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Early Results from GLASS-JWST. XXII. Rest-frame UV–Optical Spectral Properties of Lyα Emitting Galaxies at 3 < z < 6

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Abstract

Lyα emission is possibly the best indirect diagnostic of Lyman continuum (LyC) escape since the conditions that favor the escape of Lyα photons are often the same that allow for the escape of LyC photons. In this work, we present the rest-frame UV–optical spectral characteristics of 11 Lyα emitting galaxies at 3 < z < 6—the redshift range that optimizes between intergalactic medium attenuation effects and temporal proximity to the epoch of reionization. From a combined analysis of JWST/NIRSpec and MUSE data, we present the Lyα escape fraction and study its correlation with other physical properties that might facilitate Lyα escape. We find that our galaxies have low masses (80% of the sample with log(M*) < 9.5 M_☉), compact sizes (median R_e ~ 0.7 kpc), low dust content, moderate [O III]/[O II] flux ratios (mean ~ 6.8 ± 1.2), and moderate Lyα escape fractions (mean f_{esc}^\alpha ~ 0.11). Our sample shows characteristics that are broadly consistent with low-reddish galaxies with Lyα emission, which are termed as “analogs” of the high-redshift population. We predict the Lyα escape fraction in our sample to be low (0.03–0.07), although larger samples in the postreionization epoch are needed to confirm these trends.

Unified Astronomy Thesaurus concepts: Galaxies (573); High-reddish galaxies (734); Lyman-alpha galaxies (978)

1. Introduction

One of the main science drivers behind the James Webb Space Telescope (JWST) is spectroscopic confirmation and characterization of the galaxies formed during the crucial Epoch of Cosmic Reionization (EoR), i.e., when the intergalactic medium (IGM) transforms from neutral to a completely ionized state (see Robertson 2022 for a review). Lyman continuum (LyC: λ < 912 Å) photons escaping into the neutral IGM from star-forming galaxies can reionize the universe by z = 6 only if a substantial fraction (∼10 %) of the photons escape from the galaxies’ interstellar and circumgalactic media (ISM and CGM, respectively; e.g., Robertson et al. 2015; Finkelstein et al. 2019). Early data from JWST have revealed insights into the ISM conditions and ionizing photon production in reionization-era galaxies at z > 6 (Curtis-Lake et al. 2023; Robertson et al. 2022; Tacchella et al. 2022; Cameron et al. 2023; Fujimoto et al. 2023; Trump et al. 2023). However, directly estimating the escape fraction of LyC photons (f_{esc}) is almost impossible at z > 4.5 since the photons get absorbed by the dense neutral IGM along the line of sight (Inoue et al. 2014).

While a number of indirect tracers have been used to predict LyC_{esc}—e.g., [S II] emission deficit, Mg II emission, and high [O III]/[O II] emission (Zackrisson et al. 2013; Nakajima & Ouchi 2014; Henry et al. 2018; Wang et al. 2021; Flury et al. 2022a; Xu et al. 2022, 2023), one of the best indicators of LyC f_{esc} is Lyα emission—the brightest nebular recombination line of hydrogen atom (e.g., Gazagnes et al. 2020; Pahl et al. 2021). LyC leakers tend to show a strong Lyα emission escape in nearby z < 0.5 sources (Verhamme et al. 2017; Izotov et al. 2018b; Flury et al. 2022b) as well as at higher redshifts (z ~ 2–3; Steidel et al. 2018; Rivera-Thorsen et al. 2019; Naidu et al. 2022). Since Lyα scatters resonantly in H I, the resultant emission profile carries information about the neutral hydrogen in the IGM and the EoR (Stark et al. 2010; Treu et al. 2012), as well as the gas covering fraction, column density, and dust geometry of the host galaxy from which the intrinsic Lyα emission emerges (Neufeld 1991). Since Lyα remains the strongest diagnostic and has now been observed in some of
the highest-redshift galaxies using JWST (Boyett et al. 2023; Bunker et al. 2023; Mascia et al. 2023; Saxena et al. 2023), it is now essential to understand the physical processes that determine Lyα escape, and to disentangle the effects of the ISM and IGM.

Over the last several years, studies have aimed to understand the escape of Lyα emission from galaxies at redshifts where the ISM is fully ionized. With the union of the Hubble Space Telescope (HST)/Cosmic Origins Spectrograph (COS) and the Sloan Digital Sky Survey (SDSS), samples of low-redshift (z < 0.5) analog galaxies have been studied with detailed spectroscopic coverage from the rest-frame UV to optical (e.g., blueberries, green peas, Lyman-break analogs, and LyC emitters; Cardamone et al. 2009; Heckman et al. 2011, 2015; Henry et al. 2015; Yang et al. 2017a, 2017b; Jaskot et al. 2019; Flury et al. 2022a, 2022b; Hayes et al. 2023). Diagnostics to predict Lyα properties have begun to emerge: Hayes et al. (2013, 2014) show how the spatial extent of the scattered Lyα emission varies with galaxy properties. Other studies investigate the escape fraction of Lyα photons and the galaxy characteristics that promote strong Lyα emission (Henry et al. 2015; Rivera-Thorsen et al. 2015; Yang et al. 2017b). Moreover, Mg II emission has been shown to correlate strongly with Lyα, further indicating low column densities in the ISM (Henry et al. 2018; Chisholm et al. 2020; Xu et al. 2022, 2023). And, importantly, low-redshift analogs have been used to develop predictors for LyC escape (Izotov et al. 2016, 2018a; Flury et al. 2022b), demonstrating the strong link between LyC and Lyα.

However, a critical question remains: are these diagnostics and correlations applicable in the EoR? The answer to this question bears heavily on our interpretation of the high-redshift galaxy samples now being uncovered with JWST. An initial and correlations applicable in the EoR? The answer to this

IGM is fully ionized. With the union of the Hubble Space

escape of Lyα

ISM and IGM.

2. Data Acquisition and Sample Definitions

This work focuses on 11 Lyα emitting sources in the field of the lensing cluster A2744. Our study uses spatially resolved optical IFU spectroscopic data from VLT/MUSE and deep near-infrared spectroscopy from JWST/NIRSpec to obtain rest-frame UV–optical spectra. The final list of targets in our sample and their properties are listed in Table 1, and the details of the sample selection are discussed in the sections to follow.

2.1. VLT/MUSE Spectroscopy

Optical spectroscopy using the VLT/MUSE instrument was performed on the A2744 cluster region as part of the GTO program 094.A-0115 (PI: Richard; Mahler et al. 2018; Richard et al. 2021). The program targeted the central regions of the massive cluster using the wide field mode, with a 2′ × 2′ mosaic of MUSE pointings. The wavelength coverage of the observations ranges between 4750 and 9350 Å, with a spectral resolution varying between R = 2000–4000. The reduced data cubes are publicly available in the form of .fits files.17 Mahler et al. (2018) published the full spectroscopic catalog of objects with measured redshifts. Richard et al. (2021) published a follow-up catalog of Lyα emission line measurements, with an emission line detection limit of (0.77–1.5) × 10−18 erg s−1 cm−2 at 5σ. This parent catalog of MUSE LAEs18 was used to select a subset of 17 LAEs that were observed with NIRSpec as part of the GLASS-JWST program.

2.2. JWST/NIRSpec Spectroscopy

This work uses near-infrared spectroscopic data in the Abell 2744 field obtained from the GLASS-JWST ERS program (ID 1324, PI: Treu; Treu et al. 2022). This observation provides high-resolution spectroscopy (R = 2700) over an observed wavelength range of \( \lambda_{\text{obs}} \approx 0.8–5.2 \, \mu m \) using the NIRSpec multiband spectroscopy mode. The GLASS-JWST observations were carried out with three spectral configurations: G140H/F100LP (0.97–1.82 μm), G235H/F170LP (1.66–3.05 μm), and G395H/F290LP (2.87–5.14 μm). Each of the three high-resolution gratings was exposed for 4.9 hours. The MSA target selection is discussed in Treu et al. (2022). All the JWST data used in this paper can be found in MAST: doi:10.17909/fqaq-p393.

We use the official STScI JWST pipeline19 (version 1.8.2) and the msasexp code20 with the updated set of reference files that include in-flight flux calibrations (CRDS_CONTEXT= “jwst_1041.pmap”) to produce Level 2 and 3 products.

17 http://archive.eso.org/scienceportal/home

18 Although historically, the term Lyα emitter or “LAE” has been used to describe galaxies with Lyα EW > 20 Å, in our study we call any galaxy with Lyα emission detected in the MUSE data an LAE regardless of their EW.

19 https://github.com/spacetelescope/jwst

20 https://github.com/gbrammer/msasexp
<table>
<thead>
<tr>
<th>No.</th>
<th>ID</th>
<th>$R_e$ (kpc)</th>
<th>$z_{sys}$</th>
<th>$v_{sys}$ (km s$^{-1}$)</th>
<th>FWHM$_{\text{Ly}\alpha}$ (km s$^{-1}$)</th>
<th>$F_{\text{Ly}\alpha}$ (10$^{-20}$ erg cm$^{-2}$ s$^{-1}$)</th>
<th>Ly$\alpha$ EW (Å)</th>
<th>$f_{\text{Ly}\alpha}$</th>
<th>$O_{32}$</th>
<th>F(Ly$\alpha$)/F(H$\alpha$)$^b$</th>
<th>F(H$\alpha$)/F(H$\beta$)$^b$</th>
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<td>174 ± 41</td>
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<td>95 ± 17</td>
<td>0.23 ± 0.04</td>
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<td>2.0 ± 0.4</td>
<td>2.89 ± 0.18</td>
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<td>5.186</td>
<td>107 ± 5</td>
<td>128 ± 19</td>
<td>177.7 ± 158.5</td>
<td>28 ± 25</td>
<td>0.02 ± 0.01</td>
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<td>0.7 ± 0.0</td>
<td>5.2 ± 1.18</td>
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<td>249.2 ± 224.1</td>
<td>6 ± 6</td>
<td>0.03 ± 0.02</td>
<td>4.5 ± 6.0</td>
<td>0.15 ± 0.3</td>
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<td>4</td>
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<td>168 ± 123</td>
<td>0.2 ± 0.15</td>
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<td>1.8 ± 5.5</td>
<td>5.2 ± 29.2</td>
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<td>2653.7 ± 444.1</td>
<td>108 ± 18</td>
<td>0.15 ± 0.02</td>
<td>12.7 ± 4.3</td>
<td>1.4 ± 0.3</td>
<td>2.92 ± 0.36</td>
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<td>54 ± 9</td>
<td>0.04 ± 0.01</td>
<td>14.0 ± 0.8</td>
<td>0.5 ± 0.1</td>
<td>3.2 ± 0.37</td>
<td>6.2 ± 1.1</td>
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<td>63 ± 8</td>
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<td>1.7 ± 0.2</td>
<td>3.26 ± 0.32</td>
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<td>349 ± 91</td>
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<td>53 ± 17</td>
<td>0.04 ± 0.01</td>
<td>...</td>
<td>0.4 ± 0.1</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>11</td>
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<td>2.94</td>
<td>159 ± 28</td>
<td>184 ± 15</td>
<td>418.0 ± 187.1</td>
<td>39 ± 18</td>
<td>0.04 ± 0.02</td>
<td>2.5 ± 2.0</td>
<td>0.4 ± 0.1</td>
<td>2.9 ± 0.59</td>
<td>5.1 ± 1.8</td>
</tr>
</tbody>
</table>

**Note.** No. indicates the object serial number matching the color scale in Figures 3 and 4.

$^a$ $O_{32}$ and $R_{23}$ denotes the dust-corrected ratio of ([O III] $\lambda$5007/[O II] $\lambda$3727, 3729) and ([O III] $\lambda$5007 + [O II] $\lambda$3727, 3739)/H$\beta$ respectively. For sources where H$\beta$ falls in the detector gaps, we perform dust correction assuming a mean $E(B-V) = 0.09$.

$^b$ Observed flux ratios.
Morishita et al. (2022) have discussed the data reduction process and observation strategy in detail. In short, we downloaded the Level 1b data products from the MAST portal. calwebb_detector1, which is the first step of the reduction, was already run on the raw detector exposures and are provided in the Level 1b outputs. We implement the second and third steps of the reduction, the calwebb_spec2 and calwebb_spec3 routines, to perform flat-fielding, wavelength calibrations, path-loss corrections, and background subtractions. Nodded observations of our MSA slitlet exposures were used to perform local background subtraction since our sources are compact. The resultant 2D spectra are visually inspected, and the 1D spectra are optimally extracted, following the method outlined by Horne (1986).

The high spectral resolution and the broad wavelength coverage of NIRSpec enable detection of standard rest-frame optical emission lines like [O II] λλ3727, 3729, Hβ, [O III] λλ4959, 5007, and Hα up to z ∼ 7, allowing for precise measurements of the optical spectral properties of our sources.  

2.3. Sample Selection

A sample of 17 MUSE LAEs with confident Lyα redshifts were included in the NIRSpec MSA configuration. This sample is not magnitude complete but provides an ideal sample to compare with the nearby UV-bright green pea population (Henry et al. 2015; Yang et al. 2017b), extreme emission line galaxies (Erb et al. 2016), Lyman-break analogs (Heckman et al. 2015), LyC-leaking galaxies (Izotov et al. 2016), and starbursts (Rivera-Thorsen et al. 2015, 2017) in the literature, which are believed to be low-redshift analogs of high-z LAEs. 12 of those 17 LAEs show strong rest-frame optical line detection whose redshifts and spectral properties can be measured with confidence (Mascia et al. 2023; G. Prieto-Lyon et al. 2023, submitted). One of these 12 shows very faint Lyα detection with an insufficient signal-to-noise ratio (S/N) below 3. We use the remaining 11 LAEs as the core sample for this work (Table 1). Our sample is identical to that of G. Prieto-Lyon et al. (2023, submitted), who focus on the Lyα velocity offsets.

2.4. Catalogs

We use the redshifts from Mahler et al. (2018) catalog primarily to select our 11 Lyα emitting galaxies at z > 3. The catalog is publicly available. We used the rest-frame UV continuum measurements from the Richard et al. (2021) catalog in our analyses. The UV continuum is derived using the photometric catalogs of A2744, which include photometry information from HST/Advanced Camera for Surveys (ACS) and WFC3/IR of the Hubble Frontier Fields project (HST-GO/DD-13495; Lotz et al. 2017). We use the ASTRODEEP catalog from Merlin et al. (2016), and Castellano et al. (2016) for reporting the stellar mass and SFRs of our targets. The stellar mass and SFR estimates are derived from spectral energy distribution (SED) fitting, taking into account the nebular emission line contribution. See Castellano et al. (2016) for details.

2.5. Comparison Sample

We aim to test whether the low-redshift (z ≤ 0.4) analogs of high-z LAEs are similar to the LAEs at a cosmologically significant redshifts (z > 3) in terms of rest-frame optical spectral properties. But first, we place our high-z sample in the context of the broader z ∼ 3–6 LAE population previously reported in the literature. To select an emission line survey for z = 3–6 LAEs to be compared with our sample, we use the publicly available MUSE observations taken in the Hubble Ultra Deep Field (HUDF) region (Inami et al. 2017; Bacon et al. 2023). We chose this survey since this is the deepest spectroscopic survey ever performed, and the catalog contains the most comprehensive measurements we require to compare with our high-redshift sources. The catalog is available through the CDS/Vizier database or the MUSE data products website.

For the low-redshift analog population, we use Hayes et al. (2023) as our primary sample, which compiles the HST/COS measurements of 87 UV-bright galaxies, observed at high resolution with the far-UV (FUV) G130M/G160M gratings. The COS data are drawn from GO 11522 (PI: Green), GO 11727 (PI: Heckman), GO 12027 (PI: Green), GO 12269 (PI: Scarlata), GO 12583 (PI: Hayes), GO 12928 (PI: Henry), GO 13017 (PI: Heckman), GO 13293 (PI: Jaskot), GO 13744 (PI: Thuan), GO 14080 (PI: Jaskot), GO 14201 (PI: Malhotra), GO 14635 (PI: Izotov), GO 15136 (PI: Izotov), GO 15639 (PI: Izotov), and GO 15865 (PI: Henry). This comprehensive sample includes sources that are frequently classified as low-redshift analogs of high-z galaxies due to their strong Lyα emission and emission line properties, like the green pea population, LyC-leaking galaxies, extreme emission line galaxies, Lyman-break analogs, and compact starbursts (Heckman et al. 2011, 2015; Wofford et al. 2013; Henry et al. 2015; Rivera-Thorsen et al. 2015, 2017; Izotov et al. 2016, 2018a, 2021; Yang et al. 2017b; Jaskot et al. 2017, 2019; Xu et al. 2022). The corresponding rest-optical data are obtained from SDSS data release 16 (DR16; Ahumada et al. 2020). The Lyα and optical emission line properties measurements for this extensive sample are obtained from Hayes et al. (2023) via private communication. These galaxies are in the redshift range between z = 0.020 and z = 0.44 and sample large ranges of stellar mass and SFRs. We refer to this compilation of galaxies as low-z analogs. In addition to the sample described above, we include 88 LyC emitter candidates from the Low-z Lyman Continuum Survey (LzLCS) sample (Flury et al. 2022a). 50% of these galaxies are confirmed LyC leakers. All galaxies in this sample exhibit strong Lyα emission. We consider them separately from the Hayes et al. (2023) sample as their low-resolution spectra preclude Lyα line profile analyses.

3. Data Analyses and Measurements

We utilize MUSE data to construct Lyα narrowband images and derive the Lyα flux, EW, line width, and velocity. We use rest-frame optical emission lines ([O III] λλ5007, Hβ, [O II] and Hβ) from JWST/NIRSpec spectra to measure the systemic redshifts and emission line ratios accurately to derive the ionization, metallicity, and dust properties. The measured Hα and Hβ ratios enabled dust correction of the observed line fluxes to estimate Lyα fLya correctly (see Table 1). We start by describing the NIRSpec-derived quantities first.
3.1. Rest-frame Optical Line Measurements

The rest-frame optical emission lines of our LAE sample are obtained from the JWST NIRSpec spectroscopy. The data reduction pipeline steps, outlined in Section 2.2, produce wavelength and flux-calibrated, combined, rectified 2D spectra for each slit. A 1D spectrum and its associated error spectrum are extracted from the 2D spectrum using an optimal extraction algorithm (Horne 1986). Figure 2 shows the Hα, [O III], and [O II] lines for three example sources. We derive the systemic redshift from the [O III] λ5007 emission line center and constrain all the other lines to have the same redshift in the given source. The fluxes and their uncertainties were derived for each emission line by fitting a Gaussian model, which are then dust corrected following the prescription outlined in Section 3.2 to produce the final flux ratio estimates reported in Table 1. For calculating the ratio of Lyα output to the rest-frame optical line flux, the optical fluxes need to be corrected by an additional slit-loss fraction to compensate for the portion of emission missed by the coverage of the NIRSpec slits. The slit-loss fraction is calculated as the fraction of the UV continuum light from within the NIRSpec slit open shutter area to the total light from the host galaxy boundary defined by the HST segmentation map. The slit-loss fractions for our sources range between 0.55 and 0.78, which are encouraging, and indicate that our line ratios are representative of most of the gas in the galaxy.

3.2. Dust Correction

We corrected the rest-frame optical emission line fluxes for dust extinction using Balmer decrement measurements. Assuming hydrogen lines emit from an optically thick H II region obeying Case B recombination, we considered the intrinsic Hα/Hβ ratio = 2.86. We adopted a Cardelli et al. (1989) extinction curve to compute the nebular color excess E(B − V). We took k_Hα = 2.53 and k_Hβ = 3.6. The corrected emission line fluxes are \( \text{Line}_{\text{corrected}} = \text{Line}_{\text{obs}} \times 10^{0.4E(B-V)k_β} \), where k_β is derived from the Cardelli et al. (1989) extinction curve at the wavelength of the specified line.

3.3. Lyα Narrowband Image Construction

We constructed pseudo-narrowband Lyα images using the MUSE data cubes, each centered on the position and wavelength of the corresponding Lyα line. We closely followed the method designed by Leclercq et al. (2017). We used a wide spatial aperture to include all the detectable Lyα emission above the noise level. The spectral bandwidths for constructing the Lyα narrowband image were chosen to include more than 95% of the total integrated Lyα line flux and to maximize the S/N within a 5″ × 5″ aperture of the said object. The chosen spectral bandwidths range between ~10 and 30 Å for our sources.

In this study, source crowding is a serious issue for many objects since almost all objects have projected close neighbors within a few arcseconds. However, these neighbors are typically at other redshifts than our chosen Lyα emitters, so they contaminate the narrowband signal only with continuum emission. To remove the continuum properly, we performed median filtering in the spectral direction in a wide window of 100 spectral pixels to ignore any emission lines in the MUSE data cube (similar to Wisotzki et al. 2016; Herenz & Wisotzki 2017; Leclercq et al. 2017). This produced a continuum-only data cube with all emission lines removed. A continuum-free data cube was then computed by subtracting this filtered data cube from the original. The resulting Lyα images for eight of our objects with surface brightness contours at 10^{-16} (inner dotted white), 10^{-17} (dashed white), and 10^{-18} erg s^{-1} cm^{-2} arcsec^{-2} (outer dotted white) are shown in Figure 1.
3.4. Integrated Lyα Flux and EW

The Lyα flux was computed by integrating the data cubes inside a circular aperture corresponding to the radius known as the curve of growth (CoG) radius or “CoG radius” (rCoG), similar to Leclercq et al. (2017). We averaged the flux in successive annuli of 1 pixel thickness around the emission center. rCoG was determined by the annular radius for which the averaged flux reaches the noise value and the cumulative flux distribution flattens. The center of this last annulus corresponds to rCoG. From this aperture, we extracted a spectrum and integrated the flux corresponding to the Lyα line width; the borders of the line are set when the flux goes under zero. This method is more robust than using a single, fixed spatial aperture for all objects. This also ensures that the Lyα flux, including the diffuse low-surface-brightness signal at the outskirts, was included for each object. Our flux values are thus higher by a factor of ∼1.5–3 from the reported values in the public catalog of Richard et al. (2021). The extracted integrated spectrum for three example objects is shown in Figure 2.

Figure 2. The Lyα line profiles extracted from rCoG from Figure 1 are shown in orange with rest-frame optical emission lines overplotted for three example LAEs in our sample. The different rows indicate different galaxies. The emission lines shown are [O III] λ5007 in the first column (green), Hα in the second column (blue), and [O II] λλ3726, 3729 in the third column (purple). Note, the emission lines shown here are not corrected for slit losses.

3.5. Lyα Escape Fraction

Following a prescription similar to Hayes et al. (2005), we calculate the Lyα escape fraction as \( f_{\text{Lyα}} = \frac{L_{\text{Lyα}}}{L_{\text{Hα}}} \). The Case B Lyα/Hα ratio is between 8.1 and 9.0. For consistency with previous studies, we use 8.7. Here, \( L_{\text{Hα}} \) is the observed Lyα luminosity and \( L_{\text{Hα}}^{\text{int}} \) is the intrinsic dust-corrected Hα luminosity. The corrected intrinsic Hα luminosity is given by \( L_{\text{Hα}}^{\text{int}} = L_{\text{Hα}}^{\text{obs}} \times 10.\exp(0.4E(B - V)) \) (see Section 3.2 for details).
3.6. Lyα FWHM and Red Peak Velocity

We nonparametrically characterize the FWHM of the red component of the Lyα emission using the specutils package of python. We corrected the FWHM of the Lyα line for the spectral line spread function (LSF) of MUSE approximating it as a Gaussian. The FWHM of the LSF is wavelength dependent, and we used the value for the MUSE Deep Mosaic fields (with ten hours of exposure time) given by Bacon et al. (2017), which follows:

\[
F_{\text{mosaic}} = 5.835 \times 10^{-8} \lambda^2 - 9.080 \times 10^{-4} \lambda + 5.983. \tag{1}
\]

It should be kept in mind that the FWHM measurement becomes unreliable for intrinsically narrow lines (FWHM\(\text{intrinsic} \lesssim 75 \text{ km s}^{-1}\)) dominated by the LSF (Verhamme et al. 2015, 2017). The red peak velocity of Lyα is determined by measuring the velocity offset of the red component of the Lyα line relative to the systemic redshift of the sources. The systemic redshifts are determined from the brightest rest-frame optical emission line (\(\text{[OIII]} \lambda 5007\)) from the JWST NIRSpec spectra.

4. Lyα Emission in the \(z > 3\) MUSE LAE Population

It is now well established that there is extended Lyα emission (or “halos”) around individual LAEs (Wisotzki et al. 2016; Leclercq et al. 2017). Studies have found that the Lyα halo fraction goes up to 80%–90% for UV-selected Lyα-emitting galaxies at high redshift (2 < \(z\) < 5). Our sample is also no exception. Figure 1 shows a representative sample of eight out of the 11 galaxies in our sample. The white horizontal bar in each panel shows the physical length scale of 5 kpc. The spatial extent of the Lyα emission spans a large range, from 10 to 50 kpc. To quantify the extent of the diffuse emission, we plot the Lyα luminosity as a function of a size ratio in Figure 3 (left panel). The latter is the ratio of rCoG (the spatial boundary of the Lyα emission shown by the green dashed circles in Figure 1) to the Petrosian radius containing 90% of the UV continuum flux (\(R_{\text{pet}}\)). The ratio of these two measured quantities is always >1 and varies from 1.5 to 9. This indicates that the Lyα emission of the galaxies is much more extended spatially than each host galaxy’s stellar light (similar to Wisotzki et al. 2016; Leclercq et al. 2017). The positive trend with Lyα luminosity states that galaxies with more extended Lyα emission have a higher rCoG and produce a higher integrated Lyα output. The solid black line overlaid on top shows the best-fit relation with 1\(\sigma\) uncertainties indicated by the dashed blue lines. The extended Lyα emission implies that our sources have a significant amount of cool/warm gas in the CGM.

4.1. Lyα Spectral Shape

The Lyα profiles of three example galaxies out of the total of 11 targets in our sample are shown in Figure 2. We see a variety of spectral morphologies in the Lyα line. Most are relatively asymmetric, with more than one component. This diversity is consistent with previous observations of galaxies with strong Lyα emission (Kulas et al. 2012; Erb et al. 2014; Henry et al. 2015; Erb et al. 2016). At a spectral resolution of \(R \sim 3000\), we see double-peaked Lyα profiles in three out of 11 galaxies (i.e., 27%). Although a double-peaked profile is not ubiquitous in typical star-forming galaxies with Lyα observations (Östlin et al. 2014), they were found in 90% of the nearby (\(z < 0.3\)) green pea population in Henry et al. (2015) and Yang et al. (2017b), and in confirmed LyC leakers in a wide range of redshifts (Rivera-Thorsen et al. 2017; Verhamme et al. 2017; Izotov et al. 2018b, 2021). On the other hand, at higher redshift, Kerutt et al. (2022) found that 33% of objects below \(z = 4\) have a blue peak in Lyα emission, but that fraction drops to 16% for \(4 < z < 5\). The significant drop in the blue peak fraction at higher redshift is due to the rising neutral gas fraction in the intervening IGM, eating away the blue component and leaving only the red peak behind in the observed spectra (Laursen et al. 2011; Hayes et al. 2021). These are consistent with our high-redshift sample at \(z = 3–6\).

4.2. Is Our Sample Representative of the Larger \(3 < z < 6\) MUSE LAE Population?

Our primary goal in this study is to measure any correlation between \(j_{\text{esc}}^{\text{Lyα}}\) and other physical properties facilitating \(j_{\text{esc}}^{\text{Lyα}}\) for...
Section 2.5. As shown in Figure 3, the increased gas and dust content of more massive galaxies, properties. We compare the Lyα measured Lyα sensitively on redshift LAEs in terms of Lyα and LyC emission properties and the output and host galaxy properties. We detect continuum in HST imaging with the population of HUDF Lyα LAEs with well-constrained masses but may be consistent with other estimates. These two galaxies fall outside the range of the MUSE HUDF measurements. Our sample shows a positive correlation of our sample are overall consistent with the HUDF sample. However, the former covers a larger range in stellar mass. Five of our galaxies show an Lyα escape difficult, hereby decreasing the measured Lyα EW. The negative correlation in our galaxies, however, is not statistically significant (τ = 0.19, p = 0.22; see Figure 3). Still, the stellar mass and Lyα EW distributions of our sample are consistent with the HUDF sample. Nine out of the 11 galaxies in our sample have stellar masses below 10^{9.5} M_⊙. Note that two galaxies in our sample have extremely low values of stellar mass with M_* < 10^{9.5} M_⊙. These two galaxies fail outside the range of the MUSE HUDF LAEs with well-constrained masses but may be consistent with the population of HUDF Lyα sources with little to no detected continuum in HST imaging (Maseda et al. 2017). The two objects may also be subjected to uncertain mass measurements with underestimated errors.

In Figure 3 (right panel), we show SFR versus the UV continuum luminosity measured at 1500 Å. Our sources occupy a similar region in the parameter space as the MUSE sample. Three sources show SFR > 2 M_⊙ yr^{-1}, slightly higher than the typical values in the HUDF sample. This possibly arises from the different SFR estimators used in the different catalog measurements. Our sample shows a positive correlation (τ = 0.59, p = 0.04), which is expected since the SFRs are derived from the UV luminosity estimates. The SFRs of our sample vary between ~0.1-10 M_⊙ yr^{-1}, which indicate a diverse population, but representative of high-z LAEs previously reported in the literature.

5. How Do the Low-redshift Analog Galaxies Compare with Galaxies at Redshift > 3?

With the measurements of Lyα emission properties and the rest-frame optical emission line ratios, we are ready to investigate how our high-z LAE sample compares with the low-redshift analogs and LyC emitters (Flury et al. 2022a; Hayes et al. 2023).

5.1. Lyα FWHM versus Red Peak Velocity

With the availability of the JWST NIRspec spectra, we can measure the systemic redshift of our z > 3 sources based on their brightest rest-frame optical emission lines. This enables us to determine the Lyα red peak velocity offset with confidence. In Figure 4 in the top left panel, we show the FWHMs of the Lyα profiles as a function of the velocity offset for our targets. Our 3 < z < 6 LAE sources are shown in circles, with each color indicating a different source, as listed in Table 1. The blue squares indicate the z < 0.5 galaxies, which are analogs to the high-z LAEs (sample from Hayes et al. 2023). We find a strong positive correlation between the velocities and FWHMs in our sample (τ = 0.67, p = 0.01), similar to the trend observed with the low-redshift analog galaxies (τ = 0.23, p = 0.003). This is also in strong agreement with the prediction from the radiative transfer (RT) theory, which states that a low, neutral hydrogen column density causes Lyα photons to scatter less and thus helps them to escape more easily. This makes the Lyα line narrower (lower FWHM), brighter (enhanced flux), and less redshifted (lower velocity offset) compared to the systemic velocity. One caveat is that the neutral IGM can have a nonnegligible effect on the Lyα profile, preferentially attenuating the flux of the blue component of the profile by a factor of 2 at z ~ 3 (Hayes et al. 2021; Hayes & Scarlata 2023). This would have an indirect effect on the Lyα red peak FWHM and velocity offsets at higher redshift (z > 9), where the damping wing of the Lyα absorption due to the IGM crosses v = 0 and spills over to the red side of the Lyα line. However, the effect at z ~ 3–5 is expected to be much less, and we do not expect any significant change to the observed correlation.

This similarity between the low-z and high-z samples, and their agreement with the RT models suggest that the mechanisms regulating the output of Lyα may not vary with redshift. The mean red peak velocity for our sample is 207 ± 53 km s^{-1}. This is consistent with the measurements from the low-z analogs, with a mean velocity = 241 km s^{-1}. The strong positive correlation for the z > 3 galaxies indicates that the Lyα line width and velocity shift may also be correlated in z > 6 galaxies, although both are impacted by neutral IGM gas at these redshifts. This empirical relation, after being properly calibrated with further z > 6 measurements, could possibly be used in the future to derive the systemic redshifts of even higher redshift galaxies from the measurement of the FWHM of the Lyα line alone.

5.2. Lyα Escape Fraction

We estimate the escape fraction of Lyα photons reaching the detector from the Lyα/Hα flux ratio, as described in Section 3.5. We find that the escape fraction varies between 0.02 and 0.26, with a mean f_{esc} = 0.10 ± 0.03, which is slightly lower than the low-redshift population (mean f_{esc} = 0.23). High-redshift LAEs from existing studies show a large range of escape fractions: Hayes et al. (2010) find f_{esc} ~ 0.05 while Steidel et al. (2011) reports f_{esc} ~ 0.3 for z ~ 2 LAEs. Trainer et al. (2015) also estimate an escape fraction of ~30% for a sample of faint LAEs at z ~ 2.7. However, we should note that many of these previously existing studies of z > 2 LAEs lacked rest-frame optical spectra with sufficient sensitivity to measure the Hα flux and correctly perform dust correction. The f_{esc} values for our sample are listed in Table 1 and are plotted against Lyα EW in the upper middle panel of Figure 4 (circles). The low-redshift analogs and the LzLCS sample are also shown using squares and triangles, respectively. The two quantities show a positive correlation for our sources (τ = 0.71, p = 0.03), similar to the low-redshift LAEs (τ = 0.45, p = 10^{-6}). Five of our galaxies show an Lyα escape fraction > 10%.
Interestingly, the low-redshift samples show a $\sim0.4$ dex spread in $\text{Ly}_\alpha$ EW for a given $f_{\text{esc}}^\text{Ly}_\alpha$, which could be related to the stellar population properties. Multiple factors like the initial mass function, metallicity, or the presence of binaries can make the ionizing spectrum harder, which can produce more ionizing photons, and therefore $\text{Ly}_\alpha$ photons, for a given nonionizing UV luminosity (Malhotra & Rhoads 2002). Compared to the low-$z$ analogs, our sample falls more toward the higher EWs for a given $f_{\text{esc}}^\text{Ly}_\alpha$, which could indicate more extreme stellar populations in the $z > 3$ galaxies.

In general, when the column density of the gas is low, $\text{Ly}_\alpha$ photons scatter much less, resulting in smaller velocity offsets and greater $\text{Ly}_\alpha$ escape. A similar relationship is also seen in the LyC leakers. Lower velocity offsets correspond to broader lines, a greater LyC escape, and a greater $\text{Ly}_\alpha$ escape fraction (Izotov et al. 2018a). Thus, we expect a negative trend between the velocity offset and the $\text{Ly}_\alpha$ escape fraction. We show the relation between these two quantities for our objects (circles) in the upper right panel in Figure 4, compared with the low-redshift analog galaxies (squares). Taken alone, our sample does not show any trend, and there is a considerable scatter in our high-$z$ sources. A larger sample can provide better inference on the validity of this relation for high-redshift galaxies.

### 5.3. Galaxy Morphology

Concentrated star formation and high-SFR surface densities are necessary for producing an ample intensity of ionizing radiation, opening ionized channels for the escape of excess $\text{Ly}_\alpha$ photons. Hence, compact, highly star-forming galaxies host strong $\text{Ly}_\alpha$ emission. Indeed, our sample of $z > 3$ LAEs is sufficiently compact in UV continuum size—90% of our sample has an effective radius $< 1.5$ kpc as observed from the HST/ACS images. Our sample’s mean effective radius ($R_e$) is $\sim1.1$ kpc, with some galaxies exhibiting $R_e$ as low as 0.1 kpc. This is expected since galaxies with strong $\text{Ly}_\alpha$ emission likely represent galaxies in earlier stages of evolution with younger ages and smaller sizes. The effective sizes of our sources are given in Table 1. This finding is also qualitatively consistent with those of Malhotra et al. (2012) and Hayes et al. (2023). They found that LAEs, in general, are drawn from the more compact end of the size distribution of normal star-forming galaxies. Quantitatively, Malhotra et al. (2012) find LAEs to...
have half-light radii close to 1.0 kpc at $z = 2$–6, which are in good agreement with our measurement of the effective radius.

5.4. Variation of the $[\text{O} \text{III}] / [\text{O} \text{II}]$ Ratio with Ly$\alpha$ Escape Fraction

The $[\text{O} \text{III}] \lambda 5007 / [\text{O} \text{II}] \lambda 3727, 3729$ ratio (or $O_{32}$, in short) traces the ionization parameter of the H II regions in a galaxy. A classical H II region model uses two zones. If the neutral gas gets sufficiently depleted due to ionizing photons from young stars, the outer edge of the H II regions gets truncated. This reduces the $[\text{O} \text{II}]$ emission, resulting in a high $O_{32}$ ratio. This scenario indicates that low, neutral gas column density channels allow Ly$\alpha$ and LyC photons to escape more easily. Thus a high $O_{32}$ ratio has been proposed to trace “density-bounded” H II regions in LAE galaxies, which can generate a lot of ionizing radiation, and thus a lot of Ly$\alpha$ photons (Jaskot & Oey 2013; Nakajima & Ouchi 2014).

Izotov et al. (2016) found observational evidence for the first time that high $O_{32}$ ratios are a potential signature of LyC leakage, and can trace a low-density path through the ISM of galaxies along the line of sight. Similarly, Nakajima et al. (2013) and Nakajima & Ouchi (2014) found that galaxies with a high $O_{32}$ ratio in low-redshift analog populations like green peas and Lyman-break analogs, and in high-redshift ($z = 2$–3) galaxies have a high Ly$\alpha$ escape fraction. Figure 4’s lower left panel shows the $O_{32}$ ratio as a function of the Ly$\alpha$ escape fraction for our sample (circles). We show the LzLCS galaxies from Flury et al. (2022a; green triangles) and low-redshift analog galaxies from Hayes et al. (2023; blue squares) for comparison. The LzLCS sample and the low-$z$ analog galaxies show a positive trend between the two quantities ($\tau = 0.51$, $p = < 10^{-7}$). In our sample, only six out of 11 galaxies have simultaneous detection of both $[\text{O} \text{III}]$ and $[\text{O} \text{II}]$ emission lines to derive the $O_{32}$ ratio. Our sources have $O_{32}$ ratios between 2.5 and 14.1 and are overall consistent with the values seen in the low-redshift sources but do not exhibit any statistically significant correlation between $[\text{O} \text{III}] / [\text{O} \text{II}]$ and $f_{\text{esc}}^{\text{Ly}\alpha}$ ($\tau = 0.06$, $p = 0.57$). Although a larger sample is needed to draw any conclusion, checking whether this correlation exists at high redshift is crucial since $O_{32}$ is one of the key diagnostics available to JWST at $z > 7$.

5.5. Ionization and Metallicity

Gas-phase metallicity is a key property of the host galaxy ISM since it is a record of a galaxy’s star formation history and gas infall/outflow. Metallicity estimates can be made with metal lines divided by hydrogen recombination lines, such as $([\text{O} \text{III}] \lambda \lambda 5007, 4959 + [\text{O} \text{II}] \lambda 3727) / H\beta (R_{23}$ index; Pagel et al. 1979; Kewley & Dopita 2002). Cowie et al. (2011) found that low-redshift LAEs exhibit lower metallicities, compact sizes, and younger ages compared to a UV-continuum-selected sample of star-forming galaxies at similar stellar masses and redshifts. These findings are consistent with the idea that LAEs are galaxies in the early stages of evolution. On the other hand, the ionization state, traced by $O_{32}$, is sensitive to the degree of excitation and the optical depth of the H II region in a galaxy (e.g., Brinchmann et al. 2008); a large $O_{32}$ may be due to a low optical depth and a high escape fraction of ionizing photons, as discussed in the previous section. But $O_{32}$ and metallicity are related: the metallicity of the gas has a direct impact on both the ionizing spectrum and relative ionic abundances of nebular oxygen (Chisholm et al. 2019). It also has a secondary effect on the electron density and temperature via photoionization and collisional cooling (Nicholls et al. 2014). Multiple studies revealed that the $O_{32}$ versus $R_{23}$ index diagram is actually a sequence in monotonically increasing metallicity from the high $O_{32}$, high $R_{23}$, high-excitation tail toward low $O_{32}$, low $R_{23}$, low-excitation regions (Andrews & Martini 2013; Shapley et al. 2015; Sanders et al. 2016). Typical high-$z$ ($z \sim 2.3$) star-forming galaxies occupy the low-metallicity–high-excitation tail of the $O_{32}$ versus $R_{23}$ diagram. Still, they follow the same distribution as local low-metallicity galaxies (Shapley et al. 2015; Sanders et al. 2016). Nakajima et al. (2013) and Nakajima & Ouchi (2014), for the first time, presented the ionization and metal properties for a very small sample of $z \sim 2$ LAEs based on multiple nebular emission lines. They found that the high-$z$ LAEs have a higher ionization parameter and lower metallicity than other typical high-$z$ star-forming galaxies.

We show the relationship between the $O_{32}$ and the $R_{23}$ index (Figure 4 lower middle panel) for our sources in circles, compared with the low-redshift analog population: Hayes et al. (2023; blue squares) and low-redshift Ly$\alpha$ emitters (Flury et al. 2022a; green triangles). Our sources occupy a broad region in the $O_{32}$ versus $R_{23}$ parameter space, although the uncertainties of the measurements are also considerably high. This large scatter in the $O_{32}$ versus $R_{23}$ diagram has also been seen with other Ly$\alpha$ emitters at $z > 4$ using JWST measurements (Mascia et al. 2023). This could imply that high-redshift LAEs exhibit a wide range of metallicity and ionization states of the gas, or it could simply be an effect of large uncertainties in the measurements.

5.6. Dust Extinction and Reddening

The effect of dust content on Ly$\alpha$ emission has been studied extensively (Scarlata et al. 2009; Hayes et al. 2010; Cowie et al. 2011; Finkelstein et al. 2011; Nakajima et al. 2012; Henry et al. 2015). Ly$\alpha$ photons produced from star-forming regions can undergo multiple scatterings from the H I gas in the ISM and CGM of galaxies. With an increase in the number of scatterings, the probability of the Ly$\alpha$ photons to be absorbed by dust grains also increases. Thus, the observed line intensities depend on the number of ionizing photons and the attenuation produced by dust along the line of sight. High dust content indicates low Ly$\alpha$ output.

In Figure 4 lower right panel, we show the Ly$\alpha$/H$\alpha$ flux ratio as a function of the observed H$\alpha$/H$\beta$ ratio for our objects. Comparing our sample with other Ly$\alpha$ emitting galaxies with published Ly$\alpha$ and optical line ratio measurements is crucial. We separate the low-$z$ analog sample into two groups—galaxies identified as “dusty” LAEs from GALEX grism surveys (Scarlata et al. 2009) shown in green triangles, and the rest of the low-redshift analog galaxies from Hayes et al. (2023), shown in blue, which include galaxies from the Ly$\alpha$ reference survey (Hayes et al. 2013, 2014), green pea population (Yang et al. 2017b), blueberries (Yang et al. 2017a), and Lyman-break analogs ( Heckman et al. 2015). In the absence of dust, for Case B recombination at $T_e \sim 10^4 \text{K}$ and $n_e = 10^5 \text{cm}^{-3}$, the expected line ratios are 2.86 and 8.7 for the H$\alpha$/H$\beta$ and Ly$\alpha$/H$\beta$ ratios, respectively (Pengelly 1964). The galaxies in our sample show a large range in Ly$\alpha$/H$\alpha$, but a comparatively small range in H$\alpha$/H$\beta$. The mean H$\alpha$/H$\beta$ ratio is $3.2 \pm 1.3$, indicating low dust content. This is similar to
the low-z analog galaxies, where 90% of the population has \( \text{H} \alpha / \text{H} \beta < 4 \). Nine out of 11 sources have simultaneous detection of both \( \text{H} \alpha \) and \( \text{H} \beta \), while the other two sources miss \( \text{H} \beta \) due to detector gaps. Eight out of those 9 galaxies have \( \text{H} \alpha / \text{H} \beta < 3.3 \) and are consistent with the low-redshift analogs, particularly the green pea population (Henry et al. 2015; Yang et al. 2017b). One galaxy shows a very high dust content with a value of 5.2, which is more consistent with the local dusty LAEs of Scarlata et al. (2009), shown in Figure 4. Our galaxies possess low \( \text{H} \alpha / \text{H} \beta \) ratios but a large range of \( \text{Ly} \alpha / \text{H} \alpha \) flux ratios and almost no visible correlation between the two quantities. This indicates that the observed \( \text{Ly} \alpha \) output cannot be explained by dust extinction alone. Other intrinsic galaxy properties like SFR, UV luminosity, galaxy size, gas column density, etc., may play an equal or greater role in the escape of \( \text{Ly} \alpha \) photons. The \( \text{Ly} \alpha / \text{H} \alpha \) ratio for all our sources is smaller than the value of 8.7 predicted from Case B recombination. They vary by almost an order of magnitude. Seven of our high-z LAE sources show \( \text{Ly} \alpha / \text{H} \alpha \) overall consistent with the low-redshift population. The remaining two sources have considerably low \( \text{Ly} \alpha \) output.

6. Discussion

6.1. Comparison with Low-z Analogs and LyC Leakers

\( \text{Ly} \alpha \) is possibly the best indirect diagnostic of LyC escape since the conditions that favor the escape of \( \text{Ly} \alpha \) photons are often the same that allow for the escape of LyC photons. In this work, we concentrate on studying \( \text{Ly} \alpha \) emission for galaxies with \( z < 6 \), thus avoiding the significant IGM attenuation but being close enough in redshift to the EoR. We study the correlation between \( f_{\text{esc}}^{\text{Ly} \alpha} \) and another indirect but promising diagnostic tested at low redshift by Flury et al. (2022a): \( O_{32} \). One of our primary goals is to determine whether the correlations observed in the low-z population prevail in the \( z = 3–6 \) regime as well. We compare our sample with two main low-z samples—(1) low-z “analogs” from Hayes et al. (2023)—which include green peas, blueberries, Lyman-break analogs, intense starbursts, and extreme emission line galaxies, and (2) low-redshift LyC emitters from Flury et al. (2022a), which are candidates for LyC leakers.

In Figure 4, we plot the relation between \( f_{\text{esc}}^{\text{Ly} \alpha} \) with \( \text{Ly} \alpha \) EW, velocity offset, and \( O_{32} \) for our JWST high-redshift sample and compare them with the local population (Flury et al. 2022a; Hayes et al. 2023). A huge caveat for our study is the small size of our sample. The objects in our sample do not show any strong correlations by themselves. Here we discuss if they are generally consistent with the correlation parameter space occupied by the low-redshift galaxies.

We find that \( f_{\text{esc}}^{\text{Ly} \alpha} \) versus \( \text{Ly} \alpha \) EW generally shows a positive trend, as expected. However, two sources (objects 8 and 10) show lower \( f_{\text{esc}}^{\text{Ly} \alpha} \) than expected for the given \( \text{Ly} \alpha \) output. One of them (object 8) shows a higher dust content which might contribute to the lower \( f_{\text{esc}}^{\text{Ly} \alpha} \). We next analyze \( f_{\text{esc}}^{\text{Ly} \alpha} \) versus velocity offset. Our sources are consistent with the Hayes et al. (2023) low-redshift analogs, although there is significant scatter. Our systemic redshift measurements are determined from the brightest rest-frame optical lines (\( \text{H} \alpha \) and [O III] 5007 Å) measured from the NIRSpec spectra. Uncertainties in the wavelength calibrations of the JWST/NIRSpec and MUSE spectra can contribute to this scatter. However, two sources (objects 2 and 3) have the lowest \( f_{\text{esc}}^{\text{Ly} \alpha} \) and \( \text{Ly} \alpha \) velocity and hence are completely offset from the low-z analogs. These are also two of our sample’s highest-redshift galaxies (\( z = 5.186 \) and 5.282, respectively). We hypothesize that this could be caused by IGM attenuation.

We now focus on \( O_{32} \). High \( O_{32} \) has been proposed as an indicator of higher \( f_{\text{esc}} \) (e.g., Nakajima & Ouchi 2014). The reasoning is that a high \( O_{32} \) ratio selects highly ionized systems, which are more likely to have density-bounded channels through which ionizing photons can escape. We do not have a direct estimate of \( \text{Ly} \alpha \) \( f_{\text{esc}} \), so we plot \( O_{32} \) versus \( f_{\text{esc}}^{\text{Ly} \alpha} \). We find that all six sources of our sample with measured \( O_{32} \) indeed lie in the region of the plot populated by low-redshift LyC leakers (Flury et al. 2022a) and analogs sample (Hayes et al. 2023). The median \( O_{32} \) is 4.5 ± 1.2. We see that the majority of our sources (four out of six galaxies) show \( O_{32} < 5 \), which has been indicated as a lower threshold for LyC leakers with an \( f_{\text{esc}} > 0.05 \) (Flury et al. 2022a). Thus our objects are predicted to have \( f_{\text{esc}} < 0.05 \). Although, some studies have shown that \( O_{32} \) does not necessarily correlate well with \( f_{\text{esc}} \) (Naidu et al. 2018; Katz et al. 2020), and thus are not expected to correlate with \( f_{\text{esc}}^{\text{Ly} \alpha} \) as well. Nonetheless, samples of LyC-leaking galaxies at low redshift generally show that the fraction of galaxies with high \( f_{\text{esc}} \) increase toward higher \( O_{32} \), even if the correlation is not tight (e.g., Izotov et al. 2016; Flury et al. 2022a). This is what we find in our sample with \( f_{\text{esc}}^{\text{Ly} \alpha} \) as well.

Finally, the \( O_{32} \) versus \( R_{23} \) index diagram is widely used to examine the gas-phase metallicity and ionization state both in the local universe (e.g., Izotov et al. 2016, 2018a; Flury et al. 2022a) and at high redshift (Vanzella et al. 2019; Nakajima et al. 2020; Reddy et al. 2022). The recent study by Nakajima et al. (2020) showed that \( z > 3 \) LyC leakers tend to populate the upper right part of this diagram, i.e., they have high \( O_{32} \) and high \( R_{23} \). This result is also seen in high-resolution cosmological radiation hydrodynamics simulations (Katz et al. 2020). However, both of these studies conclude that the \( O_{32} \) versus \( R_{23} \) plane is not the most useful to differentiate between leakers and nonleakers. Our sample occupies a broad region in the parameter space, which could reflect either a wider range of metallicity and ionization states, or the fact that we have large measurement uncertainties, very similar to the \( 4.5 < z < 8 \) LAE galaxies studied by Mascia et al. (2023).

6.2. Prediction of the LyC Escape Fraction

We try to estimate \( f_{\text{esc}} \) indirectly from our measured properties. Previous studies have attempted to estimate \( f_{\text{esc}} \) based on neutral gas properties and low ionization absorption lines. It is difficult to detect such lines and obtain neutral gas properties at higher redshifts. Hence, we adopt the fully data-driven regression analysis of observable galaxy properties presented by Mascia et al. (2023) for a similar sample of \( z = 4–8 \) \( \text{Ly} \alpha \) emitting galaxies in the GLASS data set. Note that Mascia et al. (2023) used the LzLCS sample to derive this relation and then applied it to \( z = 4–8 \) LAEs. The best-fit relation they proposed is:

\[
\log_{10}(f_{\text{esc}}) = A + B \times \log_{10}(O_{32}) + C \times r_e + D \times \beta ,
\]

where \( A = -1.92 \), \( B = 0.48 \), \( C = -0.96 \), \( D = -0.41 \), \( r_e \) is the effective radius in kpc (Table 1), and \( \beta \) is the mean UV slope = \(-2.3 \pm 0.4\), calculated by G. Prieto-Lyons et al. (2023, submitted). We find that \( f_{\text{esc}} \) varies between 0.03–0.07 with a mean value = 0.04. This is consistent with what we previously hypothesized—the majority of our sources should have
$f_{\text{esc}} < 0.05$ based on the $O_{32}$ ratio alone. The main limitation of our study is the small sample size. Our results are mostly based on six sources with the detection of both [O III] and [O II] lines. Still, our $f_{\text{esc}}$ value are rather low, with the average value lower than the median $f_{\text{esc}} \sim 0.1$ predicted by Naidu et al. (2020) and Mascia et al. (2023) for galaxies with median $z = 6$. On the other hand, the low-redshift LyC-leaking galaxies from the LzLCS sample exhibit LyC escape fractions over a large range, ranging from 0.009–0.50. However, 80% of the sample possess $f_{\text{esc}} < 0.05$ (Flury et al. 2022b). Thus, the low-redshift LyC leakers tend to show similar low values of $f_{\text{esc}}$ as our $z \sim 3$ LyC emitters. A larger and more evenly distributed sample at $3 < z < 6$ would be required to draw any conclusion on the possible redshift evolution of $f_{\text{esc}}$.

7. Summary

Thanks to the deep spectroscopic data obtained with MUSE and the outstanding JWST NIRSpec spectroscopy of selected targets in the field of the Abell 2744 cluster, we have been able to study the rest-frame UV–optical spectral properties of 11 Ly$\alpha$ emitting galaxies with spectroscopic redshifts in the range $3 < z < 6$. We aimed to answer how the Ly$\alpha$ emission and its correlation with the galaxy properties compare between our high-redshift sample and the existing low-redshift analog population. Using the combined analyses of JWST NIRSpec and MUSE spectra, we were able to measure accurate estimates of systemic redshifts, Ly$\alpha$ velocity offsets, $f_{\text{esc}}^{\text{Ly}\alpha}$, ionization states, metallicity indicators, and dust content. We report the measurements of the most prominent rest-frame optical emission lines (H$\alpha$, [O III], [O II], and H$\beta$). Our main results are summarized as follows:

1. All 11 galaxies in our sample are detected to have diffuse extended Ly$\alpha$ emission. We find a large range of physical sizes of these extended Ly$\alpha$ emissions ranging from 10 to 50 kpc, often extending beyond the host galaxy’s stellar component (similar to Hayes et al. 2013; Leclercq et al. 2017). Our Ly$\alpha$ spectral profiles are diverse, with 3/11 showing a double-peaked profile.

2. The FWHMs of the Ly$\alpha$ emission are positively correlated with the Ly$\alpha$ red peak velocity offsets. Thus, the derived low-z relation works well for $z < 6$ galaxies and can be used to estimate systemic redshifts based on measurements of Ly$\alpha$ FWHM alone, as previously proposed by Verhamme et al. (2017).

3. We compared our 11 galaxies to the low-redshift LyC emitters from Flury et al. (2022a) and low-redshift analogs from Hayes et al. (2023). Although our galaxies do not show many strong correlations if taken alone, their properties are entirely consistent with the low-redshift population in terms of Ly$\alpha$ EW, $f_{\text{esc}}^{\text{Ly}\alpha}$, $O_{32}$, Ly$\alpha$/H$\alpha$, and dust content.

4. Our high-z LAE sample has low dust content (all except three have H$\alpha$/H$\beta < 3$), compact sizes (mean $R_e \sim 1$ kpc), low masses ($M_e < 10^{10} M_\odot$) and high SFRs (SFR $\sim 0.1–10 M_\odot$ yr$^{-1}$). These are consistent with the prediction from RT models and imply that Ly$\alpha$ emitting galaxies define the early stages of a galaxy’s lifecycle. The low dust content allows the Ly$\alpha$ photons to escape without being completely absorbed. The striking similarity of the Ly$\alpha$/H$\alpha$ ratios versus Balmer decrements with the low-redshift analog population is remarkably evident even for our small sample of sources.

5. We use the empirical relation between the LyC escape fraction and the three galaxy parameters proposed by Mascia et al. (2023), to predict LyC $f_{\text{esc}}$. We find that our sources are not strong LyC leakers, with an average LyC escape fraction $\sim 0.04$. High-z studies suggest that an average LyC $f_{\text{esc}}$ $\sim 10\%–20\%$ is needed for galaxies to ionize the universe (Finkelstein et al. 2012; Robertson et al. 2013). So, these low-escape-fraction galaxies are not possibly representative of sources that ionized the IGM (although see Finkelstein et al. 2019). Sources with higher $f_{\text{esc}}$ must be present at $z > 6$.

In conclusion, our low-mass high-redshift galaxies have physical and spectroscopic properties that are broadly consistent with the low-redshift population, which are rightly considered “analog” of high-redshift LAEs. This suggests that diagnostic relations for Ly$\alpha$ and LyC, derived using low-z analogs (Runnholm et al. 2020; Flury et al. 2022a), may be applicable to early epochs. With the caveat of a small sample size, we found that the amount of escaping ionizing photons is not large in our galaxies ($f_{\text{esc}} \sim 0.03–0.07$). A larger sample covering a wider range in redshift, stellar mass, and SFR is needed to make a stronger statement about the nature of the correlations seen in the high-z LAEs. Larger JWST samples taken, for example, from the JWST IADES GTO program, will be suitable for studying more high-redshift LAEs and better calibrating the correlations we show here.

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