In recent years, Hubble Space Telescope observations at low redshift \((z \sim 0.3–0.4)\) with the Cosmic Origin Spectrograph (COS) have measured Lyman continuum (LyC) properties and stellar populations, the conditions that favor the escape of ionizing photons from galaxies, and more (see above references and Schaerer et al. 2016; Gazagnes et al. 2018; Chisholm et al. 2018). In addition, these observations have served to empirically establish “indirect indicators” of LyC escape, which can potentially be used at all redshifts, including for galaxies in the epoch of reionization, where direct observations of the LyC are not possible. Among these indirect indicators are properties of the resolved Lyman alpha (Ly\(\alpha\)) line profile (the peak separation), weak UV absorption lines, Mg\(\text{II}\) emission, a high ratio of \([O\text{III}]\lambda 4959,5007/\text{[O II] }\lambda 3727\), and a deficit of \([C\text{II}]\lambda 1589,1526\) emission (see, e.g., Feltre et al. 2016; Gutkin et al. 2016; Berg et al. 2016; Senchyna et al. 2017; Rigby et al. 2015). These include Ly\(\alpha\), C\(\text{IV}\) \(\lambda 1550\), He\(\text{II}\) \(\lambda 1640\), O\(\text{II}\) \(\lambda \lambda 1660,1666\), C\(\text{III}\) \(\lambda 1907,1909\), and other emission lines, which provide important diagnostics of their ISM and radiation field (see, e.g., Feltre et al. 2016; Gutkin et al. 2016; Nakajima et al. 2018). However, to study sources of reionization and to relate the UV line properties to LyC escape,
it is mandatory to observe the same galaxies both in the LyC and in the non-ionizing UV out to ~ 2000 Å. So far, very few such observations have been obtained, and the first spectrum of a low-z LyC emitter with a high escape fraction of LyC photons ($f_{\text{esc}} \sim 43\%$) has been obtained only recently (Schaerer et al. 2018).

Here, we present the first results of an HST program to observe the UV emission lines of known LyC emitters, sampling a range of LyC escape fractions from very low ($f_{\text{esc}} = 1.4\%$) to the highest escape currently known ($f_{\text{esc}} = 72\%$), which was observed in the compact star-forming galaxy J1243+4646 by Izotov et al. (2018b). Our observations show strong emission lines, in particular strong C IV λ1550 emission in the strongest LyC emitters. This demonstrates for the first time a connection between LyC escape and nebular C IV emission, from which we propose a new empirical criterion to select galaxies with strong LyC escape. Furthermore, our results shed new light on the recently detected C IV emitters at high redshift (see Stark et al. 2015; Mannalı et al. 2017; Schmidt et al. 2017; Tang et al. 2021; Vanzella et al. 2021; Richard et al. 2021), suggesting that some of them could be strong LyC emitters.

2. UV spectra of compact star-forming galaxies at $z \sim 0.3$ – 0.4 with varying LyC escape fractions

2.1. HST observations

Eight out of eleven compact star-forming galaxies with LyC measurements from our 2016–2018 campaign (Izotov et al. 2016b, 2018a, 2018b) have been observed in Cycle 27 (GO 15941; PI: Schaerer) and earlier (Schaerer et al. 2018). The sources span a broad range of LyC escape fractions ($f_{\text{esc}} \sim 1.4$ – 72%), metallicities in the range 12 + log(O/H) = 7.64 – 8.16 with a median of 7.92, and [O III]15007/0/1]3727 from 5 to 27.1.

The observations were taken with the Space Telescope Imaging Spectrograph (STIS) NUV-MAMA using the grating G230L with the central wavelength 2376 Å and the slit 52′′ × 0′′, resulting in a spectral resolution of $R \sim 700$ for the targeted compact galaxies. The data were reduced with the CALSTIS v3.4.2 pipeline and including data from additional observations of J1154+2443 that were not available to Schaerer et al. (2018), which improved the signal-to-noise ratio (S/N) to ~ 7 per pixel for this galaxy. Wavelength shifts between sub-exposures were insignificant, which allowed for the co-addition of gross and background counts per pixel, approximately preserving Poisson statistics. In the wavelength range of interest, the continuum S/N (accounting for Poisson flux uncertainties) ranges between 3 and 8 per ~ 1.55 Å pixel, with six out of eight spectra reaching S/N> 5.

For the remainder of this Letter, we define “strong” leakers as galaxies with a LyC escape fraction above 10% (i.e., $f_{\text{esc}} > 0.1$) to distinguish such sources, which could significantly contribute to cosmic reionization, from those with a low or negligible escape of ionizing photons. In our current sample, three out of eight galaxies are classified as strong leakers (see Fig. 2.2).

2.2. Main UV emission line features

Examples of the observed STIS spectra are shown in Fig. 2.1 ordered – from top to bottom – by decreasing LyC escape fraction. The top two sources shown have very high escape fractions. In the spectral range covered by the observations (rest-frame wavelengths of ~ 1200–2000 Å), the main detected emission lines are Lyα (not illustrated here), C IV λ1550, He II λ1640, O III] λ1666, and C III] λ1909. We note that with the given resolution, the C IV λ1550 and C III] λ1909 doublets are not resolved. Hints of blended Si III] λ1883,1892 are also visible in some of the spectra (see Fig. 2.1).

We now mainly focus on the carbon and helium lines, and leave a more exhaustive report and analysis for subsequent publications. We note that the low resolution of our spectra does not allow us to exclude some contribution from stellar emission
After Lyα, the lines with the highest EWs are C iv λ1909 and C iv λ1550, with EW(C iv) = 4 ± 20 Å and EW(C iv) = 3 ± 15 Å. The C iv λ1909 line is detected in all the sources, and C iv λ1550 in five out of eight galaxies above 4 σ.

In Fig. 2.2 we plot the C iii and C iv EWs of our targets as a function of metallicity (using O/H as a proxy) along with measurements from other low-redshift galaxies for comparison. The C iii EWs of the LyC emitters do not occupy a particularly unique domain in this figure, and EW(C iv) does not show a dependence on the LyC escape fraction. The “envelope” of the observed distribution of the C iii EWs show a metallicity dependence that is fairly well reproduced by photoionization models using the spectral energy distributions of young stellar populations, as shown in several studies (Jaskot & Kavirannadra et al. 2018; Nakajima et al. 2018; Ravindranath et al. 2020).

Interestingly, the C iv EWs of the strong leakers are among the highest observed so far. Furthermore, J1248+4259 stands out as the low-ζ galaxy (ζ ≲ 0.4) with the highest C iv λ1550 EW (EW(C iv) = 15.14 ± 2.14 Å); however, it shows a low escape fraction (fesc = 0.014 ± 0.004). Again, the observed EWs are also in fair agreement with the predictions from photoionization models (Nakajima et al. 2018; Ravindranath et al. 2020).

He ii λ1640 emission is detected at ~4 ± 6 σ in all strong leakers, showing EWs of EW(He ii) = 3.7 ± 8.0 Å, which are among the highest values observed in star-forming galaxies. The He ii line is also detected above 3σ in two other sources (i.e., in five of the eight spectra). We comment on the strength of the He ii λ1640 emission below.

2.3. Strong LyC leakers show strong C iv λ1550 emission and a high C iv/C iii ratio

In addition to exhibiting strong C iv and He ii λ1640 emission lines, the main distinguishing feature of the strong leakers is the high ratio, C43 = I(C iv λ1550)/I(C iii λ1909) ≥ 0.75, of the carbon line intensities, which is fairly exceptional, as shown in Fig. 2.2 (left panel), in comparison with other low-ζ galaxies where both carbon lines have been detected. And interestingly, except for the galaxy J1248+4259 discussed below, the carbon line ratio increases with the LyC escape fraction, as shown in the right panel. Although the sample of galaxies for which both observations of the LyC and the non-ionizing UV spectrum, including C iii and C iv, are covered is admittedly small, we suggest that, based on the available data, star-forming galaxies with I(C iv λ1550)/I(C iii λ1909) ≥ 0.75 have escape fractions fesc > 0.1 and hence show “significant” amounts of LyC emission.

If generally applicable, our postulate implies that the galaxy J1248+4259 reported by Izotov et al. (2018b) should be a strong LyC emitter; that is, it should have a true LyC escape fraction of at least ~5 times that measured from the COS spectrum, which could be possible if, for example, the emission of LyC photons is not isotropic. There are indeed other indications that J1248+4259 could be a strong leaker: First, it shows a very strong Lyα emission with an EW of EW(Lyα) = 256 ± 5.2 Å, comparable to strong leakers. Second, the Lyα line profile is clearly double-peaked, with a fairly low separation of the two peaks (Vsep = 283.8 ± 15.9 km s⁻¹), which would yield fesc = 0.13 if the mean relation between fesc and Vsep from Izotov et al. (2018b) was applied. Finally, J1248+4259 is also somewhat of an “outlier” in the scattered relation between Ω32 = [O iii]/[O ii] and fesc, showing a lower-than-average escape fraction for its high Ω32 = 11.8 (see Izotov et al. 2021).

The other low-ζ galaxies that show I(C iv λ1550)/I(C iii λ1909) ≥ 0.75 in Fig. 2.2 are J084236 and J104447. They are low-mass low-metallicity galaxies at ζ ~ 0.01 that both show very strong C iv emission with EW(C iv) ~ 6–10 Å (Berg et al. 2019b). Based on high-resolution COS spectra, which show strong nebular C iv emission in the two doublet lines and indications for minor radiation transfer effects in these lines, Berg et al. (2019a) have suggested that J1044457 is optically thin to ionizing radiation, at least at energies above ~4.7 eV, the ionization potential of C iv (see also Benchyna et al. 2021). It also shares other properties of strong LyC leakers, such as a very high Ω32 = 16.2. Although no direct observations of the LyC are possible at these redshifts, the available data for J1044457 appear fully consistent with our postulate that this galaxy is a strong LyC leaker. We suggest that J084236 may also be a strong LyC leaker.

Intrinsically, the C43 ratio traces the ionization structure of the nebula, similarly to Ω32, which has already been suggested as a potential indicator of LyC escape (Jaskot & Oey 2013; Nakajima & Ouchi 2014). However, since C iv λ1550 is a resonance line, it is a priori affected by recombination transfer effects; this is in contrast to the nebular oxygen lines, which should be optically thin. Therefore, the C iv λ1550 line and the C43 ratio could be a more sensitive tracer of LyC escape than Ω32. To first order, both C43 and Ω32 trace the ionization parameter, U, and are independent of metallicity. Furthermore, an examination of photoionization models shows that both C43 and Ω32 vary with the LyC escape fraction. For moderate to high U, the predicted variations in C43 appear stronger than in Ω32, again providing some theoretical support for our empirically based postulate. A detailed comparison with models will be presented in future work.

3. Discussion and implications

3.1. Comparison with high-ζ LyC emitters and candidates

We first compared our results with confirmed high-ζ LyC emitters, although relatively few high-ζ galaxies with established or potentially strong LyC escape (absolute escape fractions fesc ≥ 0.1) are known. Well-studied sources with the highest LyC escape fractions are Ions2, the Sunburst arc, and probably Ions3 with relative escape fractions fesc,rel ≥ 0.5, according to Vanzella et al. (2020). VLT/XShooter spectroscopy of Ions2 at α = 3.2 indeed shows the presence of nebular emission in both C iv and C iii, with a ratio I(C iv λ1550)/I(C iii λ1909) = 0.61 ± 0.23; this is consistent with our findings, although the lines are relatively weak (e.g., EW(C iv) = 2.6 Å and EW(He i) = 2.8 Å; Vanzella et al. 2020). For the other objects, the reported data are insufficient to examine C iv and C iii. Similarly, no detailed rest-UV spectra have been published for the z = 3.1 LyC emitting galaxies of Fletcher et al. (2019). The robust sample of z ~ 3 LyC emitters from Steidel et al. (2018) and Pahl et al. (2021) provides average properties to avoid the inherent limitations in determining fesc for individual sources that are due to the stochastic

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2 We here refer to relative escape fractions since absolute values cannot reliably be determined for individual sources at high z (e.g., Steidel et al. 2018).
intergalactic medium transmission at high $z$. Their LyC emitting sample has an average escape fraction of $f_{\text{esc}} = 0.06 \pm 0.01$, which is below our definition of strong emitters, and the stacked UV spectrum illustrated in Steidel et al. (2013) does not show strong C iv emission, although no details on carbon emission lines are reported in their study.

Another comparison is possible with Ly$\alpha$ emitters at $z \sim 2$, where the LyC escape fraction was recently estimated using indirect empirical spectral indicators by Naidu et al. (2021) and Matthee et al. (2021). Stacking rest-UV spectra of Ly$\alpha$ emitters with estimated $f_{\text{esc}} \geq 0.2$ (high escape) and $f_{\text{esc}} \leq 0.05$ (low escape), they find several significant differences between the two subsamples, in particular the presence of nebular C iv $\lambda$1550, C iii $\lambda$1909, He ii $\lambda$1640, and O iii $\lambda$1666 emission in the high escape sources, whereas the low escape sources only show C iii and O iii emission. Although the C iv emission of their strong emitters (EW(C iv) = 2.0 ± 0.4 Å) is weaker than that of our three sources with $f_{\text{esc}} > 0.1$, which show EW> 2.5 Å, and despite C iii $\lambda$1909 being stronger than C iv, their finding of nebular C iv and He ii $\lambda$1640 emission in strong leaker candidates is compatible with our results.

We therefore conclude that both low- and high-redshift observations seem to consistently show (i.e., in about three out of four cases) that the UV spectra of strong leakers (with $f_{\text{esc}} \geq 0.1 - 0.2$) are characterized by nebular C iv $\lambda$1550 and C iii $\lambda$1909 emission and C43 $\geq 0.75$. Although the available data are still relatively scarce, our observations provide the first such quantitative estimate.

### 3.2. Implications for high-$z$ CIV emitters

So far, very few high-redshift galaxies showing nebular C iv $\lambda$1550 emission have been reported. Since the recent discoveries of several lensed galaxies at $z \sim 6 - 7$ with nebular C iv (Stark et al. 2015; Mainali et al. 2017; Schmidt et al. 2017), other C iv emitters have been found both in blank fields (e.g., at $z \sim 2.2$; Tang et al. 2021) and in lensed galaxies (see Stark et al. 2014; Vanzella et al. 2021; Richard et al. 2021). The stacked rest-UV spectrum of lensed sources with median $z = 3.2$ and median $M_{1500} = -17.1$ from Vanzella et al. (2021) shows strong nebular C iv $\lambda$1550, C iii $\lambda$1909, and numerous other emission lines. The C iv line in several of these sources is strong, with EWs of...
up to EW(C iv) = 38 ± 16 Å in A1703-zd6 (Stark et al. 2015) and C43 > 0.8 in several of them. Our results suggest that these sources are strong LyC emitters, which is overall in agreement with the other observational properties they share with LyC emitters (e.g., strong Lyα emission). The fact that C iv emission is found in many strongly lensed sources probably also indicates that the fraction of strong LyC emitters increases toward fainter, lower-mass galaxies, a trend also found in the z ~ 0.3 – 0.4 reference samples (see Izotov et al. 2021; Flury et al. 2022b).

### 3.3. Strong emission lines and high C43 ratios explained

This leads us to the questions of what the strong observed UV emission lines (high EW of nebular lines) tell us and how they can be understood. Since EWs measure the strength of the emission line with respect to the continuum, the EW of a UV recombination line such as He II λ1640 can be cast in the following simple form,

\[
\text{EW}(1640)/\AA = \xi_{1640} \frac{Q(\text{HeII})}{Q_H} c_{1640} \lambda^2 / 3 \times 10^{18},
\]

where \( \xi_{1640} = Q(\text{HeII})/L_{1500} \) is the ionizing photon efficiency per unit intrinsic monochromatic UV luminosity in the commonly used units of erg^{-1} Hz, \( c_{1640} = 5.67 \times 10^{-12} \) erg relates the recombination line flux to the ionizing photon flux (e.g., Schaerer 2003), and \( \lambda \approx 1640 \) Å. This shows that the EW is proportional to \( \xi_{1640} \) and to the hardness of the ionizing spectrum, expressed here as \( Q \text{HeII}/Q_H \), the ratio of the ionizing photon flux above 54 eV and 13.6 eV, respectively. From this we can easily see that the observed EWs in our three strongest leakers, EW(1640) ~ 3 – 8 Å, are plausible. Indeed, the EWs can be explained with a relatively high ionizing photon production, \( \log(\xi_{1640}) \approx 25.6 – 25.8 \) erg^{-1} Hz (cf. Schaerer et al. 2018), which then implies \( Q \text{HeII}/Q_H \approx 0.01 – 0.04 \). This hardness translates to optical line ratios of \( I(\text{HeII}λ4686)/I(\text{Hβ}) \approx 1.74 Q \text{HeII}/Q_H \approx 0.016 – 0.07 \), similar to the observations of J1154+2443 and J1248+4259, which are \( I(\text{HeII})/I(\text{Hβ}) \approx 0.02 – 0.03 \) (Guseva et al. 2020), and comparable to the line intensities typically observed in galaxies at comparable metallicity (at 12 + log(O/H) ~ 8.0; see, e.g., Schaerer et al. 2019). This simple estimate shows that the high He II λ1640 EWs reached in these leakers do not require exceptional conditions and/or exceptionally hard ionizing spectra compared to other galaxies (weak or non-leakers) at similarly low metallicity. The same conclusion also applies to, for example, the strong leaker candidates found by Naidu et al. (2021) among their Lyα emitter sample. However, the observed spectra are clearly harder at > 54 eV than predicted by normal stellar population models, and the source of these He^+ ionizing photons remains to be elucidated (see, e.g., Stasinska et al. 2015).

To predict the strengths of the metallic lines of C iv and C iii, which depend on the ionization parameter, spectral energy distribution, nebular abundances, and other factors, detailed photoionization models are required. The models of Nakajima et al. (2018), for example, show maximum values of EW(C iv) ~ 8 – 10 Å and EW(C iii) ~ 10 – 18 Å at metallicities 12 + log(O/H) ~ 7.7 – 8.0, of the same order as our observed EWs. We also examined density-bounded models at appropriate metallicities, using the BOND set of CLOUDY models from the 3 Million Models Database of Morisset et al. (2015). The models indeed show an expected increase in the C iv/C iii] ratio with increasing LyC escape fraction, and several models show C iv/C iii] ratios comparable to those of our observations. From these simple considerations, we conclude that both the observed EWs and UV line ratios of the strong low-z leakers seem “reasonable” and that we probably do not need peculiar or extreme ionizing spectra to reproduce their emission line spectra. Tailored photoionization models to examine the behavior of the major UV and optical emission lines of the LyC emitters and comparison sources will be presented in a subsequent publication.

### 4. Conclusion

With the STIS spectrograph on board HST, we have obtained new UV spectra from ~ 1200 – 2000 Å, the rest-frame spectra of eight z ~ 0.3 – 0.4 LyC emitters from Izotov et al. (2016a,b, 2018a,b), which cover a large range of LyC escape fractions. We detect multiple emission lines, including Lyα, C iv λ1550, He II λ1640, O iii] λ1666, and C iii] λ1909. The Lyα and C iii] lines are detected in all the sources. Our main results can be summarized as follows:

- We report the detection above 4σ of C iv λ1550 emission in six out of eight galaxies, with the EWs in two galaxies (J1243+4646 and J1248+4259), EW(C iv) ~ 12 – 15 Å, exceeding the previously reported maximum in low-z galaxies (J1044+57; Berg et al. 2019a).
- Strikingly, C iv λ1550 emission is detected in all LyC emitters with escape fractions f_{esc} > 0.1, and the flux ratio of C iv λ1550/C iii] λ1909 appears to increase with f_{esc}.
- Based on the available data, we suggest that strong leakers, galaxies with f_{esc} > 0.1, are characterized by C iv λ1550/C iii] λ1909 ≥ 0.75, adding another indirect indicator of LyC escape to those already established.
- All strong leakers also show strong He II λ1640 emission with EW(He ii) = 3.7 – 8.0 Å, which are among the highest values observed in star-forming galaxies.
- A simple estimate shows that the high EW of the He ii λ1640 line is primarily due to a high ionizing photon production, \( \xi_{1640} \), and that it does not require unusually hard ionizing spectra, compared to normal galaxies at similar metallicity that frequently show optical He ii λ4686 emission lines.

In short, our observations provide an important new reference for understanding the UV spectra of LyC emitting galaxies and thus also analogs of the sources of cosmic reionization. The spectra of the strong low-z leakers share many similarities with those of the C iv λ15500 emitters recently discovered at high redshifts (e.g., Stark et al. 2015; Mainali et al. 2017; Schmidt et al. 2017), and our results suggest that these objects are good candidates for strong LyC escape. If universally applicable, the empirical criterion of using the carbon line ratio C iv λ1550/C iii] λ1909 ≥ 0.75 to identify strong LyC leakers could represent an additional important tool for studying the sources of cosmic reionization.

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