The REBELS ALMA Survey: efficient Ly $\alpha$ transmission of UV-bright $z \sim 7$ galaxies from large velocity offsets and broad line widths

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ABSTRACT
Recent work has shown that UV-luminous reionization-era galaxies often exhibit strong Lyman-alpha emission despite being situated at redshifts where the IGM is thought to be substantially neutral. It has been argued that this enhanced Ly $\alpha$ transmission reflects the presence of massive galaxies in overdense regions which power large ionized bubbles. An alternative explanation is that massive galaxies shift more of their Ly $\alpha$ profile to large velocities (relative to the systemic redshift) where the IGM damping wing absorption is reduced. Such a mass-dependent trend is seen at lower redshifts, but whether one exists at $z \sim 7$ remains unclear owing to the small number of existing systematic redshift measurements in the reionization era. This is now changing with the emergence of [C II]-based redshifts from ALMA. Here, we report MMT/Binospex Ly $\alpha$ spectroscopy of eight UV-bright ($M_{UV} \sim -22$) galaxies at $z \sim 7$ selected from the ALMA REBELS survey. We detect Ly $\alpha$ in four of eight galaxies and use the [C II] systemic redshifts to investigate the Ly $\alpha$ velocity profiles. The Ly $\alpha$ lines are significantly redshifted from systemic (average velocity offset $= 223 \text{ km s}^{-1}$) and broad (FWHM $\sim 300–650 \text{ km s}^{-1}$), with two sources showing emission extending to $\sim 750 \text{ km s}^{-1}$. We find that the broadest Ly $\alpha$ profiles are associated with the largest [C II] line widths, suggesting a potential link between the Ly $\alpha$ FWHM and the dynamical mass. Since Ly $\alpha$ photons at high velocities transmit efficiently through the $z = 7$ IGM, our data suggest that velocity profiles play a significant role in boosting the Ly $\alpha$ visibility of the most UV-luminous reionization-era galaxies.

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

1 INTRODUCTION
Reionization is a landmark event of early cosmic history, reflecting when the first luminous objects began ionizing nearly every hydrogen atom in the Universe (Dayal & Ferrara 2018; Robertson 2022). Over the past decade, substantial progress has been made in revealing the timeline of reionization thanks to a variety of observational efforts. The frequent detections of Ly $\alpha$ and Ly $\beta$ forests in the spectra of $z \sim 6$ quasars indicate that reionization was largely complete by $z = 5.9$ with an IGM neutral fraction $x_{HI} \approx 10\%$ (McGreer, Mesinger & D’Odorico 2015). Quasars at slightly higher redshifts ($z \approx 7–7.5$) show strong Lyman-alpha damping wing features, indicating a significantly neutral IGM only $\approx 200 \text{ Myr}$ earlier ($x_{HI} \sim 50\%$; Mortlock et al. 2011; Greig et al. 2017; Bañados et al. 2018; Davies et al. 2018; Wang et al. 2020; Yang et al. 2020). This timeline is consistent with the reionization mid-point of $z = 7.8 \pm 0.7$ inferred from the cosmic microwave background (CMB; Planck Collaboration VI 2020).

Lyman-alpha emission from high-redshift galaxies is another tool often utilized to study reionization (Ouchi, Ono & Shibuya 2020). Because Ly $\alpha$ resonantly interacts with H I, its observed strength is very sensitive to the ionization state of the surrounding IGM (e.g. Miralda-Escudé 1998). Deep spectroscopic surveys have demonstrated that the fraction of typical star-forming galaxies showing strong (rest-frame equivalent width $> 25 \text{ Å}$) Ly $\alpha$ emission declines abruptly at $z > 6$ (Fontana et al. 2010; Stark et al. 2010; Ono et al. 2012; Caruana et al. 2014; Pentericci et al. 2014, 2018; Schenker et al. 2014; Jung et al. 2017, 2020; Hoag et al. 2019; Fuller et al. 2020) suggesting a highly neutral IGM at $z \sim 7–7.5$ ($x_{HI} \gtrsim 50\%$ per cent; e.g. Mason et al. 2018a; Hoag et al. 2019; Jung et al. 2020; Whittle et al. 2020). It has also been shown that the faint end of the Ly $\alpha$ luminosity function declines faster than the UV continuum luminosity function at $z > 6$ (Hu et al. 2010; Ouchi et al. 2010; Kashikawa et al. 2011; Konno et al. 2014, 2018; Ota et al. 2017; Zheng et al. 2017; Ilon et al. 2018; Hu et al. 2019; cf. Wold et al. 2022), suggesting a similar reionization timeline consistent with inferences from quasars and the CMB.

Over the past few years, attention has shifted towards using Ly $\alpha$ observations to study the structure of reionization. Recent data suggest that the Ly $\alpha$ emission strengths of UV-bright ($M_{UV} \lesssim -21$)
galaxies do not strongly evolve between $z \sim 6$ and $z \sim 7$ (Stark et al. 2017; Endsley et al. 2021b), even though the neutrality of the IGM changes substantially over this time period. One likely explanation for these findings is that UV-bright galaxies (which preferentially trace massive systems; e.g. Barone-Nugent et al. 2014; Harikane et al. 2018a) often reside in large ionized bubbles powered by the enhanced number of neighbouring galaxies in their local overdensities (e.g. Wyithe & Loeb 2005; Dayal et al. 2009; Zitrin et al. 2015; Castellano et al. 2016; Hutter et al. 2017; Weinberger et al. 2018; Endsley et al. 2021b; Garaldi et al. 2022; Kannan et al. 2022; Leonova et al. 2022; Qin et al. 2022). The presence of these $\text{HII}$ regions boosts Ly$\alpha$ transmission by enabling the photons to cosmologically redshift pass the resonant core and into the damping wing before encountering intergalactic $\text{H1}$ (Mesinger, Haiman & Cen 2004; Mason & Gronke 2020; Park et al. 2021; Smith et al. 2022). Reports of UV-bright Ly$\alpha$-emitting galaxies at $z \gtrsim 7$ lying in close proximity may further support the picture that large ionized structures commonly surrounded early massive galaxies (Vanzella et al. 2011; Castellano et al. 2018; Jung et al. 2020; Tilvi et al. 2020; Hu et al. 2021; Endsley et al. 2021b; Endsley & Stark 2022).

However, ionized bubbles are not the only mechanism capable of boosting Ly$\alpha$ transmission during reionization. Resonant interactions within galaxies can shift Ly$\alpha$ emission redward of systemic velocity by $\gtrsim 100 \text{ km s}^{-1}$ (e.g. Shapley et al. 2003; Erb et al. 2014; Shibuya et al. 2014), and thereby push the photons into the damping wing even before they escape the CGM. If such high Ly$\alpha$ velocity offsets are common among luminous reionization-era galaxies, this would help explain their enhanced Ly$\alpha$ visibility and lessen the need for very large $\text{HII}$ regions in their vicinity (e.g. Stark et al. 2017; Mason et al. 2018b). Unfortunately, our understanding of velocity offsets at $z > 6$ has remained limited by challenges in detecting not only Ly$\alpha$ from such early systems, but also a non-resonant line tracing the systemic redshift (e.g. [CII]158 μm). As a result, there are currently only four Ly$\alpha$ velocity offset measurements among extremely UV-luminous ($M_{\text{UV}} < -22$) Lyman-break selected galaxies at $z > 6$ (Willott et al. 2015; Stark et al. 2017; Hashimoto et al. 2019). Until a better census of these velocity offsets is obtained, considerable uncertainties will persist in how to connect the Ly$\alpha$ transmission of $z \gtrsim 7$ galaxies to the structure of reionization.

In this work, we aim to significantly increase the number of Ly$\alpha$ velocity offset measurements among UV-luminous reionization-era galaxies. Recently, the ongoing ALMA large program REBELS (Reionization-Era Bright Emission Line Survey; Bouwens et al. 2022) yielded systemic [CII]158-μm line detections from $\geq 22$ UV-bright ($-23 \lesssim M_{\text{UV}} \lesssim -21.5$) Lyman-break selected galaxies at $z \geq 6.5$. These systems were primarily selected from the wide-area COSMOS and XMM fields ($\approx 7 \degree^2$ total). Here, we use the Cycle 7 data from REBELS which delivered the large majority ($\sim 85\%$) of all planned observations for this program. The details of the ALMA data reduction and processing for [CII] and dust continuum are described in Schouws et al. (in preparation) and Inami et al. (2022), respectively. In this section, we begin by describing our spectroscopic Ly$\alpha$ observations for a subset of these REBELS galaxies (Section 2.1) and then detail how we infer physical properties among our Ly$\alpha$-targeted sample (Section 2.2).

### 2.1 Lyman-alpha observations

We have thus far targeted Ly$\alpha$ emission in eight [CII]-detected REBELS galaxies at $z = 6.5-7.1$ using the MMT/Binospec optical spectrograph (Fabricant et al. 2019). For all observations, we utilized the 6000 mm$^{-1}$ grating which provides sensitive coverage between $\approx 0.7$ and 1 μm at moderate resolution ($R \approx 4400$) given our adopted slit width of 1.0 arcsec. We report the total exposure time, average seeing, wavelength coverage, and mask position angle (PA) describing the Binospec observations of each REBELS source in Table 1. The typical exposure time per source was 5.6 h with a typical seeing of 0.9 arcsec. Two of our target REBELS galaxies (REBELS-14 and REBELS-39) were observed using two separate masks with slightly different wavelength coverage and PA (see Table 1). Initial Ly$\alpha$ results of REBELS-14, REBELS-15, REBELS-23, REBELS-26, and REBELS-39 were previously presented in Endsley et al. (2021b, hereafter E21b) and therein identified as

<table>
<thead>
<tr>
<th>ID</th>
<th>Exposure Time (s)</th>
<th>Seeing (arcsec)</th>
<th>Wavelength Coverage (Å)</th>
<th>PA (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>REBELS-03</td>
<td>13500</td>
<td>0.73</td>
<td>7385–9909</td>
<td>-37.0</td>
</tr>
<tr>
<td>REBELS-05</td>
<td>13500</td>
<td>0.73</td>
<td>6992–9516</td>
<td>-37.0</td>
</tr>
<tr>
<td>REBELS-14</td>
<td>22500</td>
<td>0.87</td>
<td>7548–10070</td>
<td>-52.0</td>
</tr>
<tr>
<td>REBELS-15</td>
<td>27000</td>
<td>0.91</td>
<td>7783–10306</td>
<td>-12.0</td>
</tr>
<tr>
<td>REBELS-23</td>
<td>18100</td>
<td>0.91</td>
<td>7806–10330</td>
<td>-116.2</td>
</tr>
<tr>
<td>REBELS-26</td>
<td>23400</td>
<td>0.99</td>
<td>7435–9959</td>
<td>-98.5</td>
</tr>
<tr>
<td>REBELS-27</td>
<td>32400</td>
<td>1.09</td>
<td>7207–9731</td>
<td>-98.5</td>
</tr>
<tr>
<td>REBELS-39</td>
<td>16200</td>
<td>0.94</td>
<td>7493–10017</td>
<td>-98.5</td>
</tr>
<tr>
<td></td>
<td>7200</td>
<td>0.98</td>
<td>7250–9773</td>
<td>+45.0</td>
</tr>
<tr>
<td></td>
<td>14400</td>
<td>0.73</td>
<td>7355–9875</td>
<td>-155.0</td>
</tr>
</tbody>
</table>

any evidence of a connection between [CII] luminosity at fixed SFR and Ly$\alpha$ equivalent width (Section 4.3). Finally, we discuss how the large velocity offsets and broad line widths of massive, UV-luminous reionization-era galaxies result in efficient Ly$\alpha$ transmission through a significantly neutral IGM (Section 5). We summarize our main conclusions in Section 6.

In this work, we quote all magnitudes in the AB system, assume a Chabrier (2003) initial mass function (IMF) with limits of 0.1–300 $M_{\odot}$, and adopt a flat $\Lambda$CDM cosmology with parameters $h = 0.7, \Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$.
XMM3-227436, XMM3-504799, COS-469110, COS-534584, and COS-862541, respectively. Here, we extend this previous work by exploring the Lyα emission properties of this sample in greater detail using the [CII] and dust continuum information now available from our ALMA observations. Furthermore, we have since obtained significantly deeper (i.e. 3–5 x longer exposure time) Binospec data on REBELS-14 and REBELS-39 enabling a more detailed analysis of their Lyα line profiles.

Our Binospec data reduction largely follows the approach described in E21b, which we briefly review here. We first process each individual exposure separately using the public Binospec data reduction pipeline (Kansky et al. 2019) which performs telluric correction. We then calibrate each exposure (for an individual mask) using the weighting scheme of Kriek et al. (2015) and apply optimal extraction (Horne 1986) to obtain the 1D spectra of each source. To determine the spatial axis width for the optimal extraction, we first fit a Gaussian to the observed emission line profile. Absolute flux calibration is determined using the spectra of multiple bright stars placed on each mask. For REBELS-14 and REBELS-39, we coadd the data from different masks using an inverse variance weighting approach. slit loss correction factors are derived by adopting the size–luminosity relation from Curtis-Lake et al. (2016) and assuming a Sérsic profile with n = 1.0, resulting in small correction factors of ≈5–10 per cent. Because these slit loss corrections assume that the Lyα surface brightness profile tracks the rest-UV emission, our reported fluxes will underestimate the total line flux throughout the extended Lyα halo surrounding each galaxy. We also compute the Lyα EWs following the approach of E21b as we aim to compare the EWs of our REBELS sources to the EW distribution inferred among UV-bright (−22.5 < MUV < −20.5) z ∼ 7 galaxies in E21b.

That is, we adopt a continuum flux density (in μJy) from the photometric band closest to the Lyα yet fully redward of the Lyα break, which effectively assumes a flat UV continuum (i.e. β = −2 where Fλ ∝ λ^β+2) between Lyα and the adopted band. While the true continuum is likely weaker immediately redward of Lyα (e.g. Shapley et al. 2003; Steidel et al. 2016), we use the photometric continuum approach above since high signal-to-noise ratio (S/N) spectroscopic UV continuum measurements do not yet exist for our galaxies.

For objects with no apparent Lyα detection, we determine upper limits on the Lyα EW by calculating the integrated noise from the fully reduced 1D spectrum over a wavelength interval assumed relevant for the Lyα line. This wavelength interval is set to begin at a value corresponding to the assumed Lyα redshift and spans a range equivalent to an assumed FHWM of the line. We assume a range of possible Lyα redshifts corresponding to velocity offsets of Δλ_{Lyα} = 0–800 km s^{-1} relative to [CII], where these values encompass all robust Δλ_{Lyα} measurements in the literature at z > 6 (see Table 4). Given the broad Lyα profiles observed in our four Lyα-detected REBELS sources (Section 3), we consider line widths ranging between FHWM = 300 and 700 km s^{-1}. The range of 5σ upper limits for each REBELS galaxy not detected in Lyα is reported in Table 3, where these limits depend on not only the total exposure time and seeing of the observations, but also whether skylines are impacting the spectrum noise around the possible Lyα feature.

### 2.2 Galaxy properties

The physical properties (e.g. stellar mass and [O III] + Hβ EW) of each REBELS galaxy are inferred using the SED fitting code BEAGLE (Chevallard & Charlot 2016). BEAGLE adopts the photoionization models of star-forming galaxies from Gutkin, Charlot & Bruzual (2016) which incorporate both stellar and nebular emission by combining the latest version of the Bruzual & Charlot (2003) stellar population synthesis models with CLOUDY (Ferland et al. 2013). We assume a delayed star formation history (SFR \propto t^{-\eta\tau}) with an allowed recent (<10 Myr) burst and we force star formation to have begun at least 1 Myr ago, consistent with the fitting approach of Endsley et al. (2021a) and E21b. While the fiducial REBELS SED fits assume a constant star formation history (Stefanon et al., in preparation), our motivation for adopting this alternative ‘delayed + burst’ fitting approach is twofold. First, we wish to provide a self-consistent comparison of [O III] + Hβ EWs with those inferred in Endsley et al. (2021a) since it has been shown that higher [O III] + Hβ EWs connect to larger Lyα EWs at z ∼ 7 (Castellano et al. 2017, E21b).

Secondly, we aim to open up the possibility that the subset of our sources with very strong IRAC colours (and hence very large [O III] + Hβ EWs; e.g. REBELS-15 and REBELS-39) have not necessarily assembled all of their stellar mass within the past few Myr (see Endsley et al. 2021a). We adopt a Chabrier (2003) IMF with mass limits of 0.1–300 M⊙ and apply an SMC dust prescription (Pettini 1992). The metallicity and ionization parameter are allowed to lie between −2.2 ≤ log(Z/Z⊙) ≤ 0.24 and −4 ≤ log U ≤ −1, respectively, both with log-uniform priors. During the fits, we only use photometry from bands redward of the Lyα break to avoid any bias due to sightline variations in IGM transmission. Details of the near-infrared photometry used for these fits will be described in Stefanon et al. (in preparation). From our BEAGLE fits, we report the median and inner 68 per cent credible interval values marginalized over the posterior probability distribution function as determined from MULTINEST (Feroz & Hobson 2008; Feroz, Hobson & Bridges 2009).

While our reported uncertainties do not account for variations in modelling assumptions, we note below how adopting non-parametric star formation history models may change our reported values.

<table>
<thead>
<tr>
<th>ID</th>
<th>M_{UV}</th>
<th>log(M_*/M_☉)</th>
<th>[O III] + Hβ EW (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>REBELS-03</td>
<td>−21.8 ± 0.3</td>
<td>8.9^{+0.6}_{−0.6}</td>
<td>510^{+650}_{−530}</td>
</tr>
<tr>
<td>REBELS-05</td>
<td>−21.6 ± 0.2</td>
<td>8.9^{+0.7}_{−0.5}</td>
<td>1060^{+920}_{−530}</td>
</tr>
<tr>
<td>REBELS-14</td>
<td>−22.7 ± 0.4</td>
<td>8.7^{+0.4}_{−0.3}</td>
<td>1520^{+1300}_{−900}</td>
</tr>
<tr>
<td>REBELS-15</td>
<td>−22.6 ± 0.3</td>
<td>9.1^{+0.3}_{−0.2}</td>
<td>4570^{+1830}_{−1940}</td>
</tr>
<tr>
<td>REBELS-23</td>
<td>−21.6 ± 0.5</td>
<td>8.8^{+0.4}_{−0.5}</td>
<td>830^{+520}_{−340}</td>
</tr>
<tr>
<td>REBELS-26</td>
<td>−21.8 ± 0.1</td>
<td>9.1^{+0.5}_{−0.7}</td>
<td>800^{+640}_{−390}</td>
</tr>
<tr>
<td>REBELS-27</td>
<td>−21.9 ± 0.2</td>
<td>9.5^{+0.3}_{−0.1}</td>
<td>310^{+540}_{−210}</td>
</tr>
<tr>
<td>REBELS-39</td>
<td>−22.7 ± 0.2</td>
<td>8.7^{+0.3}_{−0.1}</td>
<td>3250^{+1010}_{−930}</td>
</tr>
</tbody>
</table>

Table 2. Summary of the galaxy properties inferred for each of REBELS source considered in this work. Absolute UV magnitudes are reported at rest-frame 1600 Å. The [O III] + Hβ EWs and stellar masses are inferred using the BEAGLE SED fitting code as described in Section 2.2. We note that these values differ from those in the fiducial REBELS catalogue (Stefanon et al., in preparation) due to our alternate SED fitting approach (see Section 2.2). The reported errors do not account for uncertainties in modelling assumptions (e.g. star formation history), though we briefly discuss such uncertainties in the text.
changes in SFR results in \( \sim 0.5-1 \) dex higher inferred stellar masses for our REBELS galaxies (see Topping et al. 2022), though this does not impact any of the main conclusions in this paper. The rest-frame [O iii] + H\( \beta \) equivalent widths (EWs) of our REBELS targets (inferred from the broad-band SEDs with our fiducial BEAGLE fits) range between 310 and 4570 \AA\ with a median value of 940 \AA\ (see Table 2). This is similar to the typical [O iii] + H\( \beta \) EW inferred for the general UV-bright (\( \sim 22.5 \lesssim L_{\text{UV}} \lesssim -21 \)) \( \sim 7 \) galaxy population population (760 \pm 110 \AA\) in Endsley et al. (2021b) where the same SED fitting procedure was adopted as above (see also Labbé et al. 2013; Smit et al. 2014; De Barros et al. 2019; Stefanon et al. 2022). Because the [O iii] + H\( \beta \) EWs are much more directly constrained by the measured IRAC [3.6]–[4.5] colour, these inferred EWs do not change significantly if we instead utilize the results of the non-parametric star formation history fits described in Topping et al. (2022).

The inferred [O iii] + H\( \beta \) emission strengths of our galaxies provide an estimate of their production rate of hydrogen ionizing photons, \( N_{\text{ion}} \) (e.g. Chevallard et al. 2018; Tang et al. 2019; Emami et al. 2020), and in turn, their intrinsic Ly\( \alpha \) luminosity. With these intrinsic Ly\( \alpha \) luminosities, we determine the total escape fraction of Ly\( \alpha \) photons from each galaxy by comparing to the measured Ly\( \alpha \) fluxes. The intrinsic Ly\( \alpha \) luminosity of each galaxy is calculated as 
\[
L_{\text{Ly}\alpha} = 0.677 \times 10^{\nu_{\text{Ly}\alpha}} \times N_{\text{ion}},
\]
where \( h \) is Planck’s constant and \( \nu_{\text{Ly}\alpha} \) is the rest-frame frequency of Ly\( \alpha \). The factor of 0.677 is the fraction of hydrogen recombinations that result in the production of a Ly\( \alpha \) photon assuming case B recombination and a temperature of 10\( ^{4} \) K (Osterbrock & Ferland 2006; Dijkstra et al. 2014). We note that the \( N_{\text{ion}} \) values (which are inferred from the BEAGLE fits described above) do implicitly account for dust extinction, but may be underestimated if the dust optical depth is inhomogeneous across our galaxies. In this scenario, [O iii] + H\( \beta \) emission may be much more heavily obscured from certain star-forming regions, leading to an overestimate of the Ly\( \alpha \) escape fractions of our galaxies. With our current low-resolution (beam \( \approx 1.4 \) arcsec) ALMA data, we cannot yet test for such strong spatial variations in dust attenuation within our sample, though we note that a variety of dust morphologies have been observed in UV-bright \( \sim 7-8 \) galaxies with higher resolution maps (Bowler et al. 2022; Schouws et al. 2022). We report the inferred Ly\( \alpha \) escape fractions of each galaxy in Section 3 and estimate the role of the IGM in Section 5.

The total star formation rates of each galaxy are determined by summing their unobscured and obscured components. The fiducial unobscured SFRs are calculated from the UV luminosity (at 1600 \AA\ rest-frame) adopting the conversion SFR\( _{\text{UV}}/M_{\odot} \text{yr}^{-1} = 7.1 \times 10^{-29} \text{L}_{\odot}/\text{erg s}^{-1} \text{Hz}^{-1} \) (Stefanon et al., in preparation) which results in 0.3 dex lower SFR relative to the Kennicutt (1998) conversion. This conversion ratio assumes that the galaxy of interest has been steadily forming stars for the past \( \gtrsim 100 \) Myr, such that the UV luminosity contribution from B stars has reached equilibrium. Accordingly, our fiducial SFR\( _{\text{UV}}/L_{\odot} \) ratio may significantly underestimate the unobscured SFRs of our galaxies with very strong [O iii] + H\( \beta \) emission (\( \sim 2000 \) \AA\) which suggest a recent strong upturn in SFR. In Topping et al. (2022), we explicitly considered the age dependence on the SFR\( _{\text{UV}}/L_{\odot} \) ratio, finding that this ratio could be approximately equal to five times larger than our fiducial value for objects with the highest [O iii] + H\( \beta \) EWs. However, we find that this effect does not significantly impact our main conclusions (see Section 4.3).

To calculate the obscured SFRs, we adopt SFR\( _{\text{IR}}/M_{\odot} \text{yr}^{-1} = 1.2 \times 10^{-10} L_{\text{IR}}/L_{\odot} \) (Inami et al. 2022) which yields SFRs lower by 0.16 dex relative to Kennicutt (1998). Here, the total infrared luminosities, \( L_{\text{IR}} \), are computed as 14\( \nu L_{\nu} \), where \( \nu \) is frequency of the [C ii] line and \( L_{\nu} \), is the dust continuum flux density determined from our ALMA observations (Sommovigo et al. 2022). For sources undetected in far-IR continuum (REBELS-03, REBELS-15, REBELS-23, and REBELS-26), we estimate their IR luminosities by calculating an average infrared excess (IRX; \( L_{\text{IR}}/L_{\text{UV}} \)) in two UV slope bins (Topping et al. 2022). That is, we split all dust-undetected REBELS objects by their median UV slope (\( \beta \approx -2.04 \)) and stack the continuum data in each bin. A dust continuum detection is identified in the stack of redder galaxies and we apply the average IRX to each object in this bin (REBELS-23 and REBELS-26). The stack of bluer objects still yields a non-detection and we thus adopt upper limits on their IR luminosities from the limit on their average IRX (for REBELS-03 and REBELS-15). The resulting UV + IR SFRs of our sample span approximately 15–80 \( M_{\odot} \text{yr}^{-1} \) (see Table 3).

3 LYMAN-ALPHA SPECTRA

We have thus far targeted Ly\( \alpha \) from eight [C ii]-detected REBELS galaxies with MMT/Binospec. In this section, we begin by detailing the Binospec spectra of the four sources in which we have confidently detected (>7\( \sigma \)) Ly\( \alpha \) (Section 3.1) and then describe the EW limits of the remaining four sources that went undetected (Section 3.2). For each galaxy, we calculate the Ly\( \alpha \) escape fraction by comparing the observed line flux to the intrinsic Ly\( \alpha \) luminosity predicted from the BEAGLE SED fits as described in the previous section. We discuss these inferred Ly\( \alpha \) escape fractions in Section 3.3.

3.1 Lyman-alpha detections

3.1.1 REBELS-14

REBELS-14 is an extremely UV-luminous (\( M_{\text{UV}} = -22.7 \)) galaxy in the XMM3 field at \( z_{\text{reff}} = 7.084 \) (Bouwens et al. 2022; Schouws et al., in preparation), also referred to as XMM3-227436 in E21b. This source is inferred to have a stellar mass of log (\( M_{\odot} \)) = 8.7 and its red IRAC colour [(3.6]–[4.5] = 0.85+0.24−0.37] suggests an [O iii] + H\( \beta \) EW of 1520 \AA\). This is approximately twice the typical [O iii] + H\( \beta \) EW inferred among UV-bright (\( \sim 22.5 \lesssim L_{\text{UV}} \lesssim -21.25 \)) \( \sim 7 \) galaxies in Endsley et al. (2021a, 760 \pm 110 \AA\) where this value was determined using the same SED fitting procedures as adopted in this work.

The Binospec Ly\( \alpha \) spectrum for REBELS-14 reveals a 19.0\( \sigma \) detection with a peak wavelength of 9833.3 \AA\ (Fig. 1), corresponding to \( z_{\text{eff}} = 7.089 \) adopting a rest-frame wavelength of \( \lambda_{\text{Ly}\alpha} = 1215.67 \) Å. We measure a total Ly\( \alpha \) flux of (21.5 \pm 1.4) \times 10^{-18} \text{erg s}^{-1} \text{cm}^{-2}, corresponding to an EW of 14.6 \pm 3.0 \text{Å}. This EW is similar to the median value found among UV-bright (\( \sim 22.5 \lesssim L_{\text{UV}} \lesssim -20.5 \)) galaxies at \( z \approx 7 \) (10 A; E21b), indicating that the Ly\( \alpha \) emission strength of REBELS-14 is fairly typical. Here, we are adopting the VIRCam J-band flux density (0.59 \pm 0.14 \mu Jy) for the continuum of REBELS-14 given its [C ii] redshift (see Section 2.1), and we note that the effective wavelength of the J band corresponds to a rest-frame wavelength of \( \lambda_{\text{eff, rest}} = 1544 \) Å. The measured Ly\( \alpha \) flux from REBELS-14 suggests a Ly\( \alpha \) escape fraction of \( f_{\text{esc, Ly}\alpha} = 5.0^{+2.9}_{-1.4} \) per cent, where we use the intrinsic line luminosity predicted from the BEAGLE SED fits as described in Section 2.1. We note that the escape fraction estimates in this section include the transmission of Ly\( \alpha \) through the galaxy (ISM and CGM) as well as the IGM. As shown in Fig. 1, a moderate-strength skyline over laps with the redder portion of the Ly\( \alpha \) profile from REBELS-14, possibly obscuring some of the line flux. To estimate the potential extent of the obscuration, we assume that the line flux density in this skyl ine region is \( 1.0 \times 10^{-18} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1} \), a value consistent with the
Table 3. Summary of Lyα and [C II] properties of each REBELS source measured from our Binospec and ALMA observations, respectively. For sources undetected in Lyα, we quote the range of 5σ EW (and associated total Lyα escape fraction) upper limits assuming Lyα redshifts corresponding to $\Delta v_{Ly} = 0–800$ km s$^{-1}$ and FWHMs between 300 and 700 km s$^{-1}$ (see Section 2.1). For REBELS-23, we report lower limits on the Lyα EW, escape fraction, and FWHM given the possibility of significant skylines obscuration on the red side of the line. For sources undetected in the ALMA continuum data, we report 3σ upper limits on their far-infrared luminosities.

<table>
<thead>
<tr>
<th>ID</th>
<th>$z_{\text{c}}$</th>
<th>$z_{\text{Ly}}$</th>
<th>Lyα EW (Å)</th>
<th>$f_{\text{esc}, \text{Ly}}$ (per cent)</th>
<th>$\Delta v_{Ly}$ (km s$^{-1}$)</th>
<th>Lyα FWHM (km s$^{-1}$)</th>
<th>L$<em>{\text{IR}}$ ($10^{12}$ L$</em>{\odot}$)</th>
<th>L$<em>{\text{C II}}$ ($10^{12}$ L$</em>{\odot}$)</th>
<th>SFR$<em>{\text{UV+IR}}$ (M$</em>{\odot}$ yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>REBELS-03</td>
<td>6.969</td>
<td>&lt;14.7–35.5</td>
<td>&lt;5.2–12.6</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&lt;2.8</td>
<td>3.2 ± 0.6</td>
<td>16$^{+7}_{-3}$</td>
</tr>
<tr>
<td>REBELS-05</td>
<td>6.496</td>
<td>&lt;3.8–4.5</td>
<td>&lt;0.9–1.1</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>3.3±2.5</td>
<td>6.9 ± 0.4</td>
<td>53$^{+23}_{-23}$</td>
</tr>
<tr>
<td>REBELS-14</td>
<td>7.084</td>
<td>14.6 ± 3.0</td>
<td>5.0$^{+2.9}_{-1.4}$</td>
<td>177±30</td>
<td>640$^{+60}_{-30}$</td>
<td>3.4±2.6</td>
<td>3.7 ± 0.5</td>
<td>76$^{+26}_{-30}$</td>
<td></td>
</tr>
<tr>
<td>REBELS-15</td>
<td>6.875</td>
<td>6.883</td>
<td>3.7 ± 0.8</td>
<td>0.4$^{+0.2}_{-0.1}$</td>
<td>324±138</td>
<td>&lt;3.6</td>
<td>19.0 ± 3.3</td>
<td>34$^{+16}_{-9}$</td>
<td></td>
</tr>
<tr>
<td>REBELS-23</td>
<td>6.645</td>
<td>6.650</td>
<td>≥13.5</td>
<td>≥3.3</td>
<td>227±30–92</td>
<td>≥330</td>
<td>&lt;3.9</td>
<td>1.3 ± 0.2</td>
<td>24$^{+12}_{-10}$</td>
</tr>
<tr>
<td>REBELS-26</td>
<td>6.598</td>
<td>&lt;5.4–6.1</td>
<td>&lt;1.9–2.2</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&lt;4.8</td>
<td>2.0 ± 0.4</td>
<td>28$^{+5}_{-5}$</td>
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<tr>
<td>REBELS-27</td>
<td>7.090</td>
<td>&lt;5.6–13.9</td>
<td>&lt;3.2–8.0</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>2.9±2.2</td>
<td>6.1 ± 0.6</td>
<td>52$^{+20}_{-20}$</td>
</tr>
<tr>
<td>REBELS-39</td>
<td>6.845</td>
<td>6.849</td>
<td>10.0 ± 1.7</td>
<td>1.7$^{+0.4}_{-0.3}$</td>
<td>165±36–35</td>
<td>640$^{+60}_{-40}$</td>
<td>4.3±1.2</td>
<td>7.9 ± 1.4</td>
<td>88$^{+30}_{-30}$</td>
</tr>
</tbody>
</table>

flux density measured just outside both ends of the skyline. This suggests that a small fraction (14 per cent) of the total Lyα flux is obscured by this skylines which we have accounted for in the values reported above.

REBELS-14 clearly exhibits a broad asymmetric Lyα profile (Fig. 1). Given the asymmetry, we calculate the width of the line directly from the 1D spectrum, i.e. the separation between data points at half maximum flux. To account for uncertainties, we add 100% realizations of noise to the 1D spectrum and take the median and 68 per cent confidence intervals on the derived FWHM values across all realizations. We derive a FWHM = 640$^{+60}_{-30}$ km s$^{-1}$, where this value is corrected for the instrument resolution ($\approx$68 km s$^{-1}$). We come back to discuss the possible physical origin of such a broad Lyα profile in Section 4.2 and the implications for Lyα transmission during reionization in Section 5.

3.1.2 REBELS-15

REBELS-15 is an extremely UV-luminous ($M_{UV} = -22.6$) galaxy in the XMM3 field at $z_{\text{c}} = 6.875$ (Schouws et al., in preparation) with an inferred stellar mass of log ($M_*/M_\odot$) = 9.1. This source was identified as XMM3-504799 in E21b and exhibits a very blue IRAC colour ([3.6]–[4.5] = 1.16±0.03) suggesting an [O III] + Hβ EW = 4570 Å. At this redshift, [O III] λ5007 only contributes slightly to the 3.6-μm excess, requiring extremely strong H β and [O III] λ4959 emission to produce the observed IRAC colour.

Our Binospec data reveal a 7.5σ Lyα detection with a peak wavelength at 9583.2 Å corresponding to $z_{\text{Ly}α} = 6.883$ (Fig. 1). The total Lyα flux is measured to be (5.5 ± 1.0) $\times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ indicating an EW of 3.7 ± 0.8 Å using the VIRCam Y-band photometry ($\lambda_{\text{eff}, \text{rest}} = 1295$ Å) for the continuum flux density ($0.58 ± 0.09$ μJy). REBELS-15 is, thus, a relatively weak Lyα emitter among the UV-bright $z \approx 7$ population, and is particularly weak with respect to the sub-population with strong [O III] + Hβ emission (EW > 800 Å; E21b). Consistent with this result, we estimate a very low total Lyα escape fraction of 0.43$^{+0.07}_{-0.05}$ per cent from REBELS-15. The Lyα line profile of this source has a FWHM of 340$^{+80}_{-140}$ km s$^{-1}$.

3.1.3 REBELS-23

REBELS-23 is a UV-bright ($M_{UV} = -21.6$) galaxy situated in the wide-area COSMOS field at $z_{\text{c}} = 6.645$ (Schouws et al., in preparation) and was identified as COS-469100 in Endsley et al. (2021a,b). This galaxy is inferred to have a stellar mass of log ($M_*/M_\odot$) = 8.8 and its moderately blue IRAC colour ([3.6]–[4.5] = 0.53±0.18) suggests an [O III] + Hβ EW = 830 Å, similar to the typical value of $z \approx 7$ galaxies.

The Binospec data reveal a 7.5σ Lyα detection with a peak wavelength at 9299.3 Å corresponding to $z_{\text{Ly}α} = 6.650$ (Fig. 1). From the portion of the spectrum that is unobscured by strong skylines, we measure a Lyα flux of (9.7 ± 1.4) $\times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ indicating an EW of 13.5 ± 3.6 Å using the VIRCam Y-band photometry ($\lambda_{\text{eff}, \text{rest}} = 1334$ Å) for the continuum flux density (0.27 ± 0.07 μJy). The measured line flux implies $f_{\text{esc}, \text{Ly}α} = 3.3^{+2.9}_{-1.1}$ per cent for REBELS-23. Due to the patch of strong skylines redward of 9305 Å, we are unable to estimate the amount of obscured line flux and thus treat the above Lyα flux, and escape fraction measurements as lower limits. The Lyα profile in the unobscured portion of the spectrum has a FWHM = 330$^{+60}_{-100}$ km s$^{-1}$, though this width may also be underestimated due to the skylines.

3.1.4 REBELS-39

REBELS-39 is an extremely UV-luminous ($M_{UV} = -22.7$) galaxy in the COSMOS field at $z_{\text{c}} = 6.845$ (Bouwens et al. 2022; Schouws et al., in preparation) and was identified as COS-862541 in Endsley et al. (2021a,b). This source has an inferred stellar mass of log ($M_*/M_\odot$) = 8.7 and a very blue IRAC colour ([3.6]–[4.5] = 1.32$^{+0.27}_{-0.27}$) (E21b). The IRAC colour suggests an extremely large [O III] + Hβ EW of 3250 Å given that this galaxy lies at a redshift where [O III] λ5007 is only slightly transmitting through the [3.6] filter.

The Binospec data of REBELS-39 reveal a confident (15.3σ) Lyα detection with a peak wavelength of 9542.3 Å corresponding to $z_{\text{Ly}α} = 6.849$ (Fig. 1). We measure a total Lyα flux of (15.6 ± 1.3) $\times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$, indicating an EW of 10.0 ± 1.7 Å using the VIRCam Y-band photometry ($\lambda_{\text{eff}, \text{rest}} = 1300$ Å) for the continuum flux density (0.61 ± 0.12 μJy). While this Lyα EW is typical of UV-bright $z \approx 7$ galaxies (E21b), the line flux from REBELS-39 implies a low total Lyα escape fraction of 1.7$^{+0.4}_{-0.3}$ per cent given the extremely high [O III] + Hβ EW inferred for this system (3250$^{+100}_{-930}$ Å). The Lyα profile for REBELS-39 does overlap with a moderate-strength skylines at $\approx$9553 Å, though the Binospec data suggest that any obscuration is likely small. Because the observed Lyα profile is
consistent with zero flux density at both ends of the skyline (Fig. 1), we do not introduce a correction factor for possible flux obscuration. Similar to REBELS-14, the Lyα profile of REBELS-39 is extremely broad with FWHM = 640$^{+60}_{-40}$ km s$^{-1}$.

### 3.2 Lyman-alpha non-detections

#### 3.2.1 REBELS-03

REBELS-03 is a UV-bright ($M_{UV} = -21.8$) galaxy situated in the XMM1 field at $z_{\mathrm{spec}} = 6.969$ (Bouwens et al. 2022; Schouws et al., in preparation). This galaxy has an inferred stellar mass of log ($M_*/M_\odot$) = 8.9 and a relatively weak [O iii] + H β EW of 510 Å given its flat IRAC colour ([3.6]−[4.5] = 0.01$^{+0.22}_{-0.23}$). We have observed REBELS-03 for 3.75 h with MMT/Binospec with clear conditions and relatively good seeing (0.73 arcsec). We find no indication of significant (>5σ) Ly α emission from this source after searching our Binospec spectrum in conservative wavelength range corresponding to velocity offsets between −500 and 1000 km s$^{-1}$ (Fig. 2). Due to the presence of a strong skylines around the expected wavelength of Ly α, the 5σ EW upper limit for REBELS-03 is quite poor ranging from 14.7–35.5 Å for the various
Lyα Velocity Offset [km/s]

-500  0  500  1000

REBELS-03
REBELS-05
REBELS-26
REBELS-27

Figure 2. Each panel shows the 2D S/N map of the MMT/Binospec spectra of each REBELS source lacking a Lyα detection (<5σ). We show wavelengths corresponding to a conservative Lyα velocity offset range of Δν_{Lyα} = −500 to 1000 km s^{-1} (relative to [C II]) with each panel centered on the expected spatial position of the source.

assumed velocity offsets and FWHMs (see Section 2.1). Here, we have used the UKIRT J-band photometry (λ_{eff, rest} = 1564 Å) for the continuum flux density (0.29 μJy). The corresponding range of 5σ limiting Lyα fluxes translate to an upper limit on the total Lyα escape fraction of <5.2–12.6 per cent.

3.2.2 REBELS-05

REBELS-05 is another UV-bright (M_{UV} = −21.6) galaxy in the XMMI field that lies at z_{c, eff} = 6.496 (Bouwens et al. 2022; Schouws et al., in preparation) and was first identified as ID = 118 717 in Bowler et al. (2014). Because this source lies at z < 6.6 where both IRAC bands are contaminated by strong nebular emission lines (i.e., [O III] + H β in [3.6] and H α in [4.5]), there is significant degeneracy between the inferred stellar mass and [O III] + H β EW (e.g. Schaerer & de Barros 2010). The median posterior values from BEAGLE suggest a stellar mass of log(M_{*}/M_☉) = 8.9 and an [O III] + H β EW of 1060 Å given its moderately blue IRAC colour ([3.6]−[4.5] = −0.47^{+0.35}_{−0.29}). REBELS-05 was observed using the same Binospec mask as REBELS-03 with a total exposure time of 3.75 h under clear conditions and relatively good seeing (0.73 arcsec).

We again search for Lyα at wavelengths corresponding to Δν_{Lyα} = −500 to 1000 km s^{-1} and find no evidence of significant emission (Fig. 2). To calculate the EW upper limit, we adopt the same set of assumed velocity offsets and FWHM values as REBELS-03 and use the VIRCam Y-band photometry (λ_{eff, rest} = 1360 Å) for the continuum flux density (0.35 μJy). This results in 5σ limiting EWs ranging between <3.8 and 4.5 Å. Such stringent EW constraints are enabled by the fact that no strong skylines exist in the wavelength regime where Lyα is expected for REBELS-05. The upper limits on Lyα flux translate to f_{esc, Lyα} < 0.9−1.1 per cent for REBELS-05.

3.2.3 REBELS-26

REBELS-26 is a UV-bright (M_{UV} = −21.8) galaxy in the wide-area COSMOS field at z_{c, eff} = 6.598 (Schouws et al., in preparation) and was first identified as ID = 104 600 in Bowler et al. (2014). Due to this redshift, the inferred stellar mass and [O III] + H β EW of REBELS-26 are quite degenerate similar to REBELS-05. The median posterior values from BEAGLE suggest log(M_{*}/M_☉) = 9.1 and [O III] + H β EW = 800 Å for REBELS-26 given its moderate IRAC colour ([3.6]−[4.5] = −0.42^{+0.16}_{−0.17}). We have observed this galaxy for 9.0 h with Binospec under largely clear conditions and moderate seeing on average (1.09 arcsec).

We find no indication of significant emission in our Binospec spectra for REBELS-26 at wavelengths corresponding to Δν_{Lyα} = −500 to 1000 km s^{-1} (Fig. 2). Because no strong skylines exist around the expected wavelength of Lyα, we derive stringent 5σ EW upper limits between 5.4–6.1 Å. Here, we have used the VIRCam Y-band photometry (λ_{eff, rest} = 1342 Å) for the continuum flux density (0.37 μJy). The total Lyα escape fraction of this system is inferred to be <1.9–2.2 per cent using the range of 5σ upper limits on the line flux.

3.2.4 REBELS-27

REBELS-27 is another UV-luminous (M_{UV} = −21.9) galaxy identified across the wide-area COSMOS field located at z_{c, eff} = 7.090 (Bouwens et al. 2022; Schouws et al., in preparation). This source was referred to as UVISTA-Y-004 in Stefanon et al. (2017, 2019) and UVISTA-301 in Bowler et al. (2020). It has an inferred stellar mass of log(M_{*}/M_☉) = 9.5 and its flat IRAC colour ([3.6]−[4.5] = 0.10^{+0.23}_{−0.22}) suggests relatively weak [O III] + H β emission (EW = 310 Å). We have observed REBELS-26 for 4.5 h with Binospec under clear conditions and moderate seeing (0.94 arcsec).

After searching for Lyα at wavelengths corresponding to Δν_{Lyα} = −500 to 1000 km s^{-1}, we find no indication of significant line emission (Fig. 2). The 5σ upper limiting EW ranges between 5.6–13.9 Å given that a moderate-strength skyline impacts part of the relevant wavelength regime. For the continuum flux density, we use the VIRCam J-band photometry (λ_{eff, rest} = 1543 Å) measurement of 0.47 μJy. The total Lyα escape fraction from REBELS-27 is inferred to be <3.2–8.0 per cent.

3.3 Lyman-alpha escape fractions from REBELS galaxies

It is well-established that luminous, UV-selected galaxies at z ~ 2–3 tend to have low Lyα escape fractions (≈5 per cent) due to their substantial dust content and high H I covering fractions (e.g. Hayes et al. 2010; Steidel et al. 2011; Ciardullo et al. 2014; Matthee et al. 2016; Weiss et al. 2021). It is, however, much less clear how efficiently Lyα photons are able to escape from galaxies at z > 6. On average, these very early systems are found to be much bluer with considerably larger SFRs relative to typical galaxies at z ~ 2 (e.g. Stark et al. 2013; Bouwens et al. 2014; Béthermin et al. 2015; Salmon et al. 2015; Strat et al. 2020; Stefanon et al. 2022), suggesting they may have physical conditions more conducive to efficient Lyα escape. Our REBELS sample enables us to investigate this possibility among the most UV-luminous (−22.7 ≤ M_{UV} ≤ −21.6)
and massive (M_* \geq 10^9 M_\odot) galaxies at z \sim 7. In the previous sub-section, we quantified the Ly \alpha escape fraction of each of our Binospec-targeted REBELS galaxies and the resulting values are summarized in Table 3. Notably, the [C II] systemic redshifts enable us to place confident upper limits on the escape fraction for sources which went undetected in Ly \alpha since we know whether their Ly \alpha profiles may overlap with strong skylines.

None of the eight UV-luminous (−22.7 \leq M_{UV} \leq −21.6) z \sim 7 REBELS galaxies which we have targeted with Binospec appear to show strong Ly \alpha emission (EW > 25 Å). This is particularly striking given that a large fraction (75 per cent) of these systems are inferred to exhibit high EW [O III] + H \beta emission (\geq 500 Å) implying efficient production of hydrogen ionizing photons (Chevallard et al. 2018; Tang et al. 2019; E21b). As expected from this result, we find that at least half our REBELS galaxies have low Ly \alpha escape fractions (<2.5 per cent (Table 3). Even after correcting these values for Ly \alpha transmission through the IGM (T \approx 50–80 per cent) see Section 5, we find that only 3–4 per cent of Ly \alpha photons typically escape our REBELS galaxies, comparable to that of similarly massive (\gg 10^9 M_\odot) systems at z \sim 2–3. This suggests that much of the Ly \alpha photons are resonantly trapped within the galaxy, likely due in part to a large column density of neutral hydrogen close to the systemic velocity (e.g. Neufeld 1990; Mas-Hesse et al. 2003; Verhamme, Schaerer & Maselli 2006; Steidel et al. 2010) though destruction by dust likely plays a significant role as well.

While our Binospec-targeted REBELS galaxies are blue in the rest-UV (median \beta = −1.94), our ALMA data none the less indicate the presence of substantial dust reservoirs in many of these systems (M_{dust} \sim 10^3 M_\odot; Dayal et al. 2022; Ferrara et al. 2022) which likely contribute significantly to the absorption of their Ly \alpha photons (see e.g. Behrens et al. 2019). It may be expected that we find a correlation between Ly \alpha escape fraction and far-infrared luminosity among our REBELS sample. In reality, such a trend is challenging to recover with our current data set for two reasons. First, our ALMA data only provide shallow upper limits on the far-infrared luminosity for sources undetected in dust continuum (see Table 3), allowing for the possibility of large dust masses within these systems. Secondly, our sample is limited by small statistics and a narrow dynamic range in Ly \alpha escape fraction (\lesssim 5 per cent). Indeed, we find that when we separate our sample by low (<2.5 per cent) and moderate (2.5–5 per cent) Ly \alpha escape fractions, we do not find a clear difference in the average far-infrared luminosity. The two sources with moderate Ly \alpha escape fractions (REBELS-14 and REBELS-23) have far-infrared luminosities of 3.4 \times 10^{11} and 3.9 \times 10^{11} L_\odot, respectively, where we quote 3\sigma upper limits for non-detected objects. Our ALMA data are consistent with similar far-infrared luminosities among the four galaxies with low (<2.5 per cent) Ly \alpha escape fractions within current sensitivity limits (\lesssim 3.3 \times 10^{11} to 4.3 \times 10^{11} L_\odot; see Table 3).

Here, we are ignoring the two sources with Ly \alpha escape fraction upper limits above 2.5 per cent (i.e. REBELS-03 and REBELS-27) since we cannot determine which bin these galaxies fall into. Further Ly \alpha observations of the REBELS sample as well as improved constraints on their far-infrared luminosity would enable a better assessment of the impact of dust on Ly \alpha escape among massive (\gg 10^9 M_\odot) reionization-era galaxies.

4 ANALYSIS

All of the galaxies considered in this work have ALMA detections of their [C II] 158-\mu m emission (Bouwens et al. 2022). In this section, we first use the [C II] data to measure the Ly \alpha velocity offsets of the four galaxies with Binospec detections, and discuss our results in context of the literature (Section 4.1). We then consider how the broad Ly \alpha line widths of these four z \sim 7 REBELS galaxies likely assist in enhancing transmission through the IGM (Section 4.2). Finally, we explore whether our sample shows any evidence of a connection between Ly \alpha EW and [C II] luminosity at fixed SFR (Section 4.3).

4.1 Lyman-alpha velocity offsets of UV-bright z > 6 galaxies

An increasing number of observations have demonstrated that UV-bright (M_{UV} \lesssim −21) galaxies do not show strong evolution in their Ly \alpha line strengths between z \sim 6 and z \sim 7 (Ono et al. 2012; Stark et al. 2017, E21b) even as the IGM neutral fraction rises rapidly over this time period (e.g. McGrreer et al. 2015; Davies et al. 2018; Wang et al. 2020; Yang et al. 2020). This indicates that Ly \alpha photons from UV-luminous z \sim 7 galaxies are somehow able to avoid strong resonant interactions with the surrounding intergalactic H. One possible explanation is that their photons often escape the CGM at velocities significantly redward of systemic (>100 km s^{-1}), placing them beyond the resonant core and well into the damping wing where transmission is greatly enhanced. While such large Ly \alpha velocity offsets are commonly observed among similarly bright galaxies at z \sim 2–3 (Hashimoto et al. 2013; Erb et al. 2014; Shibuya et al. 2014), a statistical analysis at z \sim 6 has been hindered by observational challenges. To date, only a small fraction of UV-luminous z > 6 galaxies have been detected in Ly \alpha, and much fewer have detections of a second emission line tracing the systemic redshift (e.g. [C II]158 \mu m). Here, we help address this issue using new [C II] detections of UV-luminous z \geq 6.5 galaxies from the ALMA REBELS program (Bouwens et al. 2022).

We have thus far detected Ly \alpha emission in four REBELS galaxies at z_{Ly\alpha} = 6.6–7.1 (REBELS-14, REBELS-15, REBELS-23, and REBELS-39; Section 3.1). All of four of these systems are in the UV luminosity range where Ly \alpha transmission appears to not be strongly evolving between z \sim 6 and z \sim 7 (M_{UV} \sim −22). We compute the Ly \alpha velocity offsets of these galaxies using systemic redshifts corresponding to the central [C II] wavelength from Gaussian fits to the 1D ALMA spectra (Schouw et al., in preparation). The Ly \alpha redshifts are measured from the wavelength of peak line flux (see Section 3.1) similar to the approach of many previous studies (Maiolino et al. 2015; Stark et al. 2015, 2017; Carniani et al. 2017, 2018b; Mainali et al. 2017; Matthee et al. 2020). From our redshift measurements, we calculate Ly \alpha velocity offsets of 177, 324, 227, and 165 km s^{-1} for REBELS-14, REBELS-15, REBELS-23, and REBELS-39, respectively (see Table 3). Our results indicate that a significant portion of Ly \alpha photons from these four UV-luminous (M_{UV} \sim −22) z \sim 7 galaxies are emerging well into the damping wing (average velocity offset of 223 km s^{-1}) where IGM transmission is significantly boosted.

To place our results in the context of previous studies, we consider the sample of z > 6 velocity offset measurements from the literature. Here, we only include measurements derived from secure (S/N > 5) Ly \alpha detections where the bluer side of the observed Ly \alpha emission feature (containing the peak of the profile) is not significantly impacted by skylines. We also ignore measurements derived from systematic line detections that were considered tentative in their published works. With our REBELS sample, we have nearly doubled the number of Ly \alpha velocity offset measurements among extremely UV-luminous (M_{UV} < −22) Lyman-break selected galaxies at z > 6, boosting available statistics from N = 4 to 7 (see Table 4; Willott et al. 2015; Stark et al. 2017; Hashimoto et al. 2019). These seven extremely bright galaxies have an average velocity offset of
Table 4. Summary of literature measurements of Ly $\alpha$ velocity offsets at $z > 6$ including those from this work. We only consider measurements derived from galaxies where the Ly $\alpha$ feature is detected at S/N $> 5$ and where the bluer side of the observed Ly $\alpha$ emission feature is not significantly impacted by skylines. We also ignore measurements derived from systemic line detections that were considered tentative in their published works.

<table>
<thead>
<tr>
<th>ID</th>
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<th>$M_{\text{UV}}$</th>
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Narrowband-selected Lyman-alpha Emitting Galaxies

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Notes: $^{a}$ Different Ly $\alpha$ redshifts and EWs are reported for COS-zs7-1 in Pentericci et al. (2016), Laporte et al. (2017), and Stark et al. (2017). We list the corresponding range of velocity offsets and EWs found between the three works.

$^{b}$ The UV magnitudes of RXJ2248-ID3 and A383-5.2 have been corrected for gravitational lensing adopting $\mu = 5.5$ and 7.3, respectively (Stark et al. 2013; Mainali et al. 2017).

$^{c}$ For A383-5.2, we report the Ly $\alpha$ velocity offset measured using the [C ii] $\lambda$1909 redshift from Stark et al. (2015) and the [C ii] $\lambda$158 µm redshift from Knudsen et al. (2016). For both measurements, we adopt the Ly $\alpha$ redshift from Stark et al. (2015).

...Moreover, each exhibits $\Delta v_{\text{sys}} > 100$ km s$^{-1}$ indicating that such large values are very common (if not ubiquitous) in the extremely UV-luminous $z > 6$ population (see Fig. 3).

We now compare the velocity offsets seen among the extremely UV-luminous ($M_{\text{UV}} < -22$) $z > 6$ galaxy population to those in the $z \sim 5$ ALMA ALPINE survey (Le Fèvre et al. 2020). Using the ALPINE DR1 catalogue (Béthermin et al. 2020; Cassata et al. 2020; Faisst et al. 2020), we find that there are twenty $M_{\text{UV}} < -22$ galaxies with both Ly $\alpha$ and [C ii] redshift measurements at $z = 4.4$−5.7. These 20 galaxies exhibit Ly $\alpha$ velocity offsets spanning $-192$ km s$^{-1}$ $\leq \Delta v_{\text{sys}} \leq 520$ km s$^{-1}$ with an average of 193 km s$^{-1}$. This average value is substantially lower than that seen among the luminosity-matched $z > 6$ sample (387 km s$^{-1}$). However, we note that the velocity offsets of these ALPINE galaxies will be weighted towards low values given their relatively high Ly $\alpha$ EWs. It has been shown that galaxies with larger Ly $\alpha$ EWs tend to exhibit smaller velocity offsets, both at $z \sim 2$−3 (e.g., Hashimoto et al. 2013; Erb et al. 2014) as well as within the $z \sim 5$ ALPINE sample (Cassata et al. 2020), likely in part because lower H$\alpha$ column densities near systemic leads to more efficient Ly$\alpha$ escape from the galaxy at $\Delta v_{\text{sys}} \sim 0$ km s$^{-1}$. According to the ALPINE catalogue, 45 per cent (9/20) of the extremely UV-luminous galaxies with offset measurements show strong Ly $\alpha$ emission ($\text{EW} > 25$ Å), a considerably larger fraction than that typically reported among Lyman-break selected UV-bright ($M_{\text{UV}} < -20.5$) galaxies at $z \sim 5$ ($\approx 25$ per cent; e.g. Stark, Ellis & Ouchi 2011; Cassata et al. 2015). This is to be expected given that the ALPINE galaxies were partially assembled from a sample of narrow-band selected Ly $\alpha$ emitters (Faisst et al. 2020). We note that the sample of seven $387$ km s$^{-1}$. Moreover, each exhibits $\Delta v_{\text{sys}} > 100$ km s$^{-1}$ indicating that such large values are very common (if not ubiquitous) in the extremely UV-luminous $z > 6$ population (see Fig. 3).

![Figure 3. Ly $\alpha$ velocity offsets measurements versus $M_{\text{UV}}$ among Lyman-break selected galaxies at $z > 6$. The stars show measurements from the REBELS sample while squares show additional measurements from the literature where points are colour-coded by the Ly $\alpha$ EW. All values shown here are tabulated in Table 4 where, in cases when a property has multiple reported values across various works, we plot the average of those reported values. The black cross shows the average velocity offset of 387 km s$^{-1}$ measured among extremely UV-luminous ($M_{\text{UV}} < -22$) $z > 6$ galaxies while the black dashed line shows the predicted relation between the average Ly $\alpha$ velocity offset and UV magnitude at $z = 7$ from Mason et al. (2018a). Available $z > 6$ velocity offset measurements at the fainter end ($M_{\text{UV}} \geq -20.5$) may be biased low given the relatively high Ly $\alpha$ EWs (40−138 Å) of these three objects.]
extremely UV-luminous \( z > 6 \) galaxies considered above exhibit fairly representative Ly \( \alpha \) EWs with respect to the broader UV-bright \( z \sim 6−7 \) population (E21b), suggesting that their Ly \( \alpha \) velocity offsets will also be representative. Only 14 per cent (1/7) of these systems show strong Ly \( \alpha \), comparable to that typically seen among UV-bright (\( M_{\text{UV}} < -20.5 \)) Lyman-break selected \( z \sim 6−7 \) samples (\( \leq 10 \) per cent; Stark et al. 2011; Ono et al. 2012; Schenker et al. 2014; De Barros et al. 2017; Pentericci et al. 2018). Moreover, the median Ly \( \alpha \) EW of these seven galaxies (13 \( \AA \)) is very similar to that inferred for the larger UV-bright \( z > 7 \) population in E21b (10 ± 3 \( \AA \)).

Many studies have established that faint (\( -20 \lesssim M_{\text{UV}} \lesssim -18 \)) galaxies exhibit a strong, rapid decline in Ly \( \alpha \) emission strength at \( z > 6 \) (e.g. Schenker et al. 2014; Pentericci et al. 2018; Fuller et al. 2020), in contrast to the bright (\( M_{\text{UV}} \lesssim -21 \)) population. This luminosity dependence on Ly \( \alpha \) transmission could arise (at least in part) from smaller velocity offsets among fainter \( z > 6 \) galaxies, as may be expected if lower mass systems have less H\( \text{I} \) gas near systemic velocity (e.g. Steidel et al. 2010; Erb et al. 2014). However, it is not clear that this is the case from existing data. There are currently only three intrinsically faint (\( M_{\text{UV}} \gtrsim -20.5 \)) galaxies at \( z > 6 \) with robust Ly \( \alpha \) velocity offset measurements (see Fig. 3 and Table 4; Maiolino et al. 2015; Stark et al. 2015; Carniani et al. 2017; Mainali et al. 2017). This limited sample size is largely the result of challenges in obtaining multilane detections of faint reionization-era systems. While all three galaxies do show velocity offsets smaller than the average of UV-luminous (\( M_{\text{UV}} < -22 \)) systems (Table 4), their Ly \( \alpha \) emission is clearly unusual. With EWs of 40−138 \( \AA \), these galaxies fall into the rare (\( \sim 5−20 \) per cent) sub-class of very strong Ly \( \alpha \) emitters among the faint \( z \sim 6−7 \) population (Pentericci et al. 2018). Because galaxies with higher EW Ly \( \alpha \) emission typically exhibit smaller velocity offsets (at least at \( z < 6 \); e.g. Hashimoto et al. 2013; Erb et al. 2014; Cassata et al. 2020), the measured offsets of these three faint galaxies may be biased towards low values. Further observations of faint \( z > 6 \) galaxies with more typical Ly \( \alpha \) emission (EW \( \lesssim 10 \) \( \AA \); Pentericci et al. 2018) are required to better assess the average velocity offset of this population.

4.2 Lyman-alpha line widths of UV-luminous \( z > 6 \) galaxies

Along with velocity offsets, the Ly \( \alpha \) line widths of \( z > 6 \) galaxies determine how efficiently their photons transit through a partially neutral IGM. Galaxies with broader Ly \( \alpha \) profiles emit a larger fraction of flux at high velocities where the damping wing absorption is weaker, thereby boosting IGM transmission. In this subsection, we discuss the Ly \( \alpha \) line widths of our UV-luminous (\( M_{\text{UV}} \sim -22 \)) REBELS galaxies and compare to those of fainter sources.

All four REBELS galaxies with Binospec detections display broad Ly \( \alpha \) lines with FWHM \( > 300 \) km s\(^{-1} \) (see Table 3). Two of these systems (REBELS-14 and REBELS-39) show extremely wide Ly \( \alpha \) profiles (FWHM \( \approx 650 \) km s\(^{-1} \)) with significant emission detected \( \approx 750 \) km s\(^{-1} \) relative to systemic (see Fig. 4). At these velocities, Ly \( \alpha \) photons are pushed far into the damping wing where the absorption cross-section is nearly 2 orders of magnitude less than that at 100 km s\(^{-1} \) (Dijkstra 2017). The presence of Ly \( \alpha \) flux at such large velocities undoubtedly enhances the visibility of these UV-luminous galaxies in a mostly neutral IGM.

We can obtain more stringent constraints on this population looking at all UV-selected \( z > 6 \) galaxies with Ly \( \alpha \) FWHM measurements. Here, we only consider S/N > 7 Ly \( \alpha \) detections where the measured width is not strongly impacted by OH skylines. In the sample of six UV-luminous (\( M_{\text{UV}} < -22 \)) galaxies, we find an average Ly \( \alpha \) FWHM of 450 km s\(^{-1} \), with values ranging from 310−640 km s\(^{-1} \) (see Fig. 5a and Table 5, Cuby et al. 2003; Willott et al. 2013; Oesch et al. 2015). If these large line widths are to preferentially boost Ly \( \alpha \) transmission with respect to less luminous galaxies, we would expect to see a luminosity-dependent trend in the FWHM of Ly \( \alpha \). In the nine UV-selected \( z > 6 \) galaxies with low luminosities (\( M_{\text{UV}} \gtrsim -20.5 \)) and published Ly \( \alpha \) line width measurements, we find FWHMs ranging from 130 to 285 km s\(^{-1} \) with an average of 185 km s\(^{-1} \) (Table 5; Nagao et al. 2005; Vanzella et al. 2011, 2014; Stark et al. 2015; Mainali et al. 2017; Hoag et al. 2019; Pelliccia et al. 2021). These are uniformly smaller than the widths of the more luminous systems considered in this paper, hinting at a luminosity-dependent trend (see Fig. 5a).

The presence of such broad Ly \( \alpha \) widths in the REBELS galaxy is not necessarily surprising. UV-luminous galaxies at \( z \approx 7 \) are likely to have neutral outflows with large column densities spanning a wide range of velocities, as are commonly seen in similarly luminous galaxies at lower redshifts (e.g. Shapley et al. 2003; Verhamme et al. 2008; Steidel et al. 2010). The Ly \( \alpha \) profiles in these systems will accordingly take on broader widths from back-scattered emission off the far side of the outflowing gas. Such resonant scattering effects surely play a significant role in transfiguring Ly \( \alpha \) photons to the large velocities described above.

Our ALMA data suggests another factor may also contribute to the broad line widths. The two systems in our sample exhibiting extremely broad Ly \( \alpha \) emission (REBELS-14 and REBELS-39) also show atypically broad [C \( \text{II} \)] profiles with FWHM \( = 300−520 \) km s\(^{-1} \) (see Table 5; cf. the median FWHM = 220 km s\(^{-1} \) among all 24 [C \( \text{II} \)]-detected REBELS galaxies; Schouws et al., in preparation), indicating that the broadest Ly \( \alpha \) emission is seen from galaxies with ISM reservoirs spanning the largest range of velocities. This is also true in the wider literature sample (see Fig. 5b). If we consider the seven UV-selected \( z > 6 \) galaxies with Ly \( \alpha \) and [C \( \text{II} \)] FWHM measurements (Table 5), the three with the largest [C \( \text{II} \)] FWHM (\( > 300 \) km s\(^{-1} \), WMH5, REBELS-39, REBELS-14) have an average Ly \( \alpha \) FWHM of 530 km s\(^{-1} \) (Willott et al. 2013, 2015). The four with lower [C \( \text{II} \)] FWHM (\( \lesssim 160 \) km s\(^{-1} \), CLM1, REBELS-15, BDF-3299, A383) have an average Ly \( \alpha \) FWHM of just 270 km s\(^{-1} \) (Cuby et al. 2003; Vanzella et al. 2011; Maiolino et al. 2015; Stark et al. 2015; Willott et al. 2015; Knudsen et al. 2016).

The connection between the Ly \( \alpha \) and [C \( \text{II} \)] line widths suggests that the velocity dispersion of the gas powering the line emission is likely playing a significant role in driving the FWHM of Ly \( \alpha \) emission. The origin of the very broad [C \( \text{II} \)] emission is still not entirely clear (Kohandel et al. 2019, 2020). High-resolution imaging from HiST potentially gives some insight, revealing that UV-luminous (\( M_{\text{UV}} < -22 \)) \( z \approx 7 \) galaxies tend to be composite systems comprised of several bright clumps separated by \( \gtrsim 2−5 \) kpc (Sobral et al. 2015; Bowler et al. 2017; Matthee et al. 2019). These clumps are likely to have significant peculiar motions (\( \gtrsim 100−500 \) km s\(^{-1} \)) given their separation and the dynamical masses of their host galaxies (\( \approx 1 \times 10^{10}−3 \times 10^{10} \) M\(_{\odot} \)), consistent with ALMA observations for a subset of these sources (Jones et al. 2017; Matthee et al. 2017; Carniani et al. 2018a; Hashimoto et al. 2019). At the spatial resolution of the REBELS [C \( \text{II} \)] maps (beam \( \approx 7 \) kpc), these putative clumps are mostly blended, which can naturally produce the broad (and potentially multipeaked) [C \( \text{II} \)] profiles seen in our data (Kohandel et al. 2019). If each clump of gas is also powering Ly \( \alpha \) emission, we would expect the intrinsic Ly \( \alpha \) profile to start out fairly broad in these luminous galaxies, mirroring the [C \( \text{II} \)] line profile. Resonant scattering off of the outflowing gas will further broaden the line and shift it to higher velocities.
Figure 4. Top panel: ALMA [CII] (blue) and dust continuum (red) contour maps overlaid on the near-infrared \( \chi^2 \) image of each REBELS source detected in Ly\( \alpha \). We show the 2\( \sigma \), 3\( \sigma \), and 4\( \sigma \) contours of detections within 1 arcsec of the source centroid from near-infrared imaging. The Binospec slit positions are shown with black lines where REBELS-14 and REBELS-39 were observed with two different slit orientations. Also shown is the ALMA beam size in the lower left-hand of each panel. Middle panel: Ly\( \alpha \) velocity profiles of each source using the systemic redshift measured from [CII]. We highlight portions of the profiles free of skyline obscuration with detected flux. Bottom panel: [CII] velocity profiles of each source. Format is similar to the middle panels.

Figure 5. (a) Ly\( \alpha \) FWHM versus \( M_{\text{UV}} \) among Lyman-break selected galaxies at \( z > 6 \). The stars represent measurements from the REBELS sample while squares show additional measurements from the literature. All values shown here are tabulated in Table 5 and we only consider sources with \( M_{\text{UV}} < -22 \) or \( > -20.5 \) to explore evidence of a luminosity dependence on Ly\( \alpha \) FWHM at \( z > 6 \). Current data suggest that brighter \( z > 6 \) sources commonly exhibit larger Ly\( \alpha \) FWHMs, with an average FWHM of 450 km s\(^{-1} \) measured among extremely UV-luminous (\( M_{\text{UV}} < -22 \)) galaxies (black cross). (b) Measurements of Ly\( \alpha \) FWHM versus [CII] FWHM when available among this same sample (see Table 5). These existing data suggest that the broadest Ly\( \alpha \) emission is seen from galaxies with ISM reservoirs spanning the largest range of velocities.
Table 5. Literature measurements of Lyα FWHM among Lyman-break selected galaxies at $z > 6$. We consider only those with either $M_{UV} \leq -22$ or $\geq -20.5$ (separated by the horizontal line) to explore a luminosity-dependent trend. This sample is limited to S/N $> 7$ Lyα detections where the measured line width is not strongly impacted by skylines. [C II] FWHM measurements are also listed where available.

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Note. * We adopt magnification factors of $\mu = 5.5, 11.5, 7.3, 3.2, 6.9,$ and 17.3 for RXJ2248-ID3, RELICS-DP7, A383-5.2, MACS0744-064, macs0717_0859, and macs0717_1730, respectively as stated by the corresponding references listed in the table.

While fainter systems are likely to also breakup into clumps, these less massive and more compact galaxies should have smaller velocity dispersions, leading to narrower initial line widths (before transfer through the outflowing gas). If the outflowing gas of these faint galaxies also has smaller velocities and lower column densities, it will further contribute to narrow Lyα widths. This physical picture will soon be easily testable with higher spatial resolution ALMA maps and $JWST$ IFU observations of Lyα and non-resonant nebular lines. If shown to be true, it would suggest that the substantial peculiar motions of clumps in very luminous galaxies will impact the observed Lyα profile and in turn the atypical visibility of Lyα emission lines in this population. It would also suggest that when multiple spectral peaks in Lyα are observed, they do not always imply that one of the peaks is blueward of the systemic redshift (e.g. Matthee et al. 2018; Meyer et al. 2021). Such blue Lyα peaks are exciting as they imply a low covering fraction of neutral gas, potentially an indicator of Lyman-continuum leakage (e.g. Henry et al. 2015; Verhamme et al. 2015; Jaskot et al. 2019; Gazagnes et al. 2020; Hayes et al. 2021). We suggest that systemic redshifts (as provided by [C II]) are critical for interpreting the Lyα profiles, as multiple peaks can arise naturally from blended clumps of gas in large composite systems.

Our Binospec data may be providing evidence of multipeaked Lyα profiles arising from separate gas clumps in extremely luminous $z \sim 7$ galaxies. As can be seen in Fig. 6, the Lyα profiles of both REBELS-14 and REBELS-39 tentatively show multiple peaks of emission even though all flux is detected redward of the systemic velocity from [C II]. In the Lyα spectra of REBELS-14, there are potentially two peaks at velocities of approximately 220 and 380 km s$^{-1}$ relative to systemic where this separation of 160 km s$^{-1}$ is more than twice the resolution of our Binospec data ($\approx 68$ km s$^{-1}$). There is also a possible third Lyα peak in REBELS-14 giving rise to the flux seen on both sides of the moderate-strength skylines at $\approx 680$ km s$^{-1}$ relative to systemic. The Lyα profile of REBELS-39 shows a similar structure. There are possibly two separate peaks at velocities of approximately 110 and 300 km s$^{-1}$ relative to systemic along with a potential third peak at $\approx 670$ km s$^{-1}$. We acknowledge that the presence of skylines and the current S/N of our data leaves significant uncertainty in the true number of Lyα peaks for each REBELS source, though we note that lower redshift ($z \sim 2-4$) galaxies have been shown to exhibit significant spatial variations in their Lyα profiles (e.g. Erb, Steidel & Chen 2018; Claeysens et al. 2019; Leclercq et al. 2020).

To assess the plausibility of these potential multipeak Lyα solutions, we fit the 1D spectra of REBELS-14 and REBELS-39 assuming three peaks of emission. During the fits, we assume that the bluest peak is a half-Gaussian while the redder two peaks are symmetric Gaussians (due to less attenuation by the IGM/CGM at higher velocities). Each peak component is convolved with the instrument resolution and regions overlapping with strong skylines are masked during the fits. For comparison, we also consider single-peak profile solutions treated as a half-Gaussian convolved with the instrument resolution. The triple-peak Lyα models are able to reproduce the observed line shapes for both REBELS-14 and REBELS-39, yielding best-fitting reduced $\chi^2$ values of 0.50 and 0.66, respectively. The single-peak models provide a poorer match to the data with best-fitting reduced $\chi^2$ values of 1.16 and 2.20, respectively, where here we are accounting for the fact that the triple-peak fits have more degrees of freedom. None the less, deeper spectra will be required to verify whether multiple emission peaks (all redward of systemic velocity) are indeed present in the Lyα profiles of these two extremely luminous ($M_{UV} = -22.7$) $z \sim 7$ galaxies. If shown to be true, these separate Lyα peaks could support the presence of multiple gas clumps with large peculiar motions within each galaxy (cf. Park et al. 2021), as may be further evidenced by their possible multipeaked [C II] profiles (Fig. 4). Such a physical picture would clearly help explain the extremely broad Lyα emission (FWHM $\approx 640$ km s$^{-1}$) observed from these two galaxies, though it is unclear in this picture why the bluest Lyα peak is the strongest given that it lies closest to systemic where the H I column density is perhaps the largest.

4.3 The dependence of [C II] production on Lyα EW at $z \sim 7$

The first ALMA surveys targeting $z \geq 7$ galaxies resulted in very few [C II] detections (Ouchi et al. 2013; Ota et al. 2014; Maiolino et al. 2015; Schaerer et al. 2015), even though the observation depths were calibrated to local empirical relations between [C II] luminosity and SFR (e.g. De Loore et al. 2014). It has been proposed that this
so-called [C II] deficit was in part due to the selection bias towards \( z \gtrsim 7 \) galaxies with strong Ly \( \alpha \) emission which had known spectroscopic redshifts (e.g. Pentericci et al. 2016; cf. Pallottini et al. 2019; Carniani et al. 2020). These strong Ly \( \alpha \) emitters may be expected to show weaker [C II] at fixed SFR due to e.g. lower metallicities relative to the typical high-redshift galaxy population (e.g. Ouchi et al. 2013; Maiolino et al. 2015; Vallini et al. 2015; Pentericci et al. 2016; Ferrara et al. 2019). Because our REBELS galaxies were selected via the Lyman break (Bouwens et al. 2022), they show Ly \( \alpha \) EWs more typical of bright \( z \sim 7 \) systems and thus provide a valuable baseline for [C II] production in the reionization era. Below, we explore whether REBELS galaxies with higher Ly \( \alpha \) EWs show significantly weaker [C II] emission at fixed SFR.

We divide our REBELS galaxies into two sub-samples split by Ly \( \alpha \) EW = 10–20 \( \text{Å} \) and EW < 10 \( \text{Å} \), where 10 \( \text{Å} \) is the approximate typical Ly \( \alpha \) EW of UV-bright \( z \sim 7 \) galaxies (E21b). For this analysis, we ignore REBELS-03 and REBELS-27 given their relatively weak upper limits on Ly \( \alpha \) EW from skyline contamination. The [C II] luminosities (Schouws et al., in preparation) and UV + IR star formation rates of each galaxy (Topping et al. 2022) are reported in Table 3.

Our current sample does not show a strong trend between Ly \( \alpha \) EW and [C II] luminosity at fixed SFR. The three galaxies with relatively weak Ly \( \alpha \) emission (EW < 10 \( \text{Å} \)) have [C II] luminosity to SFR ratios spanning \((0.06-0.13) \times 10^8 \text{L}_\odot/(\text{M}_\odot \text{yr}^{-1})\) with an average value of \((0.09 \pm 0.04) \times 10^8 \text{L}_\odot/(\text{M}_\odot \text{yr}^{-1})\). These \( L_{\text{CII}}/\text{SFR} \) ratios are very similar to the three more moderate Ly \( \alpha \) emitters (EW = 10–20 \( \text{Å} \)) which show values ranging \((0.05-0.09) \times 10^8 \text{L}_\odot/(\text{M}_\odot \text{yr}^{-1})\) with an average of \((0.06 \pm 0.02) \times 10^8 \text{L}_\odot/(\text{M}_\odot \text{yr}^{-1})\). Here, we are adopting a fixed conversion factor between UV luminosity and unobscured SFR (see Section 2.2), as is common in the literature (e.g. Maiolino et al. 2015; Pentericci et al. 2016; Matthee et al. 2019). Utilizing age-dependent \( SFR_{\text{UV}}/\text{SFR} \) ratios (e.g. Topping et al. 2022) does substantially increase the estimated unobscured SFRs of two sources (REBELS-15 and REBELS-39) given that their high [O III] \( \lambda 5007 \) EWs suggest very young ages (see Section 2.2). However, since each Ly \( \alpha \) EW bin contains one of these sources, we still find that the average \( L_{\text{CII}}/\text{SFR} \) ratios are comparable for weak and moderate Ly \( \alpha \) emitters in our sample when adopting age-dependent \( SFR_{\text{UV}}/\text{SFR} \) ratios.

There are two possible explanations for why we do not find significantly weaker [C II] emission at fixed SFR among the stronger Ly \( \alpha \) emitters in our sample. The first potential reason is that our REBELS galaxies probe a rather limited dynamic range of Ly \( \alpha \) EWs (<20 \( \text{Å} \)). Previous studies have found evidence that relatively weak [C II] production becomes more apparent among \( z \gtrsim 6 \) galaxies with Ly \( \alpha \) EW \gtrsim 50 \( \text{Å} \) (e.g. Carniani et al. 2018a; Harikane et al. 2018b; Matthee et al. 2019). It is possible that only at such high EWs do galaxy properties which reduce [C II] production (e.g. low metallicity or strong stellar feedback; Ouchi et al. 2013; Vallini et al. 2015; Ferrara et al. 2019) become significantly more common. We also may not yet have adequate statistics to identify a modest correlation between \( L_{\text{CII}}/\text{SFR} \) ratios and Ly \( \alpha \) emission at EW \lesssim 20 \( \text{Å} \). Further rest-UV spectroscopic follow-up of the REBELS sample would better establish if a correlation is present in this typical Ly \( \alpha \) EW regime.

5 DISCUSSION

Numerous observational campaigns have presented evidence that the IGM rapidly transitioned to a highly neutral state at \( z > 6 \) (e.g. Becker et al. 2001; Fan, Carilli & Keating 2006; Kashikawa et al. 2011; Konno et al. 2014; McGreer et al. 2015; Greig et al. 2017; Zheng et al. 2017; Bañados et al. 2018; Davies et al. 2018; Wang et al. 2020; Whiter et al. 2020; Yang et al. 2020), thereby greatly increasing the optical depth to Ly \( \alpha \) emission at its resonant nature. Surprisingly, UV-bright \((M_{\text{UV}} \lesssim -21)\) galaxies show no evidence of strong evolution in Ly \( \alpha \) emission strengths between \( z \sim 6 \) and \( z \sim 7 \) (Ono et al. 2012; Stark et al. 2017, E21b), raising the question of how photons from these systems were able to transmit efficiently through a partially neutral IGM. Using our ALMA observations, we have demonstrated that UV-bright \( z \sim 7 \) galaxies commonly exhibit both large Ly \( \alpha \) velocity offsets and broad Ly \( \alpha \) lines (Section 4). Here, we explore how these properties enhance Ly \( \alpha \) transmission in the reionization era.

In this paper, we have nearly doubled the number of Ly \( \alpha \) velocity offset measurements among extremely UV-luminous \((M_{\text{UV}} \lesssim -22)\) Lyman-break galaxies at \( z > 6 \) (Table 4). To quantify the expected IGM transmission of these systems, we calculate the damping wing optical depth (Miralda-Escudé 1998) faced by Ly \( \alpha \)
Efficient Lyα transfer of bright $z \approx 7$ galaxies

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**Figure 7.** Illustration of how Lyα IGM damping wing transmission during reionization depends on both the bubble size and the Lyα photon velocity relative to systemic. We assume that the emitting galaxy is at $z = 7$ and resides in the centre of a highly ionized ($x_{HI} \lesssim 10^{-5}$) bubble with radius in physical Mpc given by the $x$-axis. Extremely UV-luminous ($M_{UV} < -22$) galaxies at $z > 6$ exhibit large velocity offsets (average $\approx 400\, \text{km}\,\text{s}^{-1}$) and nearly half also show very broad profiles with detectable flux extending to $\approx 750\, \text{km}\,\text{s}^{-1}$ (Fig. 4). At these high velocities, Lyα photons transmit efficiently ($\geq 40\%$ per cent) through the neutral IGM even when emitted from within small ($R = 0.1$ physical Mpc) bubbles.

Photons at their average velocity offset ($\approx 400\, \text{km}\,\text{s}^{-1}$). We assume that the IGM outside the emitting galaxy is highly ionized ($x_{HI} \lesssim 10^{-5}$) out to a bubble radius $R$ beyond which the IGM is completely neutral. In a moderate-sized bubble ($R = 0.5$ physical Mpc), a typical extremely UV-luminous $z = 7$ galaxy will transmit a considerable fraction ($\approx 35\%$ per cent) of its Lyα emission at peak velocity ($\Delta v_{Ly\alpha} = 400\, \text{km}\,\text{s}^{-1}$, see Fig. 7). Since the Lyα photons of these luminous systems are redshifted far past the resonant core, their IGM transmission will remain significant ($T \approx 20\%$ per cent) even if situated in small ($R = 0.1$ physical Mpc) bubbles.

The combination of these two properties indicate that a substantial fraction of Lyα photons are frequently pushed deep into the damping wing where the $\text{H}\text{i}$ absorption cross-section is minimized. Indeed, nearly half (3/7) of extremely UV-luminous $z > 6$ galaxies with Lyα detections and systemic redshift measurements show Lyα flux extending to $\approx 750\, \text{km}\,\text{s}^{-1}$ (see Fig. 4 and Hashimoto et al. 2019), enabling Lyα photons transmit efficiently through the IGM even when emitted within a small ($R = 0.1$ physical Mpc) ionized bubble ($T \gtrsim 40\%$ per cent; see Fig. 7). This ability to displace Lyα photons to such high velocities clearly aids in the persistent visibility of massive, UV-luminous galaxies at $z > 6$.

With the Lyα velocity profile information of our Binospec-detected REBELS galaxies, we can estimate the net IGM transmission fraction for each system assuming a given ionized bubble size. That is, for each wavelength pixel in the observed 1D Lyα profiles (Fig. 1), we divide the line flux density by the IGM transmission fraction at the corresponding velocity and re-integrate the line profile to obtain an estimate of the line flux escaping from the interstellar and circumgalactic medium. For these UV-luminous ($-22.7 \leq M_{UV} \leq -21.6$) $z \approx 7$ galaxies, we assume a fiducial bubble size of $R = 1$ physical Mpc (Endsley & Stark 2022) and estimate that approximately half (48–54 per cent) of the Lyα flux escaping from each galaxy has escaped through the IGM. If these highly UV-luminous systems are instead often situated in the centre of very large ($R \gtrsim 3$ physical Mpc) ionized bubbles (possibly as a result of surrounding strong galaxy overdensities; e.g. Barkana & Loeb 2004; Endsley & Stark 2022; Leonova et al. 2022), we then estimate that $\gtrsim 75–80\%$ of their Lyα photons are transmitted through the IGM. Nevertheless, we expect that the high peak Lyα velocity offsets and large line widths of UV-luminous $z > 6$ galaxies lead to a relatively high net transmission ($\gtrsim 50\%$ per cent) of Lyα photons through the IGM.

In contrast to bright systems, faint ($-20 \lesssim M_{UV} \lesssim -18$) galaxies show a strong decline in Lyα emission strengths at $z > 6$ (Schenger et al. 2014; Pentericci et al. 2018; Fuller et al. 2020). It is possible that this apparent luminosity dependence on Lyα transmission is (at least in part) due to smaller velocity offsets and narrower Lyα widths at lower UV luminosities. While such a picture is consistent with existing observations, all these measurements come from faint $z > 6$ sources with exceptionally strong Lyα emission (EW = 32–342 Å; see Tables 4 and 5) thereby potentially biasing this conclusion.

Until Lyα detections become more accessible for typical faint reionization-era galaxies, expectations of their IGM transmission properties must be guided by data at lower redshift. One particularly relevant result is that Lyα velocity offsets positively correlate with UV luminosity at $z \sim 2–3$ (Erb et al. 2014). Of course, if a similar relation holds at $z > 6$, the Lyα emission of fainter galaxies would be more susceptible to scattering by intergalactic H1. To better quantify the possible extent of this effect, Mason et al. (2018a) developed a model calibrated to the $z \sim 2–3$ data that predicts a galaxy’s velocity offset given its UV luminosity and redshift. The main assumption underlying this model is that velocity offsets correlate with halo mass independently of redshift, and can therefore be linked to UV luminosity via theoretical $M_{UV}$–$M_{halo}$ relations. With our results, we can begin testing this model’s predictions at $z > 7$. From the seven extremely UV-luminous ($-23 < M_{UV} < -22$) Lyman-break galaxies at $z = 6–8$ with robust velocity offset measurements, we calculate an average of $\langle \Delta v_{Ly\alpha} \rangle = 387\, \text{km}\,\text{s}^{-1}$ (Table 4). The Mason et al. (2018a) model predicts this empirical value within $\pm 0.1\%$ ($\langle \Delta v_{Ly\alpha} \rangle \approx 380\, \text{km}\,\text{s}^{-1}$ for $M_{UV} = -22.5$ and $z = 7$), indicating reasonable agreement (see Fig. 3). Assuming this model can be applied to lower redshifts, we would expect a typical faint ($M_{UV} = -19$) galaxy at $z = 7$ to show a velocity offset of $\approx 100\, \text{km}\,\text{s}^{-1}$ which is consistent with measurements from A383-52 ($z = 6.03$, $M_{UV} = -19.3$; Stark et al. 2015; Knudsen et al. 2016). The Lyα IGM transmission at this velocity offset is nearly half that at $\Delta v_{Ly\alpha} = 400\, \text{km}\,\text{s}^{-1}$ assuming a moderate-sized ($R = 0.5$ physical Mpc) host bubble at $z = 7$ (see Fig. 7). The difference becomes much more substantial in smaller bubbles ($R = 0.1$ physical Mpc) where Lyα transmission is only $T \approx 1\%$ per cent at $100\, \text{km}\,\text{s}^{-1}$ compared with $T \approx 20\%$ per cent at $400\, \text{km}\,\text{s}^{-1}$.

Another relevant question is how we might expect Lyα FWHM to vary with UV luminosity in the reionization era. Data at lower redshift again provides a valuable baseline. Upon investigating a large set of literature Lyα observations (primarily at $z \sim 0–4$), Verhamme et al. (2018) found a positive correlation between the FWHM and the velocity offset of the red Lyα peak. This observed trend may arise in part from larger H1 column densities both broadening the Lyα line as well as pushing the peak of emission to higher velocities (e.g. Verhamme et al. 2006, 2018; Zheng et al. 2014). Outflows may also help drive this correlation since systems with gas extending to higher...
velocities would be expected to show both a wider Ly α profile and a more redshifted peak. If fainter z > 6 galaxies have systematically lower H1 column densities or slower outflows (perhaps due to lower mass), they would, thus, be expected to show narrower Ly α lines in addition to smaller velocity offsets. While the lower H1 column densities may lead to more efficient Ly α escape within the galaxy, the resulting narrower and less redshifted lines will face stronger attenuation from the partially neutral z ≥ 7 IGM. Assuming an average velocity offset of ≈100 km s−1 for faint (M_UV < −19) galaxies at z = 7 (Mason et al. 2018a), the literature compilation from Verhamme et al. (2018) suggests a typical FWHM of ≈200–250 km s−1. This is consistent with measurements from RELICs-DP7, A838-5.2, and MACS0744-064 (−19.5 ≤ M_UV ≤ −18.5) which show an average FWHM = 190 km s−1 (Stark et al. 2015; Hoag et al. 2019; Pelliccia et al. 2021), and implies that the Ly α flux from faint z = 7 galaxies would often be limited to ≲300 km s−1 relative to systemic. At these velocities, IGM transmission will be considerably suppressed (factor >3) in small (R ≈ 0.1 physical Mpc) bubbles relative to the UV-bright systems that have emission extending to ≈750 km s−1.

These predictions help explain why it has been so challenging to detect Ly α emission from faint z ≥ 7 galaxies, even those which appear to sit in the vicinity of an ionized bubble. One likely ionized region is in the BDF field where three relatively bright (M_UV ≤ −20.5) galaxies at z = 7.0–7.1 exhibit strong Ly α emission (Vanzella et al. 2011; Castellano et al. 2018). However, deep follow-up observations yielded no Ly α detections among all twelve fainter (M_UV > −20.25) z ~ 7 candidates targeted in this field (Castellano et al. 2018). While it is currently unclear whether these faint systems indeed reside in the same ionized structure(s), it is none the less expected that their Ly α photons would experience weaker IGM transmission due to smaller velocity offsets and narrower line widths. Using the predictions described above, an intrinsically faint (M_UV ~ −19) z = 7 galaxy would likely have ≈2 × lower Ly α IGM transmission relative to an extremely luminous (M_UV < −22) system assuming a moderate-sized (R = 0.5 physical Mpc) host bubble. These expectations for reduced IGM transmission also help explain the dearth of Ly α detections among faint yet lensed z ~ 7–8 galaxies (Hoag et al. 2019; Mason et al. 2019).

Our sample nearly doubles the number of velocity offset measurements among extremely UV-luminous (M_UV < −22) Lyman-break selected galaxies at z > 6. All seven of these systems show large (>100 km s−1) velocity offsets, indicating that their Ly α photons are pushed well past the strong resonant core of the H1 absorption cross-section. At their average velocity offset of 387 km s−1, Ly α photons transmit efficiently through the IGM with T ≈ 35 percent when emerging from a z = 7 galaxy situated in a moderate-sized (R = 0.5 physical Mpc), highly ionized (n_Hi = 10−5) bubble.

(iii) All four REBELS galaxies with Binospec detections display broad Ly α lines with FWHM > 300 km s−1, indicating that a large fraction of their photons are at high velocities where damping wing absorption is weaker. Two of these galaxies show extremely broad Ly α profiles (FWHM = 640 km s−1) with significant emission extending to ≈750 km s−1 relative to systemic. At such high velocities, Ly α photons transmit efficiently (T ≥ 40 percent) through the IGM, even when the emitting source resides in a small (R = 0.1 physical Mpc) ionized bubble. Broad Ly α profiles (FWHM = 300–400 km s−1) are also observed from the three other UV-luminous (M_UV < −22) continuum-selected z > 6 galaxies in the literature (Cuby et al. 2003; Willott et al. 2013; Oesch et al. 2015), indicating an average FWHM = 450 km s−1 for this population. These broad line widths undoubtedly assist in boosting the Ly α visibility of UV-bright galaxies at z ≥ 7.

(iv) A contributing factor to the broad Ly α profiles of massive, UV-bright z ≥ 6 galaxies may be that their Ly α emission is produced in gas spanning a wide range of motions, as evidenced by our ALMA data. In the two REBELS galaxies showing extremely broad Ly α profiles, we also observe very broad [C II] emission (FWHM = 300–520 km s−1) indicating that these are composite galaxies containing multiple gas clumps moving with large peculiar motions (e.g. Bowler et al. 2017; Carniani et al. 2018a). If these high-velocity gas clumps also produce Ly α emission, the intrinsic Ly α profile will mirror that of [C II] before being further broadened by resonant interactions with outflowing material. The large peculiar motions of these clumps might also produce Ly α profiles with multiple peaks redward of systemic velocity. Such profiles are different in nature from those showing a peak blueward of systemic which signal low H1 column density channels on the near side of the galaxy (e.g. Gazagnes et al. 2020). We suggest that systemic redshifts from [C II] and other non-resonant lines are critical to interpret the physical origin of multipeaked Ly α lines.

(v) We find no strong trend between the strength of Ly α emission and the [C II] luminosity at fixed SFR in our REBELS sample. The three galaxies with relatively weak Ly α emission (EW < 10 Å) show an average [C II] luminosity to SFR ratio that is very similar to the average ratio among the three more moderate Ly α emitters (EW = 10–20 Å). This lack of an apparent trend may be due to the limited dynamic range in Ly α EWs among our Lyman-break selected sample, though improved statistics are also required to test for a modest correlation in this EW regime.

(vi) Recent studies may suggest that faint galaxies in the vicinity of ionized bubbles at z ~ 7 do not show strong Ly α emission (Castellano et al. 2018). While this could imply relatively small bubbles around bright galaxies, it may also reflect a luminosity dependence on the Ly α profile properties discussed in this paper. Faint (M_UV ~ −19) z ~ 7 galaxies are expected to typically exhibit much smaller velocity offsets (∆v_c, < 100 km s−1; Mason et al. 2018a) and narrower line widths (FWHM ~ 200–250 km s−1; Verhamme et al. 2018) relative to that seen among extremely luminous (M_UV < −22) systems. These predictions imply ≈2 × lower IGM transmission among faint z = 7 galaxies at fixed moderate bubble size of R = 0.5
physical Mpc, helping explain why their emission is more difficult to detect.

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DATA AVAILABILITY

The near- and mid-infrared imaging data underlying this article are available through their respective data repositories. See http://www.eso.org/public/ via the VISTA and VIDEO data, and https://sha.ipac.caltech.edu/applications/Spitzer/SHA/ for IRAC data. The raw ALMA data are available via the science archive (program 2019.1.01634.L) and the MMT/Binospec data will be shared upon reasonable request to the corresponding author.

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