Optical Line Emission from $z \sim 6.8$ Sources with Deep Constraints on Ly$\alpha$ Visibility

M. Castellano$^{1}$, L. Pentericci$^{1}$, A. Fontana$^{1}$, E. Vanzella$^{2}$, E. Merlin$^{1}$, S. De Barros$^{2,3}$, R. Amorin$^{1}$, K. I. Caputi$^{4}$, S. Cristiani$^{5}$, S. L. Finkelstein$^{6}$, E. Giallongo$^{1}$, A. Grazian$^{1}$, A. Koekemoer$^{7}$, R. Maiolino$^{8,9}$, D. Parin$^{1}$, S. Pilo$^{1}$, P. Santini$^{1}$, and H. Yan$^{10}$

$^{1}$INAF—Osservatorio Astronomico di Roma, Via Frascati 33, I-00040 Monte Porzio Catone (RM), Italy; marco.castellano@oa-roma.inaf.it
$^{2}$INAF—Osservatorio Astronomico di Bologna, Via Ranzani 1, I-40127, Bologna, Italy
$^{3}$Observatoire de Genève, Université de Genève, 51 Ch. des Maillettes, 1290, Versoix, Switzerland
$^{4}$Kapteyn Astronomical Institute, University of Groningen, Postbus 800, 9700 AV Groningen, The Netherlands
$^{5}$INAF Osservatorio Astronomico Trieste, via G. B. Tiepolo 11, I-34143, Trieste, Italy
$^{6}$Department of Astronomy, The University of Texas at Austin, Cr400, Austin, TX 78712, USA
$^{7}$Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
$^{8}$Cavendish Laboratory, University of Cambridge, 19 J. J. Thomson Avenue, Cambridge CB3 0HE, UK
$^{9}$Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
$^{10}$Department of Physics and Astronomy, University of Missouri-Columbia, Columbia, MO 65211, USA

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Abstract

We analyze a sample of $z$-dropout galaxies in the CANDELS GOODS South and UDS fields that have been targeted by a dedicated spectroscopic campaign aimed at detecting their Ly$\alpha$ line. Deep IRAC observations at 3.6 and 4.5 $\mu$m are used to determine the strength of optical emission lines affecting these bands at $z \sim 6.5$–6.9 in order to (1) investigate possible physical differences between Ly$\alpha$ emitting and non-emitting sources; (2) constrain the escape fraction of ionizing photons; and (3) provide an estimate of the specific star formation rate at high redshifts. We find evidence of strong [O iii]+H$\beta$ emission in the average (stacked) SEDs of galaxies both with and without Ly$\alpha$ emission. The blue IRAC [3.6]–[4.5] color of the stack with detected Ly$\alpha$ line can be converted into a rest-frame equivalent width $EW([O\text{ III}]+H\beta)=1500-1570$ Å assuming a flat intrinsic stellar continuum. This strong optical line emission enables a first estimate of $f_{\text{esc}} \lesssim 20\%$ on the escape fraction of ionizing photons from Ly$\alpha$ detected objects. The objects with no Ly$\alpha$ line show less extreme $EW([O\text{ III}]+H\beta)=520-170$ Å, suggesting different physical conditions of the H II regions with respect to Ly$\alpha$-emitting ones, or a larger $f_{\text{esc}}$. The latter case is consistent with a combined evolution of $f_{\text{esc}}$ and the neutral hydrogen fraction as an explanation of the lack of bright Ly$\alpha$ emission at $z > 6$. A lower limit on the specific star formation rate, SSFR $> 9.1$ Gyr$^{-1}$ for $M_{\text{star}} = 2 \times 10^{9} M_{\odot}$ galaxies at these redshifts can be derived from the spectroscopically confirmed sample.

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

1. Introduction

The synergy between deep photometric and spectroscopic observations is becoming fundamental to understand the reionization epoch. On the one hand, selection through photometric redshifts or the Lyman-break technique has enabled the determination of the evolution of the UV luminosity density and the identification of faint star-forming galaxies as the most likely reionizers of reionization (e.g., Castellano et al. 2010, 2016; Yan et al. 2011, 2012; Bouwens et al. 2015; Finkelstein et al. 2015; Robertson et al. 2015). On the other hand, the spectroscopic follow-up of such photometrically selected samples has yielded constraints on the timeline of the reionization process (e.g., Fontana et al. 2010; Pentericci et al. 2011; Caruana et al. 2012; Ono et al. 2012; Schenker et al. 2012). Eventually, a thorough understanding of this major transition will require firm constraints of the physical properties of $z > 6$ galaxies that affect both the interpretation of the UV LF (e.g., Khaire et al. 2016; Stanway et al. 2016; Wilkins et al. 2016) and the decrease of bright Ly$\alpha$ emission (e.g., Dijkstra et al. 2014). Looking for line emission signatures in broadband photometry has recently emerged as a valuable tool for investigating the evolution of galaxy properties at high-redshift (Faist et al. 2016; Smit et al. 2016). The spectral energy distribution of objects in the reionization epoch is affected by emission from [O iii]+4959,5007 and H$\beta$ at IR wavelengths, resulting in a bluing of the IRAC 3.6–4.5 $\mu$m color at $z \sim 6.6$–6.9, where the lines affect the 3.6 $\mu$m band, and a reddening at $z > 7$ when they enter the 4.5 $\mu$m one (Wilkins et al. 2013). These signatures yielded evidence of extremely strong line emission in high-$z$ galaxies, and enabled more accurate photometric redshifts and constraints on their specific star formation rate (SSFR; Finkelstein et al. 2013; Smit et al. 2014, 2015; Zitrin et al. 2015; Roberts-Borsani et al. 2016).

In the present work, we exploit deep IRAC observations to constrain the optical line emission properties of a sample of $z$-dropout galaxies from the CANDELS GOODS-South and UDS fields (Pentericci et al. 2011; Koekemoer et al. 2011) observed by deep spectroscopic programs aimed at detecting their Ly$\alpha$ line (Pentericci et al. 2014, and references therein, P14 hereafter, and L. Pentericci et al. 2017, in preparation). In Section 2, we present the sample under consideration and the procedure used to construct average (stacked) images for subsamples with different Ly$\alpha$ emission properties. The analysis of the IRAC colors in terms of optical line contribution to the broadband photometry is given in Section 3. We discuss in Section 4 the resulting constraints on the physical properties of our targets. We present a summary in Section 5.

Throughout the paper, observed and rest-frame magnitudes are in the AB system, and we adopt the $\Lambda$-CDM concordance model ($H_{0}=70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_{m}=0.3$, and $\Omega_{\Lambda}=0.7$).

2. The High-redshift Sample

A comprehensive description of the sample will be presented in a forthcoming paper (L. Pentericci et al. 2017, in preparation).
here we summarize the information that is most relevant for the present analysis. The spectroscopic targets have been selected from the official H-band detected CANDELS catalogs of the GOODS-South (Guo et al. 2013) and UDS (Galametz et al. 2013) fields. Sources have been selected initially through appropriate recastings of the “Lyman-break” technique as described in Grazian et al. (2012). The final color–color selection criteria take into account the different sets of passbands available in the two fields (see Grogin et al. 2011; Koekemoer et al. 2011) resulting in slightly different redshift selection functions (Figure 1 of Grazian et al. 2012). In addition to the Lyman-break-selected candidates, we also inserted in the available FORS2 slits targets that did not pass the above criteria but had a photometric redshift of $z_{\text{phot}} > 6.5$. The photometric redshifts used for selection are the official CANDELS ones built from a set of different photo-z runs through the hierarchical bayesian approach described in Dahlen et al. (2013).

We complemented the large program sample with data obtained by our previous programs (Fontana et al. 2010; Pentericci et al. 2011). All objects have been observed with the FORS2 spectrograph using the 600Z holographic grating (sensitivity in the range of 8000–10.000 Å with a spectral resolution of $R = 1390$) following the observing strategy presented in P14. Finally, we add to our own sample the $z \sim 7$ targets observed by ESO programmes 086.A-0968(A) and 088.A-1013(A) (P.I. Bunker) with the same FORS2 setup. The data have been processed through our own reduction pipeline, which is fine-tuned for the detection of faint emission lines (Vanzella et al. 2011).

The final spectroscopic sample comprises 84 objects including those selected only from photometric redshifts. Only 17 of them show Ly$\alpha$, in some cases quite faint, consistently with the decline of the Ly$\alpha$ emission fraction at high-redshift (L. Pentericci et al. 2017, in preparation). In the present work, we will focus on the sources in the redshift range, where [O III]+H$\beta$ generate a sharp bluing of the 3.6–4.5 μm color. We consider 11 sources with detected Ly$\alpha$, regardless of the relevant EW, at redshift $z = 6.565$–6.836 and 25 sources with no Ly$\alpha$ emission having primary photometric-redshift solution in a slightly larger range ($6.4 < z_{\text{phot}} < 7.0$) to conservatively account for the effect of photo-z uncertainty. The samples include galaxies with H160 spanning the range of $\sim$25.0–28.0.

We analyze the photometric properties of the spectroscopic samples exploiting the available CANDELS mosaics (Koekemoer et al. 2011) in the four HST bands V606, I814, J125, and H160 that are available for both fields and the Spitzer IRAC observations in the 3.6 (CH1 hereafter), 4.5 (CH2), 5.8, and 8.0 μm channels. The IRAC mosaics of the UDS field combine observations from the SWIRE (Lonsdale et al. 2003), spUDS (PI J. Dunlop, Caputi et al. 2011) and SEDS (Ashby et al. 2013) surveys as described in Galametz et al. (2013). For the GOODS-S field, we used 5.8 and 8.0 μm observations from the

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Examples from the GOODS-South (top) and UDS (bottom) fields: 15 × 15 arcsec regions from the original CH1 map (left) compared to the residual image where all the sources surrounding the z-drop target have been subtracted with T-PHOT (right).
Table 1
The Sample

| ID  | CH1  | CH2  |
|-----|------|------|
| GS_13184 | 27.22 ± 0.91 | >27.30 |
| GS_15951 | 26.28 ± 0.32 | >27.35 |
| GS_31891 | 26.62 ± 0.79 | >26.99 |
| GS_34271 | 26.62 ± 0.69 | >27.14 |
| UDS_1920 | 24.29 ± 0.08 | 25.04 ± 0.21 |
| UDS_4812 | 24.55 ± 0.13 | 25.71 ± 0.48 |
| UDS_4872 | 24.17 ± 0.10 | 24.33 ± 0.15 |
| UDS_16291 | >27.14 | 25.65 ± 0.34 |
| UDS_19841 | 26.23 ± 0.50 | >26.86 |
| UDS_23802 | 26.28 ± 0.62 | 25.78 ± 0.48 |

Sources w/o Lyα

| ID  | CH1  | CH2  |
|-----|------|------|
| GS_9771 | 25.69 ± 0.15 | 25.84 ± 0.30 |
| GS_10377 | 24.20 ± 0.06 | 24.60 ± 0.10 |
| GS_13221 | >27.61 | >27.56 |
| GS_14756 | 24.99 ± 0.20 | 26.06 ± 0.49 |
| GS_14776 | 25.12 ± 0.13 | 25.48 ± 0.18 |
| GS_19483 | 25.95 ± 0.26 | 25.91 ± 0.25 |
| GS_20439 | >27.55 | 27.34 ± 0.85 |
| GS_21921 | >27.48 | >27.56 |
| GS_22683 | 24.84 ± 0.17 | 25.10 ± 0.21 |
| GS_23182 | >27.45 | >27.53 |
| GS_24805 | 26.83 ± 1.07 | 25.25 ± 0.32 |
| GS_26624 | 24.34 ± 0.08 | 26.24 ± 0.51 |
| GS_32103 | 26.02 ± 0.39 | 26.23 ± 0.53 |
| GS_32516 | 26.20 ± 0.33 | 26.40 ± 0.38 |
| GS_33588 | >27.50 | >27.58 |
| GS_34523 | 25.58 ± 0.34 | 25.53 ± 0.29 |
| GS_34619 | 25.91 ± 0.42 | >26.73 |
| UDS_4270 | >27.05 | >26.80 |
| UDS_11752 | 24.29 ± 0.09 | 24.61 ± 0.16 |
| UDS_14715 | 24.74 ± 0.12 | 25.09 ± 0.23 |
| UDS_18014 | 24.83 ± 0.13 | 24.77 ± 0.16 |
| UDS_20139 | 24.33 ± 0.08 | 24.03 ± 0.08 |
| UDS_22859 | 26.81 ± 0.97 | 24.73 ± 0.19 |

Note.

a Progressive numbers from Guo et al. (2013) and Galametz et al. (2013) for GOODS-South (GS) and UDS respectively.

The sources under investigation have typical mid-IR flux close to the detection limit of the deep Spitzer observations. The CH1–CH2 color of the objects in our sample is in the best cases determined with an uncertainty of 0.3–0.5 magnitudes, while more than one-third of our sources have S/N < 1 in one (mostly CH2) or both the IRAC bands. For this reason, we will base our investigation on stacked images. We separately analyze objects with detected Lyα lines and of those with no line detection to discern possible correlation between the optical and the Lyα line emission properties. We also consider subsamples of bright and faint sources to assess a possible relation between line emission properties and UV luminosity. We consider as bright objects those with H160 < 26.0 (roughly corresponding to L > L*); 4 (6) sources are brighter than this limit in the Lyα-detected (undetected) samples respectively. We build stacked images in the four IRAC channels and in the V606, I814, J125, and H160 HST bands. In this way, we can study the IRAC CH1–CH2 color as a probe of line emission as well as the overall “average” SED of the samples under consideration. For the IRAC bands, where source confusion and blending is significant, we first perform a T-PHOT second pass run using the option excfile (Merlin et al. 2016) to generate residual images where only the z ~ 7 sources under analysis are left. In this way, all sources are modeled and those close to the z ~ 7 are effectively removed (see, e.g., Figure 1) such that these cleaned images can be used to generate reliable stacked images of the candidates. We then visually inspect all our sources and exclude three objects (one Lyα emitter and two non-emitters) due to the presence of bad residual features close to the targets that can possibly affect the photometry. In Table 1, we list the sources actually used for the present analysis. The stacked images are then generated as weighted averages of the individual thumbnails and are presented in Figure 2. Together with the stacks, we generate average CH1 and CH2 PSFs from the PSFs of the individual sources. The HST stacks are generated as weighted average images of the individual thumbnails after masking all close-by sources according to the relevant SExtractor segmentation map. The HST photometry is obtained with SExtractor by performing detection and estimating total magnitude in the stacked H160 band. Total magnitudes in the other bands are computed on the basis of the relevant isophotal colors with respect to the H160 one. Photometry of stacked IRAC images is estimated with T-PHOT using the source cutout from the stacked H160 band as prior. The resulting spectral energy distributions are shown in Figures 4 and 5 (for “bright” and “faint” subsamples).
3. Evidence of Optical Line Emission

We show in Figure 3 the CH1–CH2 color of Lyα emitting and non-emitting stacks and the colors of all individual sources under consideration. We find $\text{CH1} – \text{CH2} = -1.0 \pm 0.21$ and $\text{CH1} – \text{CH2} = -0.47 \pm 0.11$ for Lyα emitting and non-emitting average sources respectively. Clearly, these colors represent the average properties of the sample.

We find that both samples show an evident relation between the UV luminosity and the CH1–CH2 color. The bright sample’s stacks have a similar CH1–CH2; $-0.25$ for both Lyα emitting and non-emitting sources. The IRAC colors of the faint subsamples are bluer. The stacks of the faint non-emitting subsample has CH1–CH2 $= -0.60 \pm 0.23$, while the stack of faint Lyα-emitting sources is extremely blue (CH1–CH2 $< -1.5$ at $1\sigma$) due to the non-detection in CH2. The difference between IRAC colors of bright and faint Lyα emitting galaxies is significant at the $\sim 2.5\sigma$ level.

As shown in Figure 3, the average negative CH1–CH2 color we find for the two samples can only be explained by the presence of optical line emission affecting the CH1 filter. The most extreme color obtained for purely stellar emission is approximately $-0.35$ (which would also require no dust and extreme galaxy properties, see Section 4), much redder than the stacked color of Lyα emitting galaxies and only marginally compatible with the color from the stacking of non-emitting galaxies, implying that the bulk of objects in the two samples has optical line emission affecting the IRAC bands. In particular, the stacked color of the bright subsamples still suggests the presence of emission lines but is also compatible with purely stellar emission from low metallicity/low extinction galaxies, while line emission is surely present in most of the objects contributing to the faint subsamples. Interestingly, this value is bluer than for the youngest and lowest metallicity templates in our library suggesting that the physical conditions in distant H II regions can be more extreme than what is assumed in our nebular emission model (Schaerer & de Barros 2009).

The evidence of optical emission lines is also shown by an SED-fitting of the stacked multi-band photometry. We fit the eight-band photometry with our $\chi^2$ minimization code (Fontana et al. 2000) fixing the redshift at the average one of the relevant sample. The fit is performed both with stellar-only templates from the library of Bruzual & Charlot (2003; BC03 hereafter) and also including the contribution of line emission as in Schaerer & de Barros (2009) assuming an escape fraction of ionizing photons $f_{\text{esc}} = 0$ (see also Castellano et al. 2014). A comparison of the stellar and stellar+nebular fits shows that the former solution is disfavored in terms of $\chi^2$ (Figure 4). By varying the contribution of nebular emission from $f_{\text{esc}} = 0$ to $f_{\text{esc}} = 1$ at 0.2 steps, we find that $f_{\text{esc}} = 0$ models are always favored. Templates with $f_{\text{esc}} > 0.4$ are excluded at 1$\sigma$ in the case of Lyα-emitting galaxies, while the difference in terms of $\chi^2$ among the various templates is not significant in the case of
Lyα-undetected ones. Considering that photometric-redshift estimates do not rely on nebular templates, the evident nebular feature in the IRAC bands of sources with no Lyα redshift, together with the deep non-detection in the stacked V606 band (>31.4 mag at 1σ), provides further evidence that these objects are robust z-dropout galaxies thus strengthening the case for a declining Lyα fraction at $z > 6$.

### 4. Discussion

We can convert the observed IRAC color into a combined rest-frame EW([O III]+Hβ) by assuming a baseline color for the intrinsic stellar emission, which, in turn, depends on age, $E(B-V)$, and metallicity of the stellar population. Intrinsic colors range from CH1–CH2 $\approx -0.35$ for a dust-free $Z = 0.02 Z_\odot$ template of Age $= 10$ Myr, to CH1–CH2 $\geq 0.2$ (e.g., Age $= 100$ Myr, $E(B-V) = 0.2$, solar metallicity). In particular, age and dust extinction are the factors that mostly affect the continuum shape, with a 0.2 mag color difference between templates at $E(B-V) = 0$ and $E(B-V) = 0.15$ (at fixed age and metallicity) and between templates at Age $= 0$ and Age $= 300$ Myr (at fixed dust extinction and metallicity). A 0.1 mag difference in color is found between $Z = 0.02 Z_\odot$ and solar metallicity templates of similar age and dust extinction. In principle, the difference between the IRAC colors of Lyα-emitting and non-emitting galaxies (~0.5 mag) can be completely explained by a difference in the underlying stellar optical continuum with Lyα-emitting being very young, metal-poor, and dust-free, and objects lacking Lyα emission being >100 Myr old, metal enriched, and mildly extincted. However, the typical UV slopes obtained from the J125-H160 stacked photometry is $\beta \approx -1.9$ for both samples and the distribution of individual UV slope in the two samples is similar (L. Pentericci et al., 2017, in preparation). We can thus exclude a significant presence of dust-free low metallicity galaxies among Lyα-emitting galaxies since such an extreme population would show a bluer slope $\beta \sim -2.7$ (considering also contribution from nebular continuum, see, e.g., Castellano et al. 2014). Therefore, different physical properties can contribute, but not completely explain, the difference between IRAC colors in our samples. For simplicity, we consider a flat CH1–CH2 $= 0.0$ for the no-emission-line case, as expected for a reference 100 Myr old $Z = 0.2 Z_\odot$ galaxy with UV slope $\beta \sim -1.9$ (corresponding to $E(B-V) \sim 0.12$), to convert IRAC colors into equivalent widths of the optical line emission. The measured color term can then be converted into EW([O III]+Hβ) = 1500$^{+400}_{-500}$ Å (Lyα detected sample) and EW([O III]+Hβ) = 520$^{+170}_{-150}$ Å (Lyα undetected sample). These values are consistent within the uncertainty with the line strength predicted by the stellar +nebular SED-fitting on the eight-band stacked photometry, thus providing further evidence that a difference in the stellar SEDs is unlikely to explain the different IRAC colors. The stacking of bright sources yield EW([O III]+Hβ) $\sim 230$–290 Å. The largest equivalent widths are obtained for the faint subsamples with EW([O III]+Hβ) = 720$^{+300}_{-350}$ Å of Lyα-undetected sources and a lower limit of EW([O III]+Hβ) $> 2900$ Å of Lyα emitting ones. In fact, given the similar color of the stacked bright subsamples, the difference between Lyα detected and undetected objects appears to be mostly confined to the subsamples of faint (H160 > 26.0) sources. We summarize in Table 2 measurements for the different

![Figure 3](image-url)
with relevant best-stellar-only and stellar subsamples. Notably, the different IRAC colors of bright and emission from sub-L*_age and UV luminosity. Moreover, such bright optical line emitting ones. A higher escape fraction of ionizing photons can also explain a lower EW of the optical emission lines and play a role in the low Ly*_α visibility. In the next section, we will discuss the relation between physical conditions of the H II regions and EW([O III]+H/3).

An alternative explanation of the difference between the two stacks can be uncertainties affecting the sample of objects with no Ly*_α We can exclude with high confidence any contamination from low-redshift interlopers since no other lines are detected in any of the objects (P14, L. Pentericci et al. 2017, in preparation) and also because of the mag >31.4 non-detection on the stacked V606 band. Moreover, the nebular feature typical of this redshift range is more evident for faint sources where a larger contamination might be expected given the lower reliability of photometric redshifts. However, we cannot exclude the possibility that the Ly*_α-undetected samples in the 6.4 < z_phot < 7.0 range actually contain sources with true redshift > 7.0, which would partially erase the line signature. At z > 7.0 the CH1–CH2 can be as red as ∼0.5–0.8 (e.g., Roberts-Borsani et al. 2016) because of [O III]+H/3 affecting the 4.5 μm passband: this can be the case of some of the sources in our sample with a positive color term (Figure 3). Similarly, H/3 emission can add to the CH2 flux of objects at z ∼ 6.5. In such a case, the EW([O III]+H/3) we measure for Ly*_α-undetected sources should be considered to be a lower limit of the real, typical line strength.

We perform two tests to ascertain possible biases due to the photometric-redshift selection. First of all, we restrict the analysis to a more conservative range 6.6 < z < 6.9 and excluding sources with red IRAC colors (CH1–CH2 > 1); we find an average CH1–CH2 ∼ −0.2 again suggestive of low EW ([O III]+H/3). As a second test, we inspected the photometric-redshift probability distribution functions of our objects to isolate those with highest probability (p > 0.75) of being in the 6.6 < z < 6.9 range. Four out of five objects have IRAC color in the range of approximately −0.26 to −0.39, the remaining one being UDS_22859 with CH1–CH2 ∼ 2. These results suggest no obvious bias due to photometric-redshift selection in the result from the stack of Ly*_α-undetected sources, though a future spectroscopic detection of optical lines themselves with JWST is likely the only way to overcome the effect of photometric-redshift uncertainties in this kind of analysis.

### 4.1. Implications on the Escape Fraction

The escape of ionizing Lyman continuum (LyC) radiation from star-forming regions affects nebular emission and line strength. In particular, a high escape fraction and a high neutral hydrogen fraction in the IGM have similar effects on Ly*_α visibility (Hutter et al. 2014, 2015), while optical emission lines such as O[III] and H/3 are only affected by f_esc. Dijkstra et al. (2014) found that the observed decline of the Ly*_α emission at high-redshift can be explained by a small increase...
of the LyC escape fraction \( \Delta f_{\text{esc}} < 0.1 \) assuming \( f_{\text{esc}} \) is already high (~0.65) at \( z = 6 \), or by a modest increase in both the escape fraction \( \Delta f_{\text{esc}} \simeq 0.1 \) and the neutral IGM fraction \( \Delta n_{\text{HI}} \simeq 0.2 \) from \( z = 6 \) to \( z = 7 \) starting from a \( f_{\text{esc}} = 0.15 \) at \( z = 6 \).

Two mechanisms can be responsible of LyC leakage: the presence of “holes” in standard radiation bounded H II nebulae, and the formation of incomplete Strömgren spheres, or “density bounded” H II regions (Zackrisson et al. 2013, Z13 herafter). Real cases of LyC leakage are most probably due to a combination of the two phenomena. As discussed in depth by Z13, a combined measurement of the UV slope and of EW(\( \text{H} \beta \)), yield to general constraints on the escape fraction of ionizing photons from high-redshift galaxies, albeit mid/far-IR rest-frame information might be needed to disentangle the effects of dust. However, the present evidence of strong line emission affecting the broadband colors of high-redshift galaxies allows us to put first constraints on the LyC leakage since line luminosity is suppressed at increasing \( f_{\text{esc}} \) with no line emitted in the extreme case of \( f_{\text{esc}} = 1 \). We compute the expected IRAC color for different \( f_{\text{esc}} \) values as a function of galaxy age in two different ways: (1) from stellar+nebular templates following Schaerer & de Barros (2009), where hydrogen lines are computed considering case B recombination, and relative line intensities of He and metals as a function of metallicity are taken from Anders & Fritze-v. Alvensleben (2003) and assumed to be independent of \( f_{\text{esc}} \), as expected in ionization bounded nebulae; (2) by modeling a density bounded nebula with CLOUDY (Ferland et al. 1998, 2013) adopting the same assumption as described in Nakajima & Ouchi (2014) and fixing the ionization parameter at \( \log(q/cm s^{-1}) = 7.75 \). Stellar templates from the BC03 library and a constant SFH with a minimum age = 10 Myr are assumed in both cases and considering \( E(B-V) = 0.15 \) (for \( Z = 0.02 Z_{\odot} \)) and \( E(B-V) = 0.10 \) (\( Z = 0.2 Z_{\odot} \)) because this is the lowest value allowed by the observed UV slope at age = 10 Myr, where line EW is the largest for any \( f_{\text{esc}} \).

In Figure 6, we compare the observed stacked colors of our samples with the color predicted for our reference models of radiation bounded (top panel) and ionization bounded (bottom) nebulae. In both cases, we find that the EW([\text{O} III]+\text{H} \beta) of the Ly\( \alpha \)-emitting stack is best reproduced by models with null escape fractions: it is consistent with \( f_{\text{esc}} \) up to 20% but only for
Our sample of spectroscopically confirmed high-redshift sources allows us, for the first time, to constrain the SSFR during the reionization epoch from a homogeneously selected sample of objects with secure redshift. On the one hand, the strength of the optical line emission can be used as a star formation rate indicator.
On the other hand, the continuum emission in the 4.5 μm band corresponds to the optical rest-frame emission and can be used as a proxy of the total stellar mass. As a first estimate, we compute a conservative lower limit on the SSFR, solely based on the stacked IRAC photometry (e.g., Smit et al. 2014). We first build a library of constantly star-forming models from both the BC03 and BPASSV2.0 libraries at different ages that we use as a reference to estimate SFR and stellar mass. We assume a Salpeter IMF and consider models with \(E(B-V)\) from 0 to 1 and metallicity \(Z = 0.02, 0.2, 1.0 Z_\odot\) (for BC03) or \(Z = 0.001, 0.004, 0.02\) (BPASSV2.0). The SFR is obtained from the IRAC color after converting the corresponding EW([O iii]+Hβ) into H\(_\alpha\) luminosity assuming standard line ratios (Anders & Fritze-v. Alvensleben 2003) and a redshift of \(z = 6.7\), which is the average value of the Ly\(_\alpha\)-detected sample. Stellar mass is obtained by computing the relevant conversion with respect to the mid-IR continuum luminosity probed by the CH2 band. Among all considered models, we look for the one yielding the lowest SSFR that we can safely assume to be a conservative lower limit for the typical SSFR at these redshifts. We find minimum values of SSFR = 9.1 Gyr\(^{-1}\) and SSFR = 10.5 Gyr\(^{-1}\) from BC03 and BPASS models, respectively, with a stellar mass of \(\sim 2 \times 10^9 M_\odot\). Our analysis points to a larger SSFR with respect to the previous estimate from Smit et al. (2014) who used emission line signatures in seven LBG candidates at \(z \sim 6-7\) to derive a lower limit of 4 Gyr\(^{-1}\). An increased SSFR in low luminosity galaxies might explain the difference between Smit et al. (2014; focused on \(L > L^*\) sources) and our sample that includes fainter galaxies. In turn, this can be related to the bimodality found in \(z \sim 5-7\) galaxies by Jiang et al. (2016) with “old” (age > 100 Myr) having SSFR \(\sim 3-4\) Gyr\(^{-1}\), and young (age < 30 Myr) having 10 times larger SSFR. The real specific star formation rate can be much higher than this limit. In fact, the nebular-stellar fit of the stacked SED yields an SSFR = \(10^{3.35+3.35}\) Gyr\(^{-1}\) (stellar mass in the range of \(M_{\text{star}} = (0.4-0.6) \times 10^9 M_\odot\) assuming an initial mass function from Salpeter 1955), which is consistently a factor \(\sim 2\) higher than the corresponding SSFR \(\sim 50\) Gyr\(^{-1}\) found by Smit et al. (2014), but similar to the SSFR of low-mass \(z > 3\) galaxies measured by Karman et al. (2017). We note that the SSFR we find for our Ly\(_\alpha\)-emitting \(z \sim 7\) sources is comparable to estimates from other spectroscopically confirmed galaxies at \(z \gtrsim 7\), ranging from \(\sim 10\) to 20 Gyr\(^{-1}\) (Oesch et al. 2015; Song et al. 2016; Stark et al. 2017) to values >100 Gyr\(^{-1}\) (Finkelstein et al. 2013; Huang et al. 2016). High SSFR at these redshift are also favored by the \(z \sim 3-6\) redshift trend presented in de Barros et al. (2014).

5. Summary and Conclusions

We have analyzed the IRAC 3.6–4.5 μm color to gather information on optical line emission of a sample of \(z \sim 7\) galaxies in the CANDELS GOODS and UDS fields that have been targeted by a spectroscopic campaign to detect their Ly\(_\alpha\) line. After dividing the sample into Ly\(_\alpha\)-detected (10 sources) and -undetected (23 sources at \(6.4 < z_{\text{phot}} < 7.0\)) subsamples, we built stacked images in the V606, I814, J125, and H160 HST bands and in the four IRAC channels at 3.6–8.0 μm. We analyzed the SEDs and the colors of the stacked sources finding the following.

1. There is evidence of strong [O III]+H\(_\beta\) emission in the average (stacked) SEDs both of galaxies with detected Ly\(_\alpha\) emission and of those lacking an Ly\(_\alpha\) line. On the basis of the \(\chi^2\), the SED-fitting including nebular contribution is clearly preferred with respect to stellar-only models. The stacked V606 band from objects lacking Ly\(_\alpha\) lines confirms the reliability of these sources as high-redshift candidates through a deep non-detection at \(\text{mag} > 31.4\), corresponding to a V606-H160 \(\sim 5\).

2. The CH1–CH2 color is bluer (\(-1.0 \pm 0.21\)) for the average object with a detected Ly\(_\alpha\) line than for non-emitting sources (\(-0.47 \pm 0.11\)). The IRAC colors can be translated into equivalent width EW([O III]+H\(_\beta\)) = 1500±340 (Ly\(_\alpha\)) emitters and EW ([O III]+H\(_\beta\)) = 520±170 (non-emitters) assuming a flat intrinsic stellar continuum. Optical emission lines appear stronger in the subsamples of faint (26.0 < H160 < 27.5) objects, with the average color of bright (H160 < 26.0) sources compatible with stellar-only emission from low metallicity young galaxies. Bright galaxies with and without confirmed Ly\(_\alpha\) emission show similar CH1–CH2 colors, such that the difference between the two populations effectively lies in the faint subsamples.

3. The different IRAC color between the two populations can be most likely explained by a difference in physical conditions of the H II regions, with Ly\(_\alpha\)-emitting galaxies being younger and/or more metal-poor, thus with harder ionization fields, or by a larger escape fraction in non-emitting sources. A possible dilution of the line signature due to \(z > 7\) galaxies in the photometric-redshift sample cannot be excluded.

4. The strong signature of optical line emission of Ly\(_\alpha\) detected objects yield to \(f_{\text{esc}} \lesssim 20\%\) on the escape fraction of ionizing photons from these objects both in the case of radiation bounded and of density bounded H II regions. A larger \(f_{\text{esc}}\) limit (\(\lesssim 50\%\)) is found when assuming the extreme case of very high density and ionization parameter and the contribution from interacting binaries to the ionizing flux. The optical line emission from Ly\(_\alpha\) undetected sources can be explained by a larger \(f_{\text{esc}}\) from very young and metal-poor galaxies, or with a similar \(f_{\text{esc}} < 20\%–40\%\) for ages up to \(\sim 80–130\) Myr. These results are qualitatively in agreement with the scenario suggested by Dijkstra et al. (2014) of a combined evolution of \(f_{\text{esc}}\) and neutral hydrogen fraction explaining the lack of bright Ly\(_\alpha\) emission at \(z > 6\).

5. By using only the spectroscopically confirmed objects, we derive SSFR = \(10^{3.35+3.35}\) Gyr\(^{-1}\) for \(M_{\text{star}} = 5 \times 10^8 M_\odot\) galaxies at \(z \sim 6.7\) from the stacked SED, and a robust lower limit of SSFR = 9–10 Gyr\(^{-1}\) (depending on the assumed library) under the most conservative assumptions on the conversion factor used to derive SFR and stellar mass using only information from the mid-IR photometry.

Mid-IR spectroscopy with JWST is clearly needed to move beyond constraints from broadband observations. In this respect, it is interesting to note that the strength of the optical line signature found in our sample implies typical [O III] and H\(_\beta\) fluxes of \(\sim 10^{-16}–10^{-17}\) erg s\(^{-1}\) cm\(^{-2}\). Such bright lines can be detected at high S/Ns by NIRspec with few minutes of integration time\(^{13}\) allowing us to fully constrain the dependence of Ly\(_\alpha\) emission on physical properties and to look for unusual

\(^{12}\) We compute the mass normalization of BPASSV2.0 constant SFR templates assuming a 50% mass fraction recycled in the ISM (e.g., Cole et al. 2000; Renzini 2016).

\(^{13}\) \url{https://jwst.etc.stsci.edu/}
line ratios as a signature of large escape fraction from density bounded regions.

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