

LETTER TO THE EDITOR

The ionizing photon production efficiency of compact $z \sim 0.3$ Lyman continuum leakers and comparison with high-redshift galaxies

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ABSTRACT

We have recently discovered five Lyman continuum leaking galaxies at $z \sim 0.3$ that were selected for their compactness, intense star formation, and high $[\text{O III}]\lambda 5007/[\text{O II}]\lambda 3727$ ratio. Here we derive their ionizing photon production efficiency, ξ_{ion} , a fundamental quantity for inferring the number of photons available to reionize the Universe. This is the first time this is done for galaxies with confirmed strong Lyman continuum escape ($f_{\text{esc}} \sim 6\text{--}13\%$). We find an ionizing photon production per unit UV luminosity, ξ_{ion} , that is higher by a factor 2–6 than the canonical value when reported to their observed UV luminosity. After correction for extinction, this value is close to the canonical value. The properties of our five Lyman continuum leakers are found to be very similar to those of the previously reported confirmed $z = 3.218$ leaker *Ion2* and very similar to those of typical star-forming galaxies at $z \gtrsim 6$. Our results suggest that UV bright galaxies at high- z such as Lyman-break galaxies can be Lyman continuum leakers and that their contribution to cosmic reionization may be underestimated.

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

1. Introduction

In the quest for identifying the main sources of cosmic reionization and understanding this early epoch of the Universe, three important factors need to be quantified. First, sources emitting Lyman continuum (LyC) photons into the intergalactic medium (IGM) must be identified and their emission quantified. Second, an average escape fraction of ionizing photons must be estimated or assumed, and third, the total ionizing photon production of galaxies (or other sources) needs to be related to a statistical quantity such as a luminosity function to compute the total amount of ionizing photons emitted and escaping from such a population.

Because the galaxy UV luminosity function at high- z is fairly well determined (e.g., Bouwens et al. 2015, Finkelstein et al. 2015), it is convenient to write the rate of ionizing photons escaping from galaxies as

$$f_{\text{esc}} \times N_{\text{LyC}} = f_{\text{esc}} \xi_{\text{ion}} L_{\nu}, \quad (1)$$

where N_{LyC} is the Lyman continuum photon production rate, f_{esc} the LyC escape fraction, L_{ν} the monochromatic UV luminosity, and therefore $\xi_{\text{ion}} = N_{\text{LyC}}/L_{\nu}$ the ionizing photon production per unit UV luminosity, or in other words, the “efficiency”. Knowing f_{esc} and ξ_{ion} , we can thus compute the total photon rate at which a given galaxy population ionizes the IGM (e.g., Robertson et al. 2013).

The production efficiency ξ_{ion} of a given stellar population is a simple prediction from synthesis models, from which canonical values of $\log(\xi_{\text{ion}}) \approx 25.2\text{--}25.3 \text{ erg}^{-1} \text{ Hz}$ are adopted for high- z studies (e.g., Robertson et al. 2013), corresponding to

constant star-formation and slightly sub-solar metallicity. Higher values may be obtained by stellar population models with young ages, non-constant star formation histories, lower metallicities, or when binary stars are included (see, e.g., Schaerer 2003; Robertson et al. 2013; Wilkins et al. 2016). Observationally, ξ_{ion} has recently been estimated by Bouwens et al. (2015) for a sample of high- z Lyman-break galaxies (LBGs) by combining indirect measurements of $\text{H}\alpha$ from photometry with the observed UV luminosity, and in another study for a lensed $z = 7$ galaxy (Stark et al. 2015), finding values of ξ_{ion} compatible with canonical values or somewhat higher. However, the ionizing photon production of galaxies known to be LyC leakers (i.e., with $f_{\text{esc}} > 0$) has not been measured so far.

Selecting star-forming galaxies for their compactness and high emission line ratio $[\text{O III}]\lambda 5007/[\text{O II}]\lambda 3727 = \text{O}_{32} > 5$ (Izotov et al. 2016a, hereafter I16a) and Izotov et al. (2016b, I16b) have recently found five $z \sim 0.3$ sources out of five showing a clear detection in the LyC with corresponding absolute escape fractions $f_{\text{esc}} \sim 6\text{--}13\%$. This breakthrough in the identification of LyC leakers at low- z now for the first time provides the opportunity of determining their ionizing photon production and other properties and of examining how representative these sources might be for galaxies at high redshift, close to and within the epoch of reionization. In this Letter we report the results from this analysis and comparison.

The ionizing properties of our sources are discussed in Sect. 2. In Sect. 3 we show that the main observed and derived properties of our $z \sim 0.3$ sources are very similar to those of “typical” galaxies at high- z . Our main results are summarized in Sect. 4. We adopt a Λ -cold dark matter cosmological model with

Table 1. Observed and derived UV and ionizing properties of our sample.

ID ^a	z^b	M_{1500}	β_{1500}	A_{UV}^b	f_{esc}^b	ξ_{ion}	ξ_{ion}^0
9	0.3013	-20.3	-1.75	1.44	0.072	25.96	25.39
11	0.3419	-20.7	-1.84	0.91	0.132	25.71	25.35
13	0.3181	-20.0	-1.73	1.09	0.056	25.50	25.07
14	0.2937	-20.3	-1.75	1.06	0.074	25.80	25.38
15	0.3557	-20.4	-2.05	0.64	0.058	25.78	25.53

Notes. Typical uncertainties on the UV slope β_{1500} are ± 0.2 and ± 0.1 (0.15) dex on ξ_{ion} (ξ_{ion}^0). ^(a) The source IDs stand for 9 = J0925+1403, 11 = J1152+3400, 13 = J1333+6246, 14 = J1442-0209, 15 = J1503+3644. ^(b) Values taken from I16a,b.

$H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. Magnitudes are given in the AB system.

2. UV and ionizing properties of $z \sim 0.3$ leakers

We used the GALEX and SDSS photometry as well as emission line measurements of the five Lyman continuum leakers reported in I16a,b to determine their ionizing photon production efficiency and other UV properties. Since the luminosity in the optical hydrogen recombination lines is proportional to the number of LyC photons absorbed in the galaxy, we determined N_{Lyc} for our sources from

$$N_{Lyc}(s^{-1}) = 2.1 \times 10^{12} (1 - f_{esc})^{-1} L(H\beta) \text{ (erg s}^{-1}\text{)}, \quad (2)$$

where $L(H\beta)$ is the (extinction-corrected) $H\beta$ luminosity from I16a,b, and the numerical coefficient is derived from Storey & Hummer (1995) for typical conditions in HII regions. Cast in terms of the absolute UV magnitude, we have $\log(\xi_{ion}) = \log(N_{Lyc}) + 0.4 \times M_{UV} - 20.64$. The absolute UV magnitude M_{1500} , uncorrected for extinction, was determined from the best-fit spectral energy distribution (SED) to the broad-band photometry of our sources using the fitting tool described below. For comparison with high- z galaxy observations (cf. below) we also used the best-fit SED to determine the UV slope β_{1500} ¹. Other data were taken from I16a,b. The most important derived quantities are summarized in Table 1. The main uncertainty on ξ_{ion} comes from the aperture correction for the $H\beta$ luminosity (I16a,b), which we estimate is $<30\text{--}40\%$. We estimate the uncertainty in the extinction correction of the UV flux to be $\sim 30\%$. We therefore adopted a typical error of ± 0.1 (0.15) dex for ξ_{ion} (ξ_{ion}^0).

In Fig. 1 we show the ionizing photon production efficiency (i.e., per UV luminosity) of our Lyman continuum leakers as a function of UV magnitude and compare them with the canonical value $\log(\xi_{ion}) \approx 25.2\text{--}25.3 \text{ erg}^{-1} \text{ Hz}$ (cf. above) and the recent estimate from observations of high-redshift galaxies (Bouwens et al. 2015, hereafter B15). Normalized to the observed UV luminosity, the ionizing photon production efficiency of our sources is found to be $\log(\xi_{ion}) \approx 25.5\text{--}26 \text{ erg}^{-1} \text{ Hz}$, which is higher by a factor 2–6 than the canonical value that is generally applied to translate the observed UV luminosity density into a global ionizing photon production rate (e.g., Robertson et al. 2013). This implies that the contribution of relatively bright galaxies, for instance, at $\sim (0.4 - 1)L_{UV}^*$ for $z \sim 6\text{--}8$ (cf. Bouwens et al. 2015; Finkelstein et al. 2015), to the cosmic ionizing photon production might be larger than commonly thought.

¹ β_{1500} is defined as the slope of the spectrum $F_\lambda \propto \lambda^\beta$ between 1300 and 1800 Å. β_{2000} , measured over 1800–2200 Å, is typically bluer by $\sim 0.2\text{--}0.4$ for our sources.

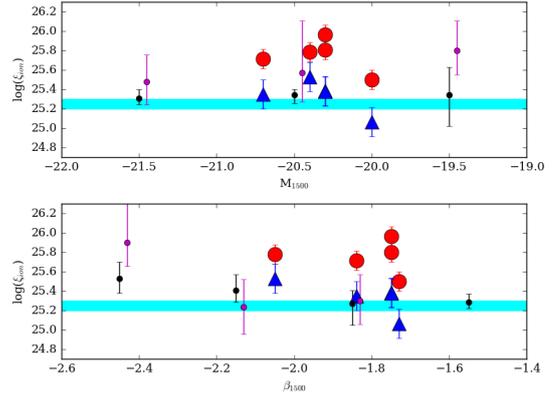


Fig. 1. Ionizing photon production per unit UV luminosity, ξ_{ion} , as a function of the absolute UV magnitude (*top panel*) and the UV slope (*bottom*) of the five Lyman continuum leakers of I16a,b. Large red symbols show ξ_{ion} , large blue symbols ξ_{ion}^0 after correction for UV attenuation (two blue triangles are indistinguishable). The cyan band illustrates canonical values for the intrinsic ξ_{ion}^0 . Recent determinations of ξ_{ion}^0 for LBGs at $z = 3.8\text{--}5$ and $z = 5.1\text{--}5.4$ from Bouwens et al. (2015) are shown by small black and magenta symbols with error bars, respectively.

The UV flux of our leaking galaxies is attenuated by a factor 1.8–3.8 with a median of 2.6 ($A_{UV} \approx 1$; cf. Table 1). After correction for dust attenuation, the resulting intrinsic ionizing photon production efficiency ξ_{ion}^0 , also listed in the table, is $\log(\xi_{ion}^0) \approx 25.1\text{--}25.5 \text{ (erg Hz}^{-1}\text{)}^{-1}$, close to the canonical value.

The behavior of the observed and dust-corrected values of ξ_{ion} and ξ_{ion}^0 , respectively, now as a function of the observed UV slope, is shown in the bottom panel of Fig. 1. Our sources have UV slopes of about $\beta_{1500} \sim -1.7$ to -2 . Broadly speaking, our results are comparable to those derived by B15, who found values of ξ_{ion}^0 compatible with the canonical one for the bulk of their sources, and a possible increase for the bluest sources ($\beta < -2.3$). However, an important point to keep in mind is that the determinations of ξ_{ion}^0 by B15 rely on using the UV slope to estimate the UV attenuation². For example, for sources with $\beta = -2$ and an intrinsic slope $\beta_0 = -2.23$, this implies $A_{UV} = 0.25$ for the SMC law, whereas our sources show a median $A_{UV} \approx 1$ for the same UV slope, a factor ~ 2 higher than the UV attenuation applied by B15. In reality the UV attenuation of the high- z galaxies analyzed by B15 might be underestimated since their true UV slope is expected to be bluer than $\beta_0 = -2.23$, as already stressed by de Barros et al. (2014) and Castellano et al. (2014). If correct, this would imply the same factor 2 downward revision of the value of ξ_{ion}^0 of B15.

Independently of dust corrections, the ionizing emissivity needed to match cosmic reionization is estimated to correspond to $\log(f_{esc}\xi_{ion}) = 24.5$ (24.9) $\text{erg}^{-1} \text{ Hz}$ if the UV luminosity function extends down to $M_{1500} = -13$ (-17) (cf. Robertson et al. 2013; Bouwens et al. 2015). Our sources show $\log(f_{esc}\xi_{ion}) = 24.24\text{--}24.83 \text{ erg}^{-1} \text{ Hz}$ with a median of 24.67, a factor 1.5 higher than the above value $\log(f_{esc}\xi_{ion}) = 24.5 \text{ erg}^{-1} \text{ Hz}$. If the escape fraction of our sources were higher, $f_{esc} = 0.2$ as assumed in these studies, they would emit $\log(f_{esc}\xi_{ion}) = 24.8\text{--}25.7 \text{ erg}^{-1} \text{ Hz}$, with a median of 25.1. We now compare other observed and derived physical properties of our sources to those of high-redshift star-forming galaxies.

² For the Small Magellanic Cloud (SMC) law their relation is $A_{UV} = 1.1(\beta - \beta_0) = 1.1(\beta + 2.23)$, where $\beta_0 = -2.23$ is the intrinsic UV slope corresponding to solar metallicity and constant SFR with age >100 Myr.

3. Comparison with high-redshift galaxies

3.1. Comparison with the $z = 3.218$ LyC leaking galaxy *Ion2*

In many respects, the properties of the compact $z \sim 0.3$ leaking sources are very similar to those of the $z = 3.218$ Lyman continuum leaker *Ion2* found by Vanzella et al. (2015) and de Barros et al. (2016). First *Ion2* is also bright in the UV, $M_{UV} = -21$, which is $\approx M_{UV}^*(z = 3)$. Its low stellar mass, $\lesssim 1.6 \times 10^9 M_{\odot}$, is similar to $M_{\star} = (0.2-4) \times 10^9 M_{\odot}$ (a median of $1 \times 10^9 M_{\odot}$) of our five sources (I16a,b). The metallicity of *Ion2*, determined from rest-frame UV and optical emission lines, is $\sim 1/6$ solar, compared to $\sim (0.1-0.2)$ solar.

The non-detection of [O II] $\lambda 3727$ translates into a 2σ lower limit of a high ratio $O_{32} > 10$ for *Ion2*, even higher than for our objects. Furthermore, *Ion2* is also a compact source with a size $\sim 300 \pm 70$ pc (cf. de Barros et al. 2016). Interestingly, the two latter properties are found a posteriori, since the source was selected from a peculiar color selection. Different selection criteria finding LyC leakers may thus pick up sources with similar properties.

Finally, *Ion2* shows strong rest-frame optical emission lines, for example, $EW(5007) = 1103 \pm 60 \text{ \AA}$ or even larger by a factor $\gtrsim 2$ if corrected for a large escape fraction of ionizing photons, compared to $EW(5007) = 900-1260 \text{ \AA}$ of the $z \sim 0.3$ leakers (I16a,b). Such high equivalent widths seem fairly typical for star-forming galaxies at $z \gtrsim 6$, as we show below (cf. Fig. 3).

3.2. Comparison with typical high- z galaxies

As is clear from Table 1, our five Lyman continuum leakers show, at the same absolute UV magnitude, a UV slope that agrees well with the average slope observed in Lyman-break galaxies at $z \sim 4-7$ (cf., e.g., Dunlop et al. 2012, Bouwens et al. 2014). Our $z \sim 0.3$ sources are also in line with the average relation between stellar mass and UV magnitude derived at high redshifts, which indicates a stellar mass $M_{\star} \sim 10^9 M_{\odot}$ for $M_{1500} \sim -20$ (cf. Duncan et al. 2014; de Barros et al. 2014; Grazian et al. 2015).

Figure 2 shows for illustration the SED fit of the first of our LyC leakers, J0925+1403 from I16a, to the broad-band photometry from the SDSS and the two GALEX bands. The fits are compatible with the more detailed SED fits to the observed COS and SDSS spectra discussed in I16a,b. The fit was obtained with a version of the *Hyperz* code including nebular emission, described in Schaerer & de Barros (2009, 2010), which has been used extensively to fit large samples of high- z LBGs (cf. de Barros et al. 2014). Since the attenuation law and the metallicity are constrained or measured (I16a), we used the SMC law and a metallicity $= 1/5$ solar, the closest value available for the Bruzual & Charlot (2003) models. Clearly, the SDSS photometry is dominated by strong emission lines in bands at $\lambda \gtrsim 5500 \text{ \AA}$, and the SED is well fit with the average emission line ratios taken from Anders & Fritze-v. Alvensleben (2003) (here for $1/5$ solar metallicity) that is adopted in our models. This demonstrates that the SED of extreme, rare objects of the nearby Universe with very strong emission lines can also be well reproduced with typical line ratios of low- z galaxies.

A salient feature of LBGs at high redshift, which has been clearly established during recent years, is the presence of strong optical emission lines, whose signature is detected in broad-band photometry and whose (average) strength increases strongly with redshift (e.g., Shim et al. 2011; Labbé et al. 2013; de Barros et al. 2014). We now compare the line strengths (equivalent widths) of our $z \sim 0.3$ LyC leakers with these

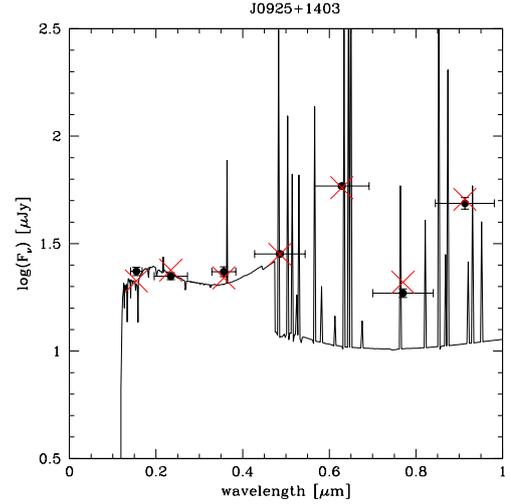


Fig. 2. Observed broad band photometry and best-fit SED (black curve) of the compact Lyman continuum leaker J09 from I16a. Red crosses indicate the synthetic flux in the corresponding filters, showing that most of the optical bands are dominated by nebular emission.

observations, summarized in Fig. 3 for $H\alpha$, [O III] $\lambda 5007$, and [O II] with fits derived by Khostovan et al. (2016) for the range of stellar mass $9.5 < \log(M_{\star}/M_{\odot}) < 10$, where these quantities can be derived over a wide redshift domain. Overplotted is the range of EW s measured in our five $z \sim 0.3$ LyC leakers reported in I16a,b. With rest-frame $EW(H\alpha) \sim 560-1060 \text{ \AA}$ and $EW([O III]\lambda 5007) \sim 900-1260 \text{ \AA}$ our sources are comparable to typical star-forming galaxies at $z \gtrsim 6$ ³. This shows that the nebular properties of extreme and rare objects of the low-redshift Universe, selected by compactness and high O_{32} ratios, appear to be very similar to those of average star-forming galaxies at high- z . By analogy with our leakers, this also suggests that Lyman continuum leaking may be frequent in high-redshift galaxies.

From Fig. 3 we note also that the observed $EW([O II] \lambda 3727) \sim 60-130 \text{ \AA}$ of our sources also agrees well with the behavior of [O II] $\lambda 3727$ extrapolated to high redshift by Khostovan et al. (2016) for the same redshift ($z \sim 6-8$), as indicated by the other emission lines. If true, this would indicate that the average O_{32} ratio continues to increase beyond $z \gtrsim 4$, continuing the trend previously observed from $z \sim 0$ to 3, as has been shown by Khostovan et al. (2016). If the current small samples are representative, high O_{32} ratios (e.g., $O_{32} > 4$) imply a LyC escape fraction $f_{esc} > 5\%$ with a possible trend of f_{esc} increasing with O_{32} (I16b). This would imply that the average star-forming galaxy at $z > 4$ would also be a leaker with $f_{esc} > 5\%$, since the average O_{32} ratio exceeds 4 above this redshift (cf. Khostovan et al. 2016).

3.3. Discussion

All the above mentioned properties show that the five $z \sim 0.3$ galaxies recently identified as Lyman continuum leakers by I16a,b are very similar to both the arguably most reliable high- z leaker, the $z = 3.218$ galaxy found by Vanzella et al. (2015) and de Barros et al. (2016), and to typical star-forming galaxies at $z \gtrsim 6$.

In terms of their very high equivalent widths of [O III] $\lambda 4959$, 5007 and $H\alpha$, our $z \sim 0.3$ sources are very rare for

³ For galaxies with a median mass $\sim 10^9 M_{\odot}$ such as our sources, these EW s may be typical even at somewhat lower redshift, since EW s increase on average with decreasing stellar mass (cf. Khostovan et al. 2016).

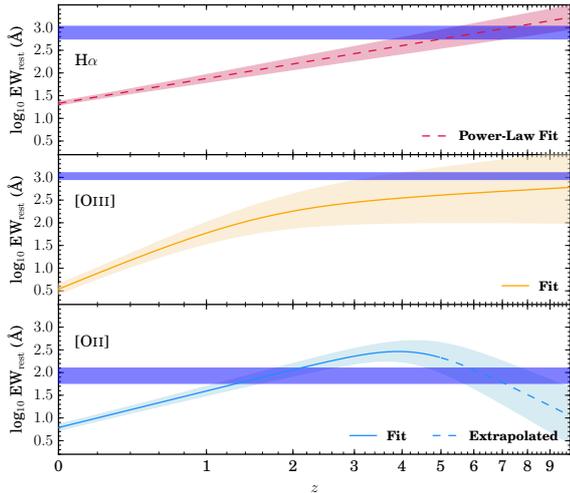


Fig. 3. *Top, middle, and bottom panels* show the redshift evolution of the average (rest-frame) equivalent widths of H α , [O III] λ 5007, and [O II] λ 3727, respectively, for galaxies with stellar masses $9.5 < \log(M_*/M_\odot) < 10$ as fitted by Khostovan et al. (2016), and the range of the EWs observed in our five $z \sim 0.3$ Lyman continuum leakers (blue horizontal bands). The leakers from our study show line equivalent widths typical of star-forming galaxies at $z \gtrsim 6$.

low- z sources. By this measure they correspond to the $<10^{-3}$ tail of the high EW distribution of SDSS DR12 galaxies. On the other hand, these high equivalent widths appear to be common, possibly even typical, for $z > 6$ LBGs, as shown in Fig. 3. This analogy with our LyC leakers suggests that the typical LBG at high redshift may also be leaking Lyman continuum radiation.

The recent work of Sharma et al. (2016) provides indirectly further support for this hypothesis. Based on simple, but plausible assumptions about local LyC escape, these authors predicted the escape fraction for galaxies from simulations, finding an increasing f_{esc} with redshift and significant escape from most high- z galaxies. They traced these trends back to the mean surface density of star formation, which is found to be very high in most of their simulated galaxies at high redshift. Interestingly, all five $z \sim 0.3$ LyC leakers from I16a,b also show a very high surface density of star formation, $\Sigma_{\text{SFR}} \sim 2\text{--}50 M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$, comparable to observations of high- z galaxies and to the predictions of Sharma et al. (2016). The success of the selection method of I16a,b in finding LyC leakers at high O₃₂ ratios may thus be related to compactness, which together with very strong emission lines indicating a high specific SFR implies a high surface density of star formation. Heckman et al. (2001, 2011) and Borthakur et al. (2014) have suggested that strong star formation like this results in strong outflows that clear channels in the ISM, allowing thus the escape of Lyman continuum photons.

4. Conclusion

We have analyzed the properties of five low-redshift Lyman continuum leaking galaxies observed with the COS spectrograph onboard HST that have recently been reported by Izotov et al. (2016a,b). The $z \sim 0.3$ sources were selected for compactness and for showing a high emission line ratio O₃₂, which has previously been suggested as a possible diagnostic for Lyman continuum escape (Jaskot & Oey 2013; Nakajima & Ouchi 2014).

We determined the ionizing photon flux production of these galaxies, which are metal poor ($\sim 1/6$ solar), dominated by young stellar populations (<10 Myr; cf. I16a,b), and are relatively UV bright ($M_{1500} \sim -20$ to -20.8 , cf. Table 1). Finally we compared the observed and derived physical properties of these

rare, extreme objects from the nearby Universe to those of high-redshift galaxies. Our main results can be summarized as follows:

- The ionizing photon production efficiency per observed UV luminosity, ξ_{ion} , of the leakers is $\log(\xi_{\text{ion}}) \approx 25.6\text{--}26 \text{ erg}^{-1} \text{ Hz}$, which is higher by a factor 2–6 than the canonical value (cf. Robertson et al. 2013; Wilkins et al. 2016).
- Although our sources show a low extinction in the optical ($A_V \sim 0.15\text{--}0.4$), their UV attenuation is $A_{\text{UV}} \sim 0.6\text{--}1.4$, which implies that the intrinsic, extinction-corrected ionizing photon flux production efficiency is $\log(\xi_{\text{ion}}^0) \approx 25.0\text{--}25.6 \text{ erg}^{-1} \text{ Hz}$, close to the canonical value.
- The five $z \sim 0.3$ sources of I16a,b share many properties with the best established high- z leaking galaxy *Ion2* (de Barros et al. 2016): absolute UV magnitude, stellar mass, metallicity, line equivalent widths, high O₃₂ ratio, and other parameters are very similar.
- The high rest-frame equivalent widths of H α and [O III] λ 5007 of the $z \sim 0.3$ leakers are very similar to those inferred for typical star-forming galaxies at $z \gtrsim 6$ from broad-band photometry. This shows that the rare, extreme galaxies selected by I16a,b from the Sloan survey might very well be fairly representative of average galaxies in the early Universe.
- Our results also suggest that UV bright galaxies at high- z such as Lyman break galaxies can be Lyman continuum leakers and that their contribution to cosmic reionization, based on canonical assumptions for ξ_{ion} , is probably underestimated.

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