $W_{\lambda}(\text{Ly}\alpha)$, and $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{SFR}}$), may be further investigated on an individual galaxy basis provided sufficiently high S/N FUV and optical spectra (e.g., Topping et al. 2020, Du et al. 2021). Additionally, several ongoing ALMA programs to constrain molecular gas masses can be used to probe gas surface densities, examine their connection to interstellar pressure, and evaluate them in the context of the high electron densities and high ionization parameters inferred for high-redshift galaxies. MOSDEF-LRIS, and the ancillary HST imaging, also enable investigations of the correlation between gas covering fraction and galaxy inclination, and the subsequent effect on Ly\$\alpha$ and LyC escape. The joint FUV and optical spectral modeling presented here can be extended to galaxies at slightly higher average redshifts ($2.7 < z < 4.0$) for which the transparency of the intervening IGM and the Earth’s atmosphere allow the modeling of the higher-order Lyman series lines and LyC emission to be probed with ground-based observatories. Upcoming observations with the James Webb Space Telescope will give access to the longer-wavelength optical lines (e.g., H$_\alpha$, [N II], [S II]) for galaxies at these redshifts, aiding in photoionization modeling of their ionized ISM. Finally, ongoing optical IFU observations with the Keck Cosmic Web Imager (KCWI) will enable studies of the resonantly-scattered Ly\$\alpha$ emission (and LyC emission) in individual galaxies, likely revealing the diversity of avenues through which Ly\$\alpha$ and LyC emission escape galaxies.

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was inferred from broadband SED modeling (Section 2.3.3). For an ensemble of galaxies, ⟨SFR⟩ from the spectral fitting, SFR(SED), most consistent with those derived based on Hα curves. For the bulk of our analysis, however, we choose to present the results with the SMC extinction curve, as this curve yields

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APPENDIX

A. CONSTRAINTS ON THE CONTINUUM ATTENUATION CURVE

As noted in Section [5.1.1] the composite FUV spectra were initially fit with the SPSneb models assuming three dust attenuation curves. For the bulk of our analysis, however, we choose to present the results with the SMC extinction curve, as this curve yields SFRs from the spectral fitting, SFR(SED), most consistent with those derived based on Hα, SFR(Hα). The calculation of SFR(Hα) for individual galaxies and composites (subsamples) is presented in Section [4.3.1]. For individual galaxies, SFR(SED) was inferred from broadband SED modeling (Section [2.3.3]). For an ensemble of galaxies, SFR(SED) was determined by the normalization of the SPSneb model that best fit the composite FUV spectrum (Section [3.1.1]), and is similar to that obtained by averaging the SFR(SED) of individual galaxies contributing to the composite. For the purposes of comparing SFR(SED) and SFR(Hα), we highlight a few additional salient details below.

Binary stellar evolution or a higher mass cutoff of the IMF results in a larger ionizing photon luminosity, Q(Hα), and hence larger L(Hα), per unit SFR. The factors used to convert the dust-corrected L(Hα) to SFR(Hα) are [2.12, 1.52, 2.69, 1.96] × 10^{-42} M_⊙ yr^{-1} erg^{-1} s for the Z = 0.001 100bin, 300bin, 100sin, and 300sin SPSneb models, respectively, and are essentially larger...
Figure A1. Comparison of SFR(H\textalpha) and SFR(SED) for individual objects with significant detections of H\textalpha and H\beta (circles) and for the 16 composites with complete coverage of the optical nebular emission lines (diamonds). SFRs derived assuming the SMC curve are denoted by the cyan and blue symbols; those derived assuming the Calzetti et al. (2000) curve are denoted by the orange and red symbols. In all cases, SFR(H\textalpha) is calculated by dust-correcting $L$(H\textalpha) using the Cardelli et al. (1989) extinction curve. The line indicates the one-to-one relation between SFR(H\textalpha) and SFR(SED). The panels show the comparisons for the four flavors of BPASS models discussed in Section 2.3.3. The average offsets (differences) in dex between log[\text{SFR(H\textalpha)}]/M\odot yr$^{-1}$ and log[\text{SFR(SED)}]/M\odot yr$^{-1}$ for the 16 composites are indicated for the SMC and Calzetti et al. (2000) cases in the lower right corner of each panel.

constant as a function of age beyond $10^7$ yr. On the other hand, SFR(SED) is primarily determined by the non-ionizing UV luminosity and therefore is not particularly sensitive to binary stellar evolution or the high-mass cutoff of the IMF (Theios et al. 2019). Similarly, the variations in SFR(H\textalpha) and SFR(SED) with $Z_*$ are generally small over the range of relevant $Z_*$—e.g., $\approx 7\%$ variations in SFR(H\textalpha) for the $Z_* = 0.001$ versus $Z_* = 0.002$ models—compared to the variations induced by changing the high-mass cutoff of the IMF or including the effects of binary stellar evolution. As noted in Section 2.3.3, we assumed the $Z_* = 0.001$ BPASS models when fitting the broadband photometry of individual galaxies while, for the galaxy ensembles, $Z_*$ is the best-fit value obtained when fitting the SPShneb models to the composite FUV spectra (Section 3.1.1).

Finally, we note that varying the dust attenuation curve can have a large effect on SFR(SED), which can change by a factor of $\approx 2 - 4 \times$ depending on the colors of the object (or ensemble). At a fixed observed FUV color, curves with a steep dependence of attenuation on wavelength yield lower reddening, and hence lower SFR(SED), than shallower curves (e.g., Pettini et al. 1998, Reddy et al. 2012b). Consequently, SFR(SED) computed with the SMC curve are systematically lower than those computed with the Calzetti et al. (2000) curve, while those computed with the Reddy et al. (2015) curve lie between the SMC and Calzetti et al.
Figure [A1] shows comparisons between $\langle SFR(H\alpha) \rangle$ and $\langle SFR(SED) \rangle$ for individual objects and composites of galaxies having complete coverage of the optical nebular emission lines. Though only individual objects with significant $H\alpha$ and $H\beta$ detections are shown in the figure, for a fixed attenuation curve their $\langle SFR(H\alpha) \rangle$ and $\langle SFR(SED) \rangle$ generally lie within 20% of the mean values obtained for the composites which include galaxies irrespective of significant individual detections of $H\alpha$ and $H\beta$.

Having computed $\langle SFR(H\alpha) \rangle$ and $\langle SFR(SED) \rangle$ using the self-consistent modeling described above, we find that the two agree within a factor of $\approx 2$ only if we assume the SMC extinction curve for the reddening of the stellar continuum. In contrast, the Calzetti et al. (2000) curve yields $\langle SFR(SED) \rangle$ that is systematically larger than $\langle SFR(H\alpha) \rangle$ by $0.4$ to $0.5$ dex in $\log([SFR/M_\odot \ \text{yr}^{-1}])$. These conclusions hold irrespective of the effects of binary stellar evolution and variations in the high-mass cutoff of the IMF between 100 and 300 $M_\odot$, as indicated in the four panels of Figure [A1].

The preference for the SMC extinction curve in describing the reddening of the stellar continuum is not unique to this analysis. Earlier studies suggested that young and low-mass galaxies at $z \gtrsim 2$ may follow an attenuation curve that is steeper than the commonly-assumed Calzetti et al. (2000) curve (e.g., Baker et al. 2001; Reddy et al. 2006; Siana et al. 2008, 2009; Reddy et al. 2010, 2012a; Lee et al. 2012; Oesch et al. 2013; De Barros et al. 2016). More recently, Reddy et al. (2018a) found that the relationship between dust attenuation—parameterized by the ratio of the infrared and unobscured FUV luminosities (i.e., IRX)—and FUV slope, $\beta$, is best reproduced by the SMC extinction curve for sub-solar metallicity stellar populations at $z \sim 2$ (see also Theios et al. 2019). ALMA dust continuum and $[C\,\text{ii}]$ surveys of modestly-reddened $z \gtrsim 2$ galaxies also point to a steep (SMC-like) dust curve (Bouwens et al. 2016a; Fudamoto et al. 2017, 2020). Such a steep curve is also favored by observations of local analogues of high-redshift galaxies (Salim et al. 2018).

The requirement of an SMC-like dust curve for obtaining consistent values of $\langle SFR(H\alpha) \rangle$ and $\langle SFR(SED) \rangle$ does not preclude the possibility that some galaxies in our sample are better described by shallower dust curves. Specifically, Shivaei et al. (2020) find that MOSDEF galaxies in the upper half of the stellar mass and gas-phase abundance distributions have a dust curve similar in shape to the Calzetti et al. (2000) curve, and shallower than the curve for lower mass (and lower gas-phase abundance) MOSDEF galaxies. This conclusion corroborates previous findings of a mass-dependence of the shape of the dust curve (e.g., Pannella et al. 2009; Reddy et al. 2010; Bouwens et al. 2016b). In the present context, we simply note that the comparison between $\langle SFR(H\alpha) \rangle$ and $\langle SFR(SED) \rangle$ implies an attenuation curve that is steeper than the Calzetti et al. (2000) curve for the subsamples formed by the parameters listed in Table [1].

**B. DIRECT ELECTRON-TEMPERATURE-BASED METALLICITIES**

The detection of the intercombination lines O IIP $\lambda\lambda 1660, 1666$ in the composite FUV spectra provides an independent measurement of the oxygen abundance via the “direct” metallicity method. The average O IIP $\lambda\lambda 1660, 1666$ luminosity was computed by directly integrating over the line pair in the composite FUV spectrum for the ALN subsample—the only subsample with complete coverage of the optical nebular emission lines where O III $\lambda 5007$ is significantly detected—after subtracting a locally-determined continuum. The O IIP luminosity was corrected for dust obscuration assuming $E(B-V)_{\text{neb}}$ and the Cardelli et al. (1989) extinction curve (Table 5). The ratio of the dust-corrected O IIP $\lambda\lambda 1660, 1666$ luminosity to that of O IIP $\lambda 5007$ yields an estimate of the electron temperature of the O IIP-emitting region, $T_e (\text{O IIP}) = 13400 \pm 1100$ K (e.g., Villar-Martín et al. 2004). Using the relationship between the temperatures of the O IIP- and O IIP-emitting regions (i.e., the $T_2 - T_3$ relation) given in Campbell et al. (1986), and the abundance relations provided in Izotov et al. (2006), we derive an O abundance of $12 + \log(O/H)_{\text{dir}} \simeq 8.01 \pm 0.10$, provided that O is predominantly in the singly- or doubly-ionized stages. Note that the abundances derived using the collisionally-excited lines are most sensitive to the highest temperature regions and will thus underestimate the abundances relative to those derived from nebular recombination lines. Based on measurements of collisionally-excited and recombination lines in star-forming knots of local galaxies (Esteban et al. 2014) and H II regions (Blanc et al. 2015), the typical offset in abundances derived from the two sets of lines is $0.24$ dex (see also discussion in Steidel et al. 2016). Adding $0.24$ dex to the direct method abundance yields $12 + \log(O/H) = 8.26 \pm 0.10$, or $(Z_{\text{neb}}) \simeq 0.37 \pm 0.09$, in excellent agreement with that obtained from the photoionization modeling. Note that there may be a potentially large (and unaccounted for) systematic error in the extrapolation of the nebular dust attenuation curve to FUV wavelengths and the resulting dust corrections to O IIP. However, the agreement between the direct-method abundance and those obtained from the photoionization modeling suggests the dust corrections inferred from the Cardelli et al. (1989) curve are reasonable.

**C. C IIP $\lambda 1907, 1909$**

As noted in Section [3.2.5] additional evidence for the higher ionization parameter of galaxies with stronger Ly$\alpha$ emission comes from C IIP $\lambda\lambda 1907, 1909$, which is frequently used as a probe of the ionizing radiation field (e.g., Garnett et al. 1995; Shapley et al. 2003; Erb et al. 2010; Stark et al. 2015; Vanzella et al. 2016; Berg et al. 2016; Schenyina et al. 2017; Maseda et al. 2017; Schaerer et al. 2018; Nakajima et al. 2018b; Hutchison et al. 2019; Du et al. 2020; Manali et al. 2020; Feltre et al. 2020; Ravindranath et al. 2020; Tang et al. 2021). The relationship between $W_\lambda (\text{Ly}\alpha)$ and $W_\lambda (\text{C IIP})$ for sub-samples ALN and WT with complete coverage of the optical nebular emission lines—and hence complete coverage of C IIP in the composite FUV spectra given the redshift distribution of the galaxies in these subsamples ($z < 2.6$)—is shown in Figure [C1]. For context, the figure also includes measurements for extreme-emission-line galaxies (EELGs) from Du et al. (2020), where $W_\lambda (\text{Ly}\alpha)$ was measured using the same methodology adopted here. The uncertainties on $W_\lambda (\text{C IIP})$ for the aforementioned composites prevents us from independently confirming a trend between $(W_\lambda (\text{C IIP}))$ and $(W_\lambda (\text{Ly}\alpha))$. However, these measurements are consistent with those

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24 An upward correction to $\langle SFR(H\alpha) \rangle$ to account for the fraction of escaping ionizing photons (as inferred from the clumpy ISM model; Sections [3.3.1] and [3.3.2]) does not significantly affect the SFR comparisons discussed here. Such corrected $\langle SFR(H\alpha) \rangle$ are considered in Section [4.3].
obtained from previous studies (e.g., Shapley et al. 2003; Stark et al. 2014, 2015; Nakajima et al. 2018a; Ravindranath et al. 2020) that find a significant correlation between $W_{\widetilde{\lambda}}$ obtained from previous studies (e.g., Shapley et al. 2003; Stark et al. 2014, 2015; Nakajima et al. 2018a; Ravindranath et al. 2020)) and $W_{\lambda}$, which lie at similar redshifts ($z \sim 2$) to MOSDEF-LRIS galaxies. For clarity, one of the EELGs from Du et al. (2020) which has $W_{\lambda}(\text{Ly}\alpha) = 132 \pm 11\; \text{Å}$ and $W_{\lambda}(\text{C}\text{III}) = 13.2 \pm 0.8\; \text{Å}$ is not shown. Composite measurements of the EELGs are indicated by the large dark green diamonds.

In addition to the shape of the ionizing spectrum, $W_{\lambda}(C\text{III})$ is also sensitive to the carbon abundance (Garnett et al. 1995). To quantify the extent to which variations in $W_{\lambda}(C\text{III})$ may be driven by changes in C abundance, we compared the C3O3 ratios (defined in Table 4) measured for the subsamples with the predictions of the best-fit photoionization models (Section 3.2) for a range of C/O. Figure C2 shows the predicted C3O3 as a function of $\log (C/O)$ for $Z_{\text{neb}} = 0.4Z_{\odot}$, the typical nebular abundance indicated by the photoionization modeling presented in Section 3.2. These predictions can be compared with the C3O3 calculated for each subsample using the measurements in Table 5. The measured C3O3 for subsamples with complete coverage of the optical nebular emission lines are also shown in Figure C2 color-coded by the $W_{\lambda}(\text{Ly}\alpha)$ for those subsamples. In considering the sample as a whole (i.e., subsample ALN), we find that the photoionization models discussed in Section 3.2 reproduce the measured C3O3 ratios if we assume $\log (C/O) = -0.46 \pm 0.13$, a value similar to that of local dwarf galaxy H I regions (Kobulnicky & Skillman 1998; Berg et al. 2019) of the same O abundance of $12 + \log (O/H) \simeq 8.3$ ($Z_{\text{neb}} \approx 0.4Z_{\odot}$). The inferred C/O in terms of the solar value ($\log (C/O)_{\odot} = -0.26$; Asplund et al. 2009) is $\log (C/O) = -0.20 \pm 0.13$. Note that this is similar to the inferred value of $\log (N/O)_{\odot} = -0.34 \pm 0.01$, where $\log (N/O) = -1.20 \pm 0.01$ (Section 3.2.1) and $\log (N/O)_{\odot} = -0.86$ (Asplund et al. 2009), and suggests a common nucleosynthetic origin for C and N.

The measurement uncertainties in C3O3 are not particularly constraining insofar as the implied $\log (C/O)$, and there does not appear to be any significant trend between $\log (C/O)$ and $W_{\lambda}(\text{C}\text{III}))$. This result is perhaps not so surprising given the lack of any significant trend in O abundance (or gas-phase metallicity, $Z_{\text{neb}}$) with $W_{\lambda}(\text{Ly}\alpha)$ (Section 3.2.2; Figure 10). Consequently, the significant correlation between $W_{\lambda}(\text{C}\text{III})$ and $W_{\lambda}(\text{Ly}\alpha)$ (Figure C1) is likely driven by changes in the ionizing radiation field rather than by abundance variations (e.g., see also Jaskot & Ravindranath 2016; Nakajima et al. 2018b; Ravindranath et al. 2020).

**Figure C1.** Variation of $(W_{\lambda}(C\text{III}))$ with $(W_{\lambda}(\text{Ly}\alpha))$. Values obtained for the ALN, WT1LN, WT2LN, and WT3LN subsamples which have complete coverage of the optical nebular emission lines are indicated by the blue filled circles. For comparison, also shown are the individual measurements (small light green diamonds) of extreme emission-line galaxies (EELGs) from Du et al. (2020), which lie at similar redshifts ($z \sim 2$) to MOSDEF-LRIS galaxies. For clarity, one of the EELGs from Du et al. (2020) which has $W_{\lambda}(\text{Ly}\alpha) = 132 \pm 11\; \text{Å}$ and $W_{\lambda}(C\text{III}) = 13.2 \pm 0.8\; \text{Å}$ is not shown. Composite measurements of the EELGs are indicated by the large dark green diamonds.

D. CORRELATIONS BETWEEN $W_{\lambda}(\text{Ly}\alpha)$ AND $R_{e}$, SFR, AND $M_*$ FOR INDIVIDUAL GALAXIES

Figure D1 summarizes the correlations between $W_{\lambda}(\text{Ly}\alpha)$ and $R_{e}$, SFR(\text{Ho}), and $M_*$ for individual galaxies in the sample. The data indicate a significant anti-correlation between $W_{\lambda}(\text{Ly}\alpha)$ and $R_{e}$ with a probability of $p_{\text{ind}} = 0.01$ that the two are

25 As is the case with O abundances determined from collisionally-excited O lines (Appendix B), C abundances derived from C III]λ1907, 1909 may underestimate those derived from the optical C recombination lines. However, in the present context, we are interested in the relative abundances derived for the different subsamples and are therefore not concerned with offsets in the absolute C abundance.
Figure C2. ⟨C3O3⟩ versus ⟨log U⟩ for the ALN, WT1LN, WT2LN, and WT3LN subsamples which have complete coverage of the optical nebular emission lines, color-coded by ⟨W(λLyα)⟩. Also shown are the photoionization model predictions for the relationships between C3O3 and log U for Z neb = 0.4Z⊙ and different values of C/O.

Figure D1. Variation in W(λLyα) with half-light radius R e (left), SFR(Hα) (middle), and M∗ (right) for individual galaxies. SFR(Hα) is shown only for those galaxies where Hα and Hβ are both detected with S/N > 3. Each panel indicates the Spearman correlation coefficient and p-value for the displayed variables.

uncorrelated based on a Spearman rank correlation test. The observation of compact (≤ 1 kpc) sizes for strong Lyα emitters has been noted in many previous studies, and likely reflects the underlying correlations between W(λLyα) and luminosity/mass, and between size and luminosity/mass (e.g., Shibuya et al. 2019 and references therein).

A Spearman test indicates a relatively high probability (p ind = 0.26) of a null correlation between W(λLyα) and SFR(Hα). Finally, the data indicate a significant anti-correlation between W(λLyα) and M∗, with p ind < 0.01 (right panel of Figure D1), a result that has been found (or suggested) by a number of other studies (e.g., Gawiser et al. 2006; Pentericci et al. 2007; Finkelstein et al. 2007; Pentericci et al. 2009; Guaita et al. 2011; Jones et al. 2012; Hagen et al. 2014; Hathi et al. 2016; Du et al. 2018; Marchi et al. 2019).
The aforementioned correlations, particularly between $W_\lambda(\text{Ly}\alpha)$ and both size and stellar mass, have generally been interpreted to reflect the less-evolved state of galaxies with stronger Ly\alpha emission. This interpretation is supported by the apparent anti-correlation between $W_\lambda(\text{Ly}\alpha)$ and age, where the latter is inferred either from broadband SED fitting or from FUV spectral fitting (Section 3.1.3). However, the strong Ly\alpha emission observed in some evolved high-redshift galaxies implies that the emergent Ly\alpha emission is not solely related to galaxy youth and may also depend on the covering fraction of gas or dust (e.g., Pentericci et al. 2009; Finkelstein et al. 2009; Kornei et al. 2010), an inference that is supported by our findings (Sections 4.2.3). Our analysis also suggests that the galaxy potential may play an important role in gas covering fraction (Section 4.3) which, consequently, gives rise to an anti-correlation between $W_\lambda(\text{Ly}\alpha)$ and stellar mass (e.g., Kim et al. 2020).