Does Lyman continuum escape fraction correlate with spectral hardness?

R. Marques-Chaves, D. Schaerer, R. O. Amorín, H. Atek, S. Borthakur, J. Chisholm, V. Fernández, S. R. Fluré, M. Gaivalioso, A. Graziani, M. J. Hayes, T. M. Heckman, A. Henry, Y. I. Izotov, A. E. Jaskot, Z. J., S. R. McCandliss, M. S. Oey, G. Östlund, S. Ravindranath, M. J. Rutkowski, A. Saldana-Lopez, H. Teplitz, T. X. Thuan, A. Verhamme, B. Wang, G. Worseck, and X. Xu

(Affiliations can be found after the references)

Received –; accepted –

ABSTRACT

The properties that govern the production and escape of hydrogen ionizing photons (Lyman continuum; LyC with energies >13.6 eV) in star-forming galaxies are still poorly understood, but they are key to identifying and characterizing the sources that reionized the Universe. Here we empirically explore the relationship between the hardness of ionizing radiation and the LyC leakage in a large sample of low-z star-forming galaxies from the recent HST Low-z Lyman Continuum Survey. Using SDSS stacks and deep X-Shooter observations, we investigate the hardness of the ionizing spectra (Q_{HeII}/Q_\text{H\beta}) between 54.4 eV (HeII) and 13.6 eV (H\beta) from the optical recombination lines He II \lambda 4686 Å and H\beta \lambda 4861 Å for galaxies with LyC escape fractions spanning a wide range. f_{esc}(LyC) \approx 0 – 90%. We find that the observed intensity of He II/H\beta is primarily driven by variations in the metallicity, but is not correlated with LyC leakage. Both very strong (<f_{esc}(LyC) \approx 0.5) and non-leakers (<f_{esc}(LyC) \approx 0) present similar observed intensities of He II/H\beta at comparable metallicity, between \approx 0.01 and \approx 0.02 for 12 + log(O/H) > 8.0 and < 8.0, respectively. Our results demonstrate that Q_{HeII}/Q_\text{H\beta} does not correlate with f_{esc}(LyC), which implies that strong LyC emitters do not show harder ionizing spectra than non-leakers at similar metallicity.

Key words. Galaxies: starburst – Galaxies: high-redshift – Cosmology: dark ages, reionization, first stars

1. Introduction

Numerous studies of star-forming galaxies at z \approx 1 – 3 have shown differences with low-z galaxies in the Sloan Digital Sky Survey (SDSS), based on shifts in the classical, optical BPT emission-line diagrams towards higher excitation in the nebular gas phase (see the review of Kewley et al. [2019] and references therein). Such shifts can be due to different physical effects causing harder ionizing spectra of their stellar populations (e.g. lower metallicities, younger ages), ISM properties (higher ionization parameter, different gas pressure and/or density), \textalpha-element enhancements, selection effects or others (cf. Steidel et al. [2016]).

Possibly larger differences have been observed in rest-UV spectra of distant galaxies, where strong nebular emission from C IV \lambda 1550 and He II \lambda 1640 has been found (e.g. Stark et al. [2015]; Mainali et al. [2017]; Vanzella et al. [2021]). These lines have also been detected in confirmed or suspected Lyman continuum (LyC) emitters at z \approx 2 – 4 (see Vanzella et al. [2018], Naïdu et al. [2021]). These observations suggest high ionizing spectra, in particular, since C IV and He II probe energies above 47.8 and 54.5 eV, respectively, and are thus sensitive to higher-energy radiation than the “classical” strong optical emission lines of [O III], [N II], [S II] (e.g. Kewley et al. [2019], Peiró et al. [2016]).

Nebular He II emission provides the best measure of the hardness of the ionizing radiation field, since its recombination lines are basically direct photons counters for energies > 54 eV, whereas the forbidden metal lines depend on many parameters (ionization parameter, and others). Naïdu et al. [2021] stacked rest-UV spectra of Ly\alpha emitters (LAEs) at z \approx 2 for which they estimated LyC escape fractions using indirect methods, finding narrow He II \lambda 1640, C IV \lambda 1550, and other lines in sources with high LyC escape, whereas low escape sources only show C III and O III emission. From this they suggest a possible relation between hardness of the ionizing spectra and LyC escape. He II is also seen in the stacks of the LyC candidates of Marchi et al. [2018] selected as Lyman break galaxies (LBGs), although the poor resolution makes it difficult to exclude a significant contribution from stellar emission. Also, nebular He II emission has not been reported in the LBG stacked LyC emitter spectra of Steidel et al. [2018]. These findings call for clarification on the possible link between LyC escape, nebular He II emission, and the hardness of the radiation between energies 13.6 and 54 eV.

At low redshift, Jaskot & Oey [2013] have examined how the presence of hard ionizing radiation can influence emission line diagnostics of the optical depth of LyC radiation in green pea galaxies, a class of strong emission line galaxies now known to contain LyC emitters. Schaerer et al. [2022] have recently discovered intense C IV and He II \lambda 1640 emission lines in three low-z LyC emitters, (f_{esc} > 0.1), with UV properties similar to the high-z galaxies mentioned above. They propose that strong C IV \lambda 1550 emission indicates high LyC escape fractions. Furthermore, they also estimate that strong LyC leakers do not have harder ionizing spectra than non-leakers, and that the presence of strong C IV and He II in the spectra of LyC leakers could be primarily due to a high ionizing photon production (Schaerer et al. [2022]).

On the other hand, Pérez-Montero et al. [2020] suggested that the observed He II \lambda 4686 emission in metal-poor low-z
The extinction curve of the Galaxy. Flux measurements are derived using Gaussian profiles and the Pecaut & Fitzpatrick (1999) and the Galactic E(B−V) values from the dust maps of Green et al. (2018) are used to correct the reddening effect of the Galaxy. Flux measurements are derived using Gaussian profiles and the Pymsol non-linear least squares function curve_fit and corresponding uncertainties using Monte Carlo. The Cardelli et al. (1998) reddening law (RV = 3.1) is adopted to correct the internal extinction using the ratios of well-detected Balmer emission lines (following Izotov et al. 1994).

Regarding the lines of interest in this work, Hβ is detected with high-significance in all galaxies, but not He ii, yielding 3σ limits of He ii/He α ≤ 0.4% on average, which are fairly above the typical intensities He ii/He α ≤ 0.02 found in other compact star-forming galaxies (e.g., Izotov et al. 2016a), including LyC emitters (Guseva et al. 2020). Therefore, we perform a stacking analysis of the SDSS spectra to improve the He ii/He α limits.

We build two different groups of stacked spectra, one composed of bins in absolute LyC escape fraction, fesc(LyC), and another one composed of bins in fesc(LyC) and 12 + log(O/H). For the first group, we define the four bins using fesc determined from the UV analysis of Saldana-Lopez et al. (2022). For the second group, we built nine stack spectra considering three bins of fesc(LyC) and three bins of metallicity. Table I contains the definition of the bins and the main derived properties from the stacked spectra.

For each bin, the SDSS spectra are de-redshifted using the systemic redshifts from the observed wavelengths of bright optical lines, and re-sampled using a linear interpolation onto a common wavelength grid. Next, we normalize the spectra at λ = 4750 − 4850 Å, that is relatively free of emission/absorption features. Finally, we stack all spectra by averaging the flux in each spectral bin. We have also tested other stacking methods, using the median and the weight-average using the uncertainty spectra, but no significant differences in the observed intensity of He ii/He α are found between these three methods. Fig. 1 shows the four stacked spectra in bins of fesc(LyC). He α is detected at least in three stacks, together with other faint lines, such as [Fe ii] 4658 Å and the [Ar iv] doublet at 4711 Å and 4740 Å. We note the lack of significant broad emission in the stacks around 4650 Å and 5808 Å, that could be associated with a significant contribution of Wolf-Rayet stars (e.g., Brinchmann et al. 2008).

2.3. XShooter/VLT observations
Spectroscopic observations of eight LzLCS sources were carried out during 2021 with the XShooter instrument on the VLT, with total integration times of 50–100 min. The XShooter spec-
Table 1: Summary of the results of SDSS stacks

| SDSS Bins (1) | Denomination (2) | Definition (3) | N (4) | $f_{\text{esc}}$ (5) | $12 + \log(O/H)$ (6) | He $\text{H}/\text{He}$ (7) | $Q_{\text{He}}/Q_{\text{H}}$ (8) |
|--------------|-----------------|---------------|-------|-----------------|-----------------|----------------|----------------|
| very strong leakers | $f_{\text{esc}} \geq 0.2$ | 8 | 0.49$^{+0.02}_{-0.02}$ | 7.849$^{+0.019}_{-0.018}$ | 0.016$^{+0.007}_{-0.007}$ | 0.005$^{+0.002}_{-0.002}$ |
| strong leakers | $0.05 \leq f_{\text{esc}} < 0.2$ | 13 | 0.11$^{+0.02}_{-0.02}$ | 8.107$^{+0.021}_{-0.021}$ | 0.013$^{+0.006}_{-0.006}$ | 0.007$^{+0.003}_{-0.003}$ |
| weak leakers | $f_{\text{esc}} < 0.05$ | 29 | 0.025$^{+0.004}_{-0.001}$ | 8.115$^{+0.021}_{-0.021}$ | 0.012$^{+0.004}_{-0.004}$ | 0.007$^{+0.002}_{-0.002}$ |
| non-leakers | SNR(He)$< 2$ | 39 | $<0.011$ | 8.175$^{+0.013}_{-0.013}$ | $<0.015$ | 0.009$^{+0.003}_{-0.003}$ |

Notes. — (1), (2), and (3) Groups, denomination, and definition of each bin; (4) number of sources in each bin; (5) and (6) mean and 68% confidence intervals (bootstrap resampling) of $f_{\text{esc}}$ and $12 + \log(O/H)$ for each bin; (7) observed He $\text{H}/\text{He}$ intensities. (8) hardness of the ionizing spectra between 54.4 eV (He$^+$) and 13.6 eV (H) following Eq. 1 and assuming $f_{\text{esc}}^\text{H} \approx 0$. Upper limits refer to a 2$\sigma$ limit.

Therefore, we use nine SDSS stacks grouped in three bins of $f_{\text{esc}}$ and three bins of $12 + \log(O/H)$ (see Table 1 for details).

The right panel of Fig. 2 shows the relationship between He $\text{H}/\text{He}$ and $12 + \log(O/H)$ for strong LyC leakers (solid circles) and non/weak LyC leakers (empty and dashed circles) in the metallicity bins. For comparison, we also show the observed intensities of He $\text{H}/\text{He}$ and metallicities of a compilation of almost 900 star-forming galaxies from SDSS DR14 (plus symbols; Izotov et al. 2016a), for which the [O III] 4363 Å line is detected with an accuracy better than 4$\sigma$, allowing thus direct abundance determinations using the $T_\gamma$-method. The overall properties of the parent sample are discussed in Guseva et al. (2019).

Two main conclusions can be drawn from the right panel of Fig. 2. First, strong LyC leakers present roughly the same He $\text{H}/\text{He}$ intensities as in non/weak-leakers at comparable metallicities. For instance, strong He $\text{H}/\text{He}$ intensities are found for both non-leakers and strong LyC leakers in the low metallicity bin (He $\text{H}/\text{He} = 0.030 \pm 0.009$ and 0.020 $\pm 0.005$, respectively), while sources with $12 + \log(O/H) = 8.0$ – 8.3 show He $\text{H}/\text{He} \sim 0.12$, independently on $f_{\text{esc}}$ (LyC). Moreover, for a specific range of $12 + \log(O/H)$, the line intensities He $\text{H}/\text{He}$ inferred for strong leakers do not differ from those typically observed in other star-forming galaxies. Izotov et al. (2016a). Second, low-metallicity star-forming galaxies present stronger He $\text{H}/\text{He}$ than high-metallicity galaxies, a trend reported already in other works of increasing the He $\text{H}/\text{He}$ intensity with decreasing metallicity.

3.2. No variations of the hardness with LyC escape

The hardness of the ionizing radiation field between energies above 54.4 and 13.6 eV, described by $Q_{\text{He}}/Q_{\text{H}}$, is to first order

Article number, page 3 of 6
related to the relative recombination line intensities by

\[
I(4686)/I(H\beta) = \frac{c_{686}}{c_{\beta}} \frac{1 - f_{\text{esc}}^{He^+}}{(1 - f_{\text{esc}})} \left( \int_{34}^{\infty} (F_\nu / \nu) d\nu \right) 
\]

\[
= 1.74 \frac{(1 - f_{\text{esc}}^{He^+})}{(1 - f_{\text{esc}})} Q_{\text{He}^+}.
\]

where \( Q \) expresses the number of ionizing photons emitted above the corresponding ionization potential, and \( c_\beta = h \nu / (\alpha_\beta, e^2) \) relates the recombination rate to the line intensity (Osterbrock & Ferland 2006). For \( c_\beta \) we have adopted typical values of the electron temperature (\( T_e = 10 \) kK). The above expression also accounts for the escape of ionizing photons, which are \textit{a priori} different for He\(^+\) and H-ionizing photons. In fact, one expects that \( f_{\text{esc}}^{He^+} \ll f_{\text{esc}} \), since the doubly-ionized He region is generally significantly smaller than the H \( \beta \) region, and in other words, He\(^+\)-ionizing photons are absorbed much closer to the source than those of lower energy. Therefore, except for extremely hard, power-law like ionizing spectra, \( f_{\text{esc}}^{He^+} \) is expected to be very low, or at least lower than \( f_{\text{esc}} \).

We have shown that the intensity of He \( n/H\beta \) does not depend on \( f_{\text{esc}} \), and is primarily driven by variations with metallicity. Therefore, Eq. (1) implies that the hardness \( Q_{\text{He}^+}/Q_H \) does not correlate with the LyC escape, since, if anything, He \( n/H\beta \) should increase with increasing \( f_{\text{esc}} \) even for constant \( Q_{\text{He}^+}/Q_H \) (see Eq. (1)). Table 1 provides the inferred values of \( Q_{\text{He}^+}/Q_H \) for all the stacks using Eq. (1) and assuming \( f_{\text{esc}}^{He^+} \approx 0 \). No variation is found in \( Q_{\text{He}^+}/Q_H \) between strong and non-leakers within the uncertainties.

3.3. Implications

Our results rule out LyC leakage to explain the origin of nebular He \( n \) emission put forward by Pérez-Montero et al. (2020). Their galaxies present roughly the same He \( n/H\beta \) intensities at comparable metallicity as those studied in our work (see their Figure 1). According to these authors, the observed intensities of He \( n \) could be explained by density-bounded H \( \beta \) regions with very high ionizing photon leaking, with a mean \( f_{\text{esc}}(\text{LyC}) \approx 0.74 \) for the entire sample. Clearly, our results shown in Fig. 2 contradict this scenario, where the same intensities of He \( n/H\beta \) are found in sources with both very high and very low \( f_{\text{esc}}(\text{LyC}) \), i.e., with no dependence on \( f_{\text{esc}} \) at all. Furthermore, the invoked mean \( f_{\text{esc}} \approx 0.74 \) is significantly higher than measured in comparable low-z galaxies (Flury et al. 2022a), and for the strongest low-z leaker known (J1243+4646 with \( f_{\text{esc}} = 0.73 \) reported by Izotov et al. 2018b), or \( f_{\text{esc}} \approx 0.89 \) inferred in Saldana-Lopez et al. 2022 we measure He \( n/H\beta \) < 0.02 (2\( \sigma \)), which is not exceptionally high compared to many other star-forming galaxies with similar metallicity (12 + log(O/H) \approx 7.90, cf. Fig. 2 right panel). Other mechanisms or sources are needed to explain the origin of nebular He \( n \) (see e.g., Olivier et al. 2021, Simmonds et al. 2021, and references therein).

At z \approx 2, Naidu et al. (2021) recently identified two groups of LAEs, one showing probably strong LyC escape and the other low LyC escape fractions. Comparing the stacked spec-
tra of these two groups, they found differences in their observed rest-frame UV spectra, with the strong leaker candidates showing the presence of high-ionization lines of C iv 1550Å and He ii 1640Å, and the other group showing only the presence of lower-ionization lines (e.g., C iii 1909Å). From this finding, Naidu et al. (2021) suggest that strong LyC leakers could have harder ionizing spectra. On the other hand, if the galaxies studied in our work are comparable to high-z LAEs, our results imply that these observed differences are not related to LyC escape.

Generally speaking, the absence of hardness variations with $f_{esc}$ shows that this property of the global radiation field does not determine the conditions for the ionizing photon escape. In contrast, other studies have found significant correlations between different physical properties and $f_{esc}$, which could hint at such physical processes. This includes, e.g., highly concentrated star-formation (high SFR surface densities), a high ionization parameter, the presence of an inhomogeneous ISM and dust distribution, and low amounts of dust (Verhamme et al. 2017; Gazagnes et al. 2018; Cen 2020; Flury et al. 2022b; Saldana-Lopez et al. 2023). Our finding does not exclude that radiative processes contribute to determining LyC escape, but they indicate that the hardness of the radiation field (over the energy range measured here) is not fundamental. For example, this suggests that LyC escape is not related to low-luminosity AGNs. However, our differential study does not explain the origin of nebular He ii emission, which is known to require sources of ionizing photons above 54 eV in amounts which are not predicted by normal stellar populations (see e.g., Shirazi & Brinchmann 2012; Stasinska et al. 2015; Schaerer et al. 2019).

4. Summary

We have investigated empirically the hardness of the ionizing spectra between 54.4 and 13.6 eV ($Q_{He}^\alpha / Q_{H\beta}$, i.e., the ionization potential of He$^+$ and that of H) as a function of the Lyman continuum (LyC) escape fraction, $f_{esc}(LyC)$, of a large sample of star-forming galaxies at low-redshift for which LyC are available from HST observations. Optical recombination lines of He ii 4686Å and H$\beta$ 4861Å from SDSS and XShooter spectra are used to determine $Q_{He}^\alpha / Q_{H\beta}$ and its dependence on $f_{esc}(LyC)$. The underlying effect of metallicity is also considered.

We have built stacked spectra in bins of $f_{esc}(LyC)$ and metallicity, allowing us to study the behaviour of He ii/H$\beta$ across a wide range of $f_{esc}(LyC)$ $\approx$ 0.5 and non-leakers ($f_{esc}(LyC)$ $\approx$ 0) have on average similar intensities of He ii/H$\beta$, of around He ii/H$\beta$ $\approx$ 0.1. We find that He ii/H$\beta$ is primarily driven by variations on the metallicity, where He ii/H$\beta$ increases with decreasing 12 + log(O/H), in particular for 12 + log(O/H) < 8.0, as known from previous studies (e.g. Shirazi & Brinchmann 2012; Schaerer et al. 2019). At comparable metallicities, strong LyC leakers present roughly the same He ii/H$\beta$ intensities as in non-weak-leakers and as in many other normal star-forming galaxies, where nebular He ii is detected.

In short, our results demonstrate that $Q_{He}^\alpha / Q_{H\beta}$ does not correlate with $f_{esc}(LyC)$. This implies that strong LyC emitters do not show harder ionizing spectra than non-leakers at similar metallicity. Future studies will address other hardness or softness indicators of the radiation field and more broadly examine the nebular properties of the galaxies from the LzLCS.

Acknowledgements. The authors thank the referee for useful comments that greatly improved the clarity of this work. Y.I.I. acknowledges support from the National Academy of Sciences of Ukraine by its priority project “Fundamental properties of the matter in the microworld, astrophysics and cosmology”. R.A. acknowledges support from ANID Fondeydt Regular Grant 1202007. Funding for the Sloan Digital Sky Survey IV has been provided by the Alfred P. Sloan Foundation, the U.S. Department of Energy Office of Science, and the Participating Institutions. SDSS-IV acknowledges support and resources from the Center for High Performance Computing at the University of Utah. The SDSS website is www.sdss.org.

References

Akritas, M. G. & Siebert, J. 1996, MNRAS, 278, 919
Brinchmann, J., Kunth, D., & Duret, F. 2008, A&A, 485, 657
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Cen, R. 2020, ApJ, 889, L22
Eisenstein, D. J., Weinberg, D. H., Agol, E., et al. 2011, AJ, 142, 72
Feltre, A., Charlot, S., & Gutkin, J. 2016, MNRAS, 456, 3354
Fitzpatrick, E. L. 1999, PASP, 111, 63
Flury, S. R., Jaskot, A. E., Ferguson, H. C., et al. 2022a, ApJS, 260, 1
Flury, S. R., Jaskot, A. E., Ferguson, H. C., et al. 2022b, arXiv e-prints, arXiv:2203.15649
Freudling, W., Romaniello, M., Bramich, D. M., et al. 2013, A&A, 559, A96
Gazagnes, S., Chisholm, J., Schaerer, D., et al. 2018, A&A, 616, A29
Green, G. M., Schlafly, E. F., Finkbeiner, D. et al. 2018, MNRAS, 478, 651
Guseva, N. G., Izotov, Y. I., Fricke, K. J., & Henkel, C. 2019, A&A, 624, A21
Guseva, N. G., Izotov, Y. I., Schaerer, D., et al. 2020, MNRAS, 497, 4293
Izotov, Y. I., Guseva, N. G., Fricke, K. J., & Henkel, C. 2016a, MNRAS, 462, 4427
Izotov, Y. I., Guseva, N. G., Fricke, K. J., et al. 2021a, A&A, 646, A138
Izotov, Y. I., Orlitová, I., Schaerer, D., et al. 2016b, Nature, 529, 178
Izotov, Y. I., Schaerer, D., Thuan, T. X., et al. 2016c, MNRAS, 461, 3683
Izotov, Y. I., Schaerer, D., Worseck, G., et al. 2018a, MNRAS, 474, 4514
Izotov, Y. I., Thuan, T. X., & Lipovetsky, V. A. 1994, ApJ, 435, 647
Izotov, Y. I., Worseck, G., Schaerer, D., et al. 2021b, MNRAS, 503, 1734
Izotov, Y. I., Worseck, G., Schaerer, D., et al. 2018b, MNRAS, 478, 4851
Jaskot, A. E. & Oey, M. S. 2013, ApJ, 766, 911
Kewley, L. J., Nicholls, D. C., & Sutherland, R. S. 2019, Annual Review of Astronomy and Astrophysics, 57, 511
Mainali, R., Kollmeier, J. A., Stark, D. P., et al. 2017, ApJ, 836, L14
Marchi, F., Pentericci, L., Guaita, L., et al. 2018, A&A, 614, A11
Naidu, R. P., Mattei, J., Oesch, P. A., et al. 2021, MNRAS [arXiv:2110.11961]
Olivier, G. M., Berg, A. D., Chisholm, J., et al. 2021, arXiv e-prints, arXiv:2109.06725
Osterbrock, D. E. & Ferland, G. J. 2006, Astrophysics of gaseous nebulae and active galactic nuclei
Pérez-Montero, E., Kehrig, C., Vilchez, J. M., et al. 2020, A&A, 643, A80
Saldana-Lopez, A., Schaerer, D., Chisholm, J., et al. 2022, arXiv e-prints, arXiv:2201.11800
Schaerer, D., Fragos, T., & Izotov, Y. I. 2019, A&A, 622, L10
Schaerer, D., Izotov, Y. I., Worseck, G., et al. 2022, A&A, 658, L11
Shirazi, M. & Brinchmann, J. 2012, MNRAS, 421, 1043
Simmonds, C., Schaerer, D., & Verhamme, A. 2021, A&A, 656, A127
Stark, D. P., Walth, G., Charlot, S., et al. 2015, MNRAS, 454, 1393
Stasinska, G., Izotov, Y., Morisset, C., & Guseva, N. 2015, A&A, 576, A83
Steidel, C. C., Bogosavljević, M., Shapley, A. E., et al. 2018, ApJ, 869, 123
Steidel, C. C., Strom, A. L., Pettini, M., et al. 2016, ApJ, 826, 159
Vanzella, E., Caminha, G. B., Calura, F., et al. 2020, MNRAS, 491, 1093
Vanzella, E., Caminha, G. B., Rosati, P., et al. 2021, A&A, 646, A57
Vanzella, E., Nonino, M., Cupani, G., et al. 2018, MNRAS, 476, L15
Verhamme, A., Orlitová, I., Schaerer, D., et al. 2017, A&A, 597, A13
Wang, B., Heckman, T. M., Leitherer, C., et al. 2019, ApJ, 885, 57

Article number, page 5 of 6
