Investigating the Lyman photon escape in local starburst galaxies with the Cosmic Origins Spectrograph

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ABSTRACT

We present a study of seven star-forming galaxies from the Cosmic Evolution Survey observed with the Cosmic Origins Spectrograph (COS) onboard the Hubble Space Telescope (HST). The galaxies are located at relatively low redshifts, z ∼ 0.3, with morphologies ranging from extended and disturbed to compact and smooth. To complement the HST observations, we also analyse observations taken with the Visible Multi-object Spectrograph (VIMOS) on the Very Large Telescope (VLT). In our galaxy sample, we identify three objects with double peak Lyman-α profiles similar to those seen in Green Pea compact galaxies and measure peak separations of 655, 374, and 275 km s⁻¹. We measure Lyman-α escape fractions with values ranging between 5 per cent and 13 per cent. Given the low flux levels in the individual COS exposures, we apply a weighted stacking approach to obtain a single spectrum. From this COS combined spectrum, we infer upper limits for the absolute and relative Lyman continuum escape fractions of \( f_{\text{abs}}(\text{LyC}) = 0.4^{+0.1+0.1} -0.0^{+0.4} \) per cent and \( f_{\text{res}}(\text{LyC}) = 1.7^{+1.5+1.5} -0.7^{+0.2} \) per cent, respectively. Finally, we find that most of these galaxies have moderate ultraviolet and optical star formation rates (SFRs) (SFRs ≤ 10 M⊙ yr⁻¹).

Key words: galaxies: ISM – galaxies: star formation – dark ages, reionization, first star.

1 INTRODUCTION

Star formation is the fundamental process transforming baryonic matter in the Universe, converting the hydrogen reservoir into heavy elements. Consequently, star formation is one of the main drivers of galaxy formation and evolution. Tracing accurately star formation is therefore of critical importance for understanding the fundamental processes operating in galaxies across cosmic time (Kennicutt & Evans 2012; Madau & Dickinson 2014).

The global stellar spectral energy distribution (SED) of star-forming galaxies is dominated by radiation of massive stars with masses of tens of solar masses (M⊙). Such stars emit the bulk of their energy in the ultraviolet (UV). Typical star-forming galaxies emit approximately 75 percent of their stellar radiation in the Balmer continuum between 912 and 3646 Å, with an additional ~25 per cent contributed by the Lyman continuum (Leitherer et al. 2002). The intrinsic stellar energy output longward of the Balmer break is typically negligible. Notably, the wavelength ranges below and above Lyman-α (Ly α) at 1216 Å make roughly equal contributions to the Balmer continuum: the energy radiated accounts for about 40 per cent of the bolometric luminosity of the full stellar SED. Characterizing the behaviour of the UV wavelength region below Ly α, above and below the Lyman break is therefore essential for understanding the recent star formation in galaxies.

Available spectroscopic data for the wavelength range below 1216 Å in the observed frame are scarce. Among the previous space missions exploring this wavelength domain, only the Hubble Ultraviolet Telescope (HUT; Davidsen et al. 1992; Kruk et al. 1999) and the Far Ultraviolet Spectroscopic Explorer (FUSE; Moos et al. 2000) had the sensitivity necessary for significant extragalactic studies. More recently, the Hubble Space Telescope (HST) Cosmic
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Origins Spectrograph (COS; Osterman et al. 2011; Green et al. 2012) has been added to the list of instruments with spectroscopic capabilities down to and below 912 Å. COS has become the instrument of choice for investigating the properties of star-forming galaxies in the local universe below the Lyman limit in particular.

Understanding the transformation of the Universe from neutral and opaque during the Dark Ages to transparent after the reionization has been an increasingly important topic in observational cosmology. There is still great uncertainty on the population of objects that reionized the Universe. Candidates range from primordial black holes and mini quasars (Madau et al. 2004) to active galactic nuclei (AGNs; Haiman & Loeb 1998; Madau & Haardt 2015), and star-forming galaxies (Robertson et al. 2010). Although AGNs have been observationally confirmed to exist at the beginning of the epoch of reionization (Venesnam et al. 2007), their population numbers may be insufficient to contribute significantly to the cosmic reionization. Star-forming galaxies are more commonly accepted as strong contributors of the ionizing background at high redshift (z > 6, Robertson et al. 2010); however, the sources identified so far are insufficient to complete the ionization of the Universe by z ~ 6 (Cowie, Barger & Trouille 2009; Iwata et al. 2009; Robertson et al. 2013). At high-z, the observed UV luminosity function appears to be steep, therefore faint, low-mass star-forming galaxies could in principle be responsible for most of the ionizing radiation (Ouchi et al. 2009; Yajima, Choi & Nagamine 2011; Bouwens et al. 2015).

The presence of ionizing stars in star-forming galaxies has been inferred at z ≤ 7 using a variety of proxies such as dust emission, stellar absorption lines, nebular emission lines, and blue galaxy colours (Barger et al. 2012; Bouwens et al. 2012; Stark et al. 2013; Finkelstein 2016). With these confirmed sources of ionizing photons at relatively high-z, measurements of the Lyman continuum escape fraction, fesc(LyC), are critical for identifying the conditions and environments that benefit their escape onto the intergalactic medium (IGM). Extensive observational studies covering a broad range of redshifts have been done to detect escaping Lyman continuum photons from star-forming galaxies (Bergvall et al. 2013). It has been proposed that for galaxies to completely reionize the intergalactic HI, their Lyman continuum escape fractions need to be of the order of 10–20 per cent (Robertson et al. 2013).

Efforts to observe escaping Lyman continuum radiation at relatively high redshifts (z > 1) are challenging not only because of possible contamination from low-redshift interlopers (Vanzella et al. 2010; Mostardi et al. 2015), but also because at redshifts z >~ 3 these star-forming galaxies are significantly affected by attenuation by the Ly α forest along the line of sight (Inoue et al. 2014). In spite of these complications, detections of escaping Lyman continuum radiation have been suggested in ~10 per cent of surveyed galaxies (Siana et al. 2015).

Attempts to measure the fesc(LyC) of local galaxies were made using HUT and FUSE. Various upper limits were established (Leitherer et al. 1995; Heckman et al. 2001; Grimes et al. 2009), and only a small number of weak detections of fesc(LyC) were found (Leitherer et al. 2011, 2013). In recent years, COS has kept pushing the limits of this field by providing direct detections of fesc(LyC) in starburst galaxies at low redshifts with values as high as 43 per cent (Borthakur et al. 2014; Leitherer et al. 2016; Izotov et al. 2016a,b; Leitherer et al. 2016; Shapley et al. 2016; Izotov et al. 2018). For this reason, several studies have proposed to use Ly α profiles as tools for identifying Lyman continuum leakers (Verhamme et al. 2015, 2017; Dijkstra, Gronke & Venkatesan 2016).

In this work, we take advantage of the far-UV capabilities of COS and analyse spectra of low redshift galaxies, that we observed in Cycle 21. Our main goals are: (i) probing the star formation properties of normal galaxies at wavelengths where the stellar populations emit the majority of their energy; (ii) measuring or providing upper limits to the escape fractions of Lyman continuum and Ly α photons; and (iii) comparing several panchromatic star formation tracers. This paper is structured as follows. In Sections 2 and 3, we present our target selection and HST observations/analysis, respectively. We discuss the spectral morphology of our objects in Section 4. In Sections 5 and 6, we describe the Ly α profiles and star formation properties, correspondingly. The Lyman continuum discussion is included in Section 7. Finally, in Section 8, we present our conclusions.

2 TARGET SELECTION

We exploit the data from HST program 13313 (PI: Boquien) observing eight star-forming galaxies with COS onboard HST. The program observed galaxies at redshifts around z ~ 0.3 given the multiple advantages of this redshift, i.e. the Lyman break is redshifted into the COS far-ultraviolet (FUV) sensitive range, and spiral galaxies at these distances have angular sizes comparable to the COS primary science aperture (PSA).

The primary selection criteria in Program 13313 were: (i) The galaxies have a redshift z ~ 0.25 to ensure that the UV domain is observed down to the Lyman break. (ii) The galaxies do not have any detected AGN activity to prevent any contamination which could affect the SED. (iii) The galaxies have a size small enough so that the bulk of the FUV emission is enclosed in the COS aperture. (iv) The galaxies are brighter than 22.5 AB magnitudes in the FUV within the COS aperture to ensure high enough signal-to-noise ratios (S/N) in a reasonable exposure time. The galaxy sample was selected from the Cosmic Evolution Survey (COSMOS; Scoville et al. 2007) with its rich body of ancillary spectroscopic and photometric data including Herschel fluxes from 70 to 500 μm. After selecting all galaxies fulfilling the aforementioned criteria, the team constituted a sample of eight galaxies spanning FUV attenuation values of 0.8 ≤ AFUV ≤ 2.5.

In Table 1, we present some information for these galaxies: target identification numbers (IDs) as listed in the Mikulski Archive for Space Telescopes (MAST), coordinates, Galaxy Evolution Explorer (GALEX; Martin et al. 2005) FUV flux, Galactic foreground extinction, redshift and distance (D). The GALEX FUV flux were obtained by extracting the GALEX FUV magnitudes from the public COSMOS catalogue, and converting these to fluxes. The Galactic foreground extinction is adopted from the NASA Extragalactic Database (NED) which is based on the Schlafly & Finkbeiner (2011) recalibration of the extinction maps by Schlegel, Finkbeiner & Davis (1998). Ad-
ditionally, the coordinates listed in Table 1 are based on the COSMOS HST ACS I band survey (Sanders et al. 2007). The luminosity distance values, \( D \), are obtained with the cosmological calculator (NED; Wright 2006) using the parameters from Planck Collaboration XIII (2016): \( H_0 = 67.8 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \) and \( \Omega_m = 0.308 \) for a flat universe where \( \Omega_{\text{vac}} = 1 - \Omega_m \). At a redshift of \( 0.25 \leq z \leq 0.32 \), the star-forming regions of these galaxies are enclosed by the 2.5° COS aperture while the instrument provides a coverage down below the rest-frame Lyman break at such redshifts.

The selected galaxies were observed with COS onboard HST (Green et al. 2012) between March and May of 2014. After the guide stars were acquired, the targets were observed in blind pointing mode. The different panels present 15′×15′ Advanced Camera for Surveys (ACS) Mosaics as seen in the I-band (F814W) along with red circles showing the COS spectroscopic 2.5° aperture. The panels show the diverse morphologies of the sample galaxies ranging from extended and disturbed, i.e. 1727315, 1535411, and 1084255, to moderately star-forming objects, with specific star formation rates (sSFRs) ranging between \( \log (\text{sSFR}) = -9.6 \, \text{yr}^{-1} \) and \( \log (\text{sSFR}) = -8.4 \, \text{yr}^{-1} \), making these galaxies hitherto unexplored yet difficult to observe.

In Fig. 1, we show the selected galaxies as observed in COSMOS. The different panels present 15′×15′ Advanced Camera for Surveys (ACS) Mosaics as seen in the I-band (F814W) along with red circles showing the COS spectroscopic 2.5° aperture. The panels show the diverse morphologies of the sample galaxies ranging from extended and disturbed, i.e. 1727315, 1535411, and 1084255, to compact and smooth, i.e. 1365128, 1508056, and 781126.

### 3 HST/COS OBSERVATIONS AND DATA REDUCTION

The selected galaxies were observed with COS onboard HST (Green et al. 2012) between March and May of 2014. After the guide stars were acquired, the targets were observed in blind pointing mode. No target acquisitions were requested for the observations as the standard HST pointing accuracy (∼0.3′) was deemed sufficient for the program. We discuss flux losses due to pointing offsets in Appendix A. For each orbit, a short exposure was taken in ACUM mode using the MIRORA (imaging mode) element. The science observations were taken in TIME-TAG mode using the low-resolution G140L grating (\( R \sim 2000 \)) configured to observe at central wavelength 1105 Å. Since the COS G140L/1105 setting shifts the zero-order image to detector Segment B, only Segment A is available for this configuration. G140L/1105 provides data with a wavelength coverage between 1105 and 2250 Å (observed frame).

Originally, the FUV channel was designed to operate optimally between wavelengths 1130 < \( \lambda \) < 1850 Å. At wavelengths \( \lambda < 1130 \) Å, the sensitivity declines by a factor of 100×, but is still comparable to that of FUSE (McCandliss et al. 2010). To reduce the well-known fixed pattern noise, we used all four focal plane positions (FP-POS). In Table 2, we provide information on the individual exposures including data set names, start times, total duration, and S/N. The S/N values per resolution element are low as the original HST program relies on binned spectra.

Before proceeding with the calibration and analysis, we inspect the short-exposure images taken before the science observations and confirm that the galaxies are indeed on the detector. We present a brief discussion of these images in AppendixA. We retrieve the individual data sets from MAST and calibrate the exposures using a modified version of the official **CALCOS** pipeline introduced in Leitherer et al. (2016). The standard **CALCOS** v3.2.1 software (Fox et al. 2015) performs a 1D spectral background subtraction, first computing the number of counts in pre-defined regions external to the science extraction box, scaling these counts by the ratio of pixel heights of the science/background regions, and finally subtracting these scaled counts from the science spectrum at each wavelength. The actual background at the target location might differ from that found in the pre-defined background regions, a behaviour that might cause **CALCOS** v3.2.1 to over- or undersubtract the background contribution from the final calibrated product.

As mentioned earlier, for wavelengths \(< 1130 \) Å the sensitivity declines by a factor of 100×, therefore for observations taken in the background-limited regime an optimal detector background subtraction is critical. In order to perform a more accurate and tailored background correction in Leitherer et al. (2016), we present a modified version of an older **CALCOS** version (v2.21) where we introduce a 2D background correction applicable to data obtained prior to 2015 February. For the analysis of these eight galaxies, we further modify **CALCOS** v2.21 to improve the handling of negative values obtained after the 2D-superdark subtraction. More details on the exact changes made to **CALCOS** v2.21d are described in AppendixB. In addition to the optimized background correction, we also perform a dedicated analysis of the COS pulse–height amplitude (PHA)\(^1\) similar to that described in Leitherer et al. (2016). The modifications to the PHA filtering do not introduce additional noise. And finally, to further increase the S/N, we decrease the size of the spectral extraction box from the standard 57-pixel size to a 20-pixel size as suggested by the COS Team.\(^2\)

The calibrated x1d files are taken and further analysed using the IDL software developed by the COS Guaranteed Time Observer

\(^1\)The PHA characterizes the total charge in the electron cloud incident triggered by an incoming photon. A PHA value basically defines the size of the electron shower/cloud.

\(^2\)http://www.stsci.edu/hst/cos/documents/newsletters/cos_stis_newsletters/full_stories/2015_03/bkg_limited_targets

### Table 1. Program galaxies.

| Target | RA (J2000) (h m s) | Dec (J2000) (° ′ ″) | GALEX FUV Flux \( (10^{-16} \, \text{erg} \, \text{s}^{-1} \, \text{cm}^{-2} \, \text{Å}^{-1}) \) | \( E(B - V)_{\text{MW}} \) (mag) | \( z^a \) | \( D^b \) (Mpc) |
|--------|------------------|-------------------|-----------------------------|------------------|------|--------|
| 1084255 | 09 58 15.487 | +02 11 35.50 | 2.87 | 0.017 | 0.265 | 1388 |
| 1535411 | 09 58 44.093 | +02 28 43.97 | 2.10 | 0.016 | 0.320 | 1724 |
| 1511408 | 09 59 03.605 | +02 33 19 | 1.02 | 0.017 | 0.261 | 1364 |
| 1508056 | 09 59 08.734 | +02 29 56 | 2.74 | 0.017 | 0.260 | 1358 |
| 1727315 | 09 59 21.341 | +02 40 30.29 | 1.28 | 0.015 | 0.265 | 1388 |
| 1235867 | 10 00 22.166 | +02 41 26 | 3.02 | 0.016 | 0.267 | 1400 |
| 781126 | 10 00 35.726 | +02 13 43 | 1.53 | 0.018 | 0.269 | 1412 |
| 1365128 | 10 02 55.675 | +02 30 25.34 | 3.02 | 0.016 | 0.267 | 1400 |

Notes: \(^a\)Redshifts are extracted from the public COSMOS catalog.
\(^b\)Luminosity distance.
Figure 1. $15'' \times 15''$ HST/ACS Mosaic $I$-band (F814W) from COSMOS for each of the galaxies studied in this work. The red circle shows the COS 2.5'' aperture. Some uncertainty is expected in the final pointing, of the order of $\sim 0.3''$ RMS, as the objects were observed using the blind pointing mode. Each stamp has north up, and east to the left as shown in the first panel.

Table 2. Observation log.

| Target  | Data set       | Start Time (UT) | Total Duration (s) | S/N (resel$^{-1}$) |
|---------|----------------|-----------------|--------------------|--------------------|
| 1084255 | LC8802020      | 2014-03-31 10:57:34 | 4889.600          | 0.3                |
|         | LC8802040      | 2014-03-31 12:29:54 |                    |                    |
| 1535411 | LC8807020      | 2014-05-21 08:57:37 | 4889.760          | 0.4                |
|         | LC8807040      | 2014-05-21 10:29:27 |                    |                    |
| 1511408 | LC8806020      | 2014-05-29 00:08:50 | 4889.696          | 1.0                |
|         | LC8806040      | 2014-05-29 01:41:31 |                    |                    |
| 1508056 | LC8805020      | 2014-05-10 06:52:26 | 4889.760          | 0.7                |
|         | LC8805040      | 2014-05-10 08:24:39 |                    |                    |
| 1727315 | LC8808020      | 2014-03-24 14:49:53 | 4889.664          | 1.4                |
|         | LC8808040      | 2014-03-24 16:21:27 |                    |                    |
| 1235867 | LC8803020      | 2014-04-15 09:26:06 | 4889.632          | 0.8                |
|         | LC8803040      | 2014-04-15 10:58:17 |                    |                    |
| 781126  | LC8801020      | 2014-03-31 07:46:29 | 4889.600          | 1.8                |
|         | LC8801040      | 2014-03-31 09:18:50 |                    |                    |
| 1365128 | LC8804020      | 2014-04-16 02:57:59 | 4889.664          | 0.9                |
|         | LC8804040      | 2014-04-16 04:30:06 |                    |                    |

Notes. $^a$1 resel = 6 pixels  
$^b$S/N at $\lambda_{obs} = 1250$ Å  
$^*$This target is classified as a QSO in SDSS and therefore excluded from the analysis.

Team (Danforth et al. 2010). This software weight combines the different FP-POS exposures by interpolating on to a common wavelength vector accounting for the non-Poissonian noise as described by Keeney et al. (2012). We opt for a standard weighting scheme where the weights are defined as $w = 1/\sigma^2$, and $\sigma_i$ are the individual errors as extracted from the calibrated x1d files. We bin the data by a COS resolution element (1 resel = 6 pixels) which corresponds to the nominal point-spread function.

4 SPECTRAL MORPHOLOGY

Before addressing the star formation properties of the individual galaxies, we correct the spectra for Galactic foreground reddening using the $E(B-V)_{MW}$ values shown in Table 1 along with the reddening law of Mathis (1990). We also transform the wavelength array from the observed to the rest frame using the redshift values in Table 1. After some inspection, we notice that the Ly $\alpha$ line in 1727315 is remarkably wider than the rest of the lines (see Fig. 2). This same target is classified as a quasi-stellar object (QSO) in the Sloan Digital Sky Survey (SDSS) and thus excluded from the rest of our analysis.

In Fig. 3, we show the galaxy spectra for each of the targets studied in detail here. We indicate the wavelengths of common spectral lines found in star-forming galaxies. The line identifications at the top of the figures refer to emission from geocoronal lines, whereas the bottom labels mark the absorption/emission from lines...
The Lyα line marks the location of the Lyα line.

Intrinsic to the galaxies, the strongest emission observed in all of the targets come from geocoronal Lyα λobs = 1216 and O I λobs = 1302.

We point out that not all the intrinsic lines marked in Fig. 3 are detected in every galaxy. The majority of the lines we detect are of interstellar origin, i.e. C III λ977, O I λ988, and N II λ1083. With both winds and ISM as expected mechanisms (Leitherer et al. 2011), we observe CuII λ1175 most prominently in 781126. Additionally, we see Lyα λ1216 emission in four out of our seven targets. We discuss in more detail the morphology of Lyα in the following section.

5 LYα EMISSION

The Lyα profiles for 1084255, 1365128, and 1508056 show double peak features resembling those observed in several Green Pea (GP) compact galaxies (Jaskot & Oey 2013; Henry et al. 2015; Izotov et al. 2016b, 2018). Verhamme et al. (2015) proposed that Lyα profiles with a double-peak morphology may indicate Lyman continuum leakage if the peak separation was ≤ 300 km s\(^{-1}\). We measure peak separation values of 655, 374, and 275 km s\(^{-1}\) for 1084255, 1365128, and 1508056, respectively. According to Verhamme et al. (2015), 1084255 and 1365128 would be more unlikely to leak Lyman continuum photons given their high peak separation values.

We point out that given that Lyα can be asymmetrically emitted and easily scattered, the Lyα radiation encompassed by the 2.5° COS aperture might not necessarily capture the Lyα emission fully. We estimate the Lyα escape fraction, \(f_{\text{esc}}(\text{Lyα})\), by comparing the extinction-corrected Lyα/Hα flux ratios shown in Table 4, and the intrinsic case B value of 8.7 corresponding to gas temperature of \(T_e = 10,000 \text{ K}\) and an electron density of \(n_e = 350 \text{ cm}^{-3}\) (see Henry et al. 2015, for a detailed discussion on adopting the 8.7 factor). The Hα equivalent widths (EWs) and flux values are extracted from the VIMOS observations described in Section 6.2. We measured the Hα fluxes by fitting a Gaussian profile to the individual lines. On the other hand, given the complexity of the Lyα profiles we measure the EWs and fluxes using a simple flux over continuum integration code written in PYTHON by Peña-Guerrero & Leitherer (2013). The continuum is estimated through a linear fit between wavelengths 1045–1550 Å. The best fit is visually inspected to confirm the continuum placement is reasonable. The Lyα fluxes have been corrected for underlying stellar absorption using the model predictions by Peña-Guerrero & Leitherer (2013). We apply the recommended underlying correction for constant SFR over ~20 Myr of the order of 7 Å. We find \(f_{\text{esc}}(\text{Lyα})\) in the range ~5–13 per cent.

Several studies have shown that GP galaxies display strong Lyα emission (Jaskot & Oey 2014; Henry et al. 2015; Verhamme et al. 2017). Yang et al. (2017) studied the Lyα profiles in a statistical sample of 43 GP galaxies and found that 2/3 of these galaxies are strong Lyα emitters. They also found a clear correlation between their Lyα EWs and the estimated \(f_{\text{esc}}(\text{Lyα})\). Similar results have also been observed by Verhamme et al. (2017). In Fig. 4, we show in blue circles the \(f_{\text{esc}}(\text{Lyα})\) as a function of EW(Lyα) as observed by Yang et al. (2017). In this same figure, we include our targets and their \(f_{\text{esc}}(\text{Lyα})\) and EW(Lyα) measurements as red stars, Lyman continuum emitters (LCEs) by Izotov et al. (2016b) as black squares, and Lyman Alpha Reference Survey galaxies (LARS, Hayes et al. 2013) by Hayes et al. (2014) as yellow circles. In general, we see that our galaxies follow the same \(f_{\text{esc}}(\text{Lyα})\)-EW(Lyα) trend as that observed by Yang et al. (2017) for GP galaxies, as well as that observed in LARS objects. We also find that 3/4 galaxies with Lyα emission in our sample have EW(Lyα) > 20 Å; as pointed out by Yang et al. (2017) in a high-z narrow-band study these objects would be classified as Lyα emitters.

To put our star-forming galaxies in context, we also compare our \(f_{\text{esc}}(\text{Lyα})\) measurements to the dependence of \(f_{\text{esc}}(\text{Lyα})\) on the EW(Hα) observed in GPs (Yang et al. 2017), LARS (Hayes et al. 2014), and LCEs (Izotov et al. 2016b). Hayes et al. (2014) report global measurements of \(f_{\text{esc}}(\text{Lyα})\) derived from Lyα and Hα imaging of normal low redshift star-forming galaxies observed as part of LARS. From Fig. 5, we see that our Lyα escape fractions show a distribution similar to that of the comparison sample. Our inferred Lyα escape fractions resemble the values measured in LARS galaxies, in contrast to those seen in Izotov et al. (2016b) with \(f_{\text{esc}}(\text{Lyα})\) values among the highest observed in GP galaxies. It is important to mention that the objects studied by Izotov et al. (2016b) were also found to be LCEs. These five LCEs from Izotov et al. (2016b) clearly fall in the upper right quadrant of Fig. 5 hinting at a general trend where LCEs have strong Lyα emission, and a very different distribution of EW(Hα) compared to LARS galaxies, GPs, and those in our sample.

6 STAR FORMATION PROPERTIES

As part of our analysis, we estimate SFRs using different methods exploring several wavelength ranges from the UV to the IR. In this section, we briefly describe and present our inferred SFR values.

6.1 UV range

We quantify the content of massive stars by comparing the UV spectra to synthetic models (Leitherer et al. 2013). As part of the analysis, we apply this same technique and use a Starburst99 model

![Graph showing Lyα emission lines present in the galaxy sample. The observed spectra have been redshift and foreground corrected. The vertical dashed line marks the location of the Lyα line.](https://academic.oup.com/mnras/article-abstract/478/1/1292/4987230)
Figure 3. Comparison of the observed spectra (black) with synthetic spectra of the best-fitting model (red). Left-hand panel: Data binned by a COS resolution element. Right-hand panel: For the benefit of visualization, we smooth the observations using a boxcar size of 10 pixels. The observed spectra have been corrected for redshift, foreground and intrinsic reddening. The different SFRs are listed in Table 3. At the top and the bottom of the panels, we identify the geocoronal ($\oplus$) and intrinsic spectral lines, respectively.

(Leitherer et al. 1999; Vázquez & Leitherer 2005; Leitherer & Chen 2009; Leitherer et al. 2014). The model parameters are: continuous star formation, age of 20 Myr, Kroupa initial mass function (IMF; Kroupa 2008) with a mass range of 0.1–100$M_\odot$, solar metallicity ($Z = 0.014$), spherically extended, blanketed, non-local thermodynamic equilibrium atmospheres, nebular continuum, and stellar evolution models with rotation (Ekström et al. 2012; Georgy et al. 2013). We opt for a solar metallicity for our star-forming galaxies given their luminosities and following the mass-metallicity relation of Tremonti et al. (2004).

Once the foreground reddening and redshift corrections are applied, we then compare the observed UV spectrum to that of the model to study the intrinsic dust attenuation. For this step, we focus on the spectral region covering wavelengths between 1000 and 1400 Å. The wavelength windows affected by geocoronal emission are masked out. We infer the intrinsic reddening, $E(B - V)_{\text{UV}}$, by fitting the COS observations ($f_{\text{obs}}$) with the unattenuated model ($f_{\text{S99}}$ - after scaling the luminosity) reddened by the Calzetti et al. (2000) attenuation law, $k(\lambda)$, using the following relationship:

$$f_{\text{S99red}}(\lambda) = f_{\text{S99}}(\lambda)10^{-0.4k(\lambda)E(B-V)_{\text{UV}}}.$$  \hspace{1 cm} (1)

The best-fitting $E(B - V)_{\text{UV}}$ is determined by iteratively searching for the values that minimize the $\chi^2$:

$$\chi^2 = \sum \frac{(f_{\text{obs}} - f_{\text{S99red}})^2}{\sigma^2_{\text{err}}}.$$  \hspace{1 cm} (2)

As the Calzetti law does not extend to wavelengths bluer than 1200 Å, we complement the attenuation law with that of Leitherer et al. (2002) generated from a sample of star-forming galaxies studied with HUT. The Leitherer et al. relation allows for a smooth transition of the Calzetti law to shorter wavelengths, and their results were later verified by the far-UV attenuation curves derived by Reddy et al. (2016) and Buat et al. (2002). This addition to the attenuation law facilitates studies near the Lyman break. We use the PYTHON package scipy.optimize to infer the $E(B - V)_{\text{UV}}$ values shown in Table 3. The errors in column 2 are calculated by taking the square root of the covariance matrix of the parameter estimates.
point out that the SFR$_{\text{UV}}$ values derived here are dependent on the centrering of the object and vignetting of the PSA caused by extended targets. Given that the COS observations relied on the HST pointing accuracy ($\sim0.3''$), a small offset in the pointing could lead to variations in the flux. The COS Team, however, states that the flux calibration for extended targets is reasonably accurate for COS FUV observations.\footnote{http://www.stsci.edu/hst/cos/documents/newsletters/cos_stis_newsletters/full_stories/2015_03/available_unsupported_modes} Given that the dominant source of measurement uncertainty in the SFR$_{\text{UV}}$ is the reddening correction, $E(B-V)_\text{UV}$, we estimate the errors in the inferred SFR$_{\text{UV}}$ values by taking the upper/lower errors in the $E(B-V)_\text{UV}$ and re-calculating the SFR$_{\text{UV}}$. Additionally, in Fig. 3 we show the galaxy spectra corrected for redshift, foreground, and intrinsic attenuation, along with the best model spectra with the parameters presented in Table 3. The strong emissions observed in Fig. 3 are geocoronal lines (Ly $\alpha$, Ni, and O$\lambda$).

### 6.2 Optical range

The zCOSMOS survey (Lilly et al. 2009) observed targets in the COSMOS field using the VIMOS spectrograph on the Very Large Telescope (VLT) at ESO’s Cerro Paranal Observatory, Chile. In the zCOSMOS Data Release DR3, we find optical spectroscopic observations for six out of seven targets studied in this work. We correct the observations for foreground reddening and redshift as described in Section 5.

We derive the intrinsic colour excess, $E(B-V)_\text{OPT}$, from the Balmer decrements. Similar to the work of Domínguez et al. (2013), in our analysis we assume a value of (H$\alpha$/H$\beta$)$_\text{abs} = 2.86$ for Case B recombination corresponding to a temperature $T = 10^4$ K and electron density $n_e = 10^5$ cm$^{-3}$ (Osterbrock 1989). The colour excess is then obtained using the standard relation,

$$E(B-V)_\text{OPT} = 1.97 \log_{10} \left( \frac{(H\alpha/H\beta)_\text{abs}}{2.86} \right).$$

We note that (H$\alpha$/H$\beta$)$_\text{abs}$ refer to the ratio of the H$\alpha$ and H$\beta$ emission line fluxes extracted from the foreground-redshift corrected VIMOS observations. No correction for underlying stellar absorption is applied to these values. In column 4 of Table 3, we list the individual $E(B-V)_\text{OPT}$ values as inferred from the optical observations. Correcting the optical observations for intrinsic reddening using these colour excess values we obtain the line fluxes presented in Table 4.

The observed H$\alpha$ fluxes, $I(H\alpha)$, are transformed to luminosities using the distance ($D$) values described in Section 2 and listed in Table 1. We estimate the SFR$_\text{OPT}$ using the inferred H$\alpha$ luminosities, $L(H\alpha)$, along with the linear relation from Starburst99 models:

$$\text{SFR}_\text{OPT} = \frac{L(H\alpha)}{3.39 \cdot 10^{41} \text{erg s}^{-1}} \cdot M_\odot \text{ yr}^{-1}.$$  

The Starburst99 model parameters are similar to those described and adopted in Section 6.1. The SFR$_\text{OPT}$ values derived from the H$\alpha$ luminosities are listed in column 5 of Table 3. The quoted uncertainties are estimated as described in Section 6.1.

### 6.3 Comparison between UV and optical

Comparing the average reddening values, $E(B-V)_\text{UV}$ and $E(B-V)_\text{OPT}$, we find values of $\sim0.12$ and $\sim0.23$ mag, respec-
SFRUV and SFROPT, respectively. Looking closer at the individual starburst galaxies, Calzetti et al. (1994) find that the difference in their SFR UV and estimates, we find the best agreement in galaxies 1535411 and slightly higher than their corresponding SFR OPT and absorption. It is around one-half of the optical depths of the two Balmer lines. These results have been interpreted as the combined continuum and emission lines sampling different galaxy components of the complete stellar population (Keel 1993). The ionizing hot stars reside near their birth places, close to dust molecular clouds, therefore their associated nebular recombination radiation is more strongly affected by the presence of dust in the environment. Older stars contributing mostly to the UV and optical continuum, on the other hand, are expected to have drifted away from their progenitor cloud, moving to regions where dust is less concentrated.

Turning to the SFRs inferred from the UV/COS observations and those obtained from the optical/VIMOS data, we find that the individual SFRs are marginally consistent within the errors; however, there is an offset for most of the targets with the optical SFRs being slightly higher than the UV rates with the exception of 1535411 and 1365128. We find average values of $\sim 0.96$ and $\sim 2.5 M_{\odot} \text{yr}^{-1}$ for SFRUV and SFROPT, respectively. Looking closer at the individual SFR estimates, we find the best agreement in galaxies 1535411 and 1365128; coincidently, their SFRUV and $E(B - V)_{\text{UV}}$ values are slightly higher than their corresponding SFROPT and $E(B - V)_{\text{OPT}}$ estimates. From the values in Table 3, we identify a trend where the highest offsets between SFRUV and SFROPT are observed in those galaxies with highest ISM reddening, $E(B - V)_{\text{OPT}}$, where SFR appears buried, and is not observed through stellar light.

To obtain a better picture of the star formation activity in these starburst galaxies, we investigate the SFRs using the SED modelling Code Investigating Galaxy Emission (CIGALE) (Noll et al. 2009; Bosquen et al. in preparation). The code is based on an energy–balance principle: the energy absorbed by dust from the UV to the near-IR is re-emitted self-consistently in the mid- and far-IR. To model the galaxies in this sample, we used the COSMOS broadband observations in the FUV, NUV, u, g, V, r, i, z, Spitzer/MIPS 3.6 μm, Spitzer MIPS 24 μm, Herschel/PACS 100 and 160 μm, and Herschel/SPIRE 250, 350, and 500 μm. We find an average SFR value of $\sim 6 \pm 1 M_{\odot} \text{yr}^{-1}$, higher than the inferred SFRs from the UV and the optical. This indicates there is more star formation activity buried than what is seen in the UV and optical ranges.

We also note that the VIMOS observations use 1.0″ slits, which do not enclose the galaxies entirely. Given the different morphologies, a small offset in the pointing could lead to variations in the flux. In general, the SFROPT values might better represent a lower limit on the true SFR.

One explanation for the difference between the SFRs can be attributed to attenuation caused by dust. Adopting the dust luminosity computed by CIGALE and combining it with the dust SFR estimator of Kennicutt & Evans (2012), we find SFRs that are more comparable to initial CIGALE SFR values than those inferred from the UV and optical observations. Care is required when comparing the different values presented in this work as the inferred SFRs have an intrinsic dependence on the models used. As mentioned in Section 6.1 for the case of the SFRUV, the stellar evolution used in estimating the

### Table 3. Star formation properties.

| Target     | $E(B - V)_{\text{UV}}$ (mag) | SFR$_{\text{UV}}$ ($M_{\odot} \text{yr}^{-1}$) | $E(B - V)_{\text{OPT}}$ (mag) | SFR$_{\text{OPT}}$ ($M_{\odot} \text{yr}^{-1}$) |
|------------|-------------------------------|---------------------------------|-------------------------------|---------------------------------|
| 1084255    | 0.20±0.08                     | 1.51±0.32                       | 0.53±0.18                     | 5.4±5.1                        |
| 1535411    | 0.22±0.16                     | 2.18±0.48                       | 0.06±0.02                     | 1.4±0.1                        |
| 1511408    | 0.05±0.15                     | 0.18±0.08                       | 0.21±0.08                     | 1.0±0.3                        |
| 1508056    | 0.05±0.14                     | 0.31±0.15                       | 0.14±0.02                     | 1.2±0.1                        |
| 1235867    | 0.09±0.14                     | 0.21±0.14                       | –                             | –                              |
| 781126     | 0.07±0.02                     | 1.48±0.43                       | 0.33±0.13                     | 5.4±2.8                        |
| 1365128    | 0.13±0.07                     | 0.84±0.48                       | 0.11±0.10                     | 0.6±0.3                        |

### Table 4. Emission lines.

| Target     | $I(Ly \alpha)^a$ | EW(Ly $\alpha$)$^b$ | $I(H\beta)^b$ | EW(H$\alpha$)$^b$ | $I(H\beta)^a$ | EW(H$\alpha$)$^a$ | $I(Om)^a$ | $L(H\alpha)^c$ | $f_{esc}(Ly \alpha)^d$ |
|------------|------------------|---------------------|---------------|-------------------|---------------|-------------------|-----------|----------------|-----------------|
| 1084255    | 69.4             | 33                  | 79.3          | 66                | 30.6          | 9                 | 35.6      | 18.3           | 10.1            |
| 1535411    | –                | –                   | 13.7          | 452               | 4.8           | 77                | 16.2      | 4.7            | –               |
| 1511408    | –                | –                   | 14.5          | 38                | 5.3           | 7                 | 4.7       | 3.2            | –               |
| 1508056    | 6.1              | 147                 | 11.7          | 210               | 4.1           | 27                | 15.7      | 4.2            | 6.0             |
| 1235867    | –                | –                   | –             | –                 | –             | –                 | –         | –              | –               |
| 781126     | 36.94            | 18                  | 77.3          | 226               | 28.0          | 36                | 126.0     | 18.1           | 5.5             |
| 1365128    | 9.6              | 98.0                | 8.0           | 34                | 3.1           | 7                 | 4.6       | 1.9            | 13.0            |

**Notes:**

$^a$ Observed flux density in $10^{-16}$ erg s$^{-1}$ cm$^{-2}$. These values include foreground and intrinsic dust corrections. $I(Ly \alpha)$ have been corrected for stellar absorption.

$^b$ Restframe equivalent width in Å. EW(Ly $\alpha$) have been corrected for stellar absorption.

$^c$ Luminosity in $10^{41}$ erg s$^{-1}$.

$^d$ Escape fraction of Ly $\alpha$ in percent.
was mainly chosen to avoid regions affected by the noisy detector edges. The LyC escape fractions are inferred from the ratios \( \frac{F_{\lambda, \text{pred}}}{F_{\lambda, \text{mod}}} \) and \( \frac{F_{\lambda, \text{obs}}}{F_{\lambda, \text{mod}}} \) for \( f_{\text{obs}} \) and \( f_{\text{abs}} \), respectively. In Table 5, we present our measured LyC escape fractions.

From the ddereddened observations, we find a relative escape fraction of \( 1.7^{+0.7}_{-0.4} \) per cent. This value represents the percentage of LyC photons that would escape such galaxies in the absence of dust. A more representative estimate of the escaping LyC photons is the absolute escape fraction, \( f_{\text{abs}} \), which accounts for the obscuration caused by the intrinsic dust. We infer an absolute escape fraction of \( 0.4^{+0.1}_{-0.04} \) per cent. The uncertainties account for the statistical errors extracted and propagated from the x1d files \((\sigma^2)\). The final errors listed in Table 5 were computed from the combined spectra as follows:

\[
\sigma = \sqrt{\sum \sigma_i^2 / N^2}.
\]

Given the relatively large uncertainties in the derived escape fractions, we conservatively consider these values as upper limits. In general, a low absolute escape fraction agrees with the predictions from Verhamme et al. (2015) proposing that when present, the Ly \( \alpha \) peak separation traces the column density of the scattering medium. They predict that peak separations of the order of \( \gtrsim 300 \text{ km s}^{-1} \) would describe objects in the optically thick regime where LyC photons would be unable to escape. We point out that we measure peak separations of the order of \( \gtrsim 300 \text{ km s}^{-1} \), where one would expect no escape of LyC radiation due to the thick ISM.

Izotov et al. (2016a), Izotov et al. (2016b), and Izotov et al. (2018) have measured some of the highest LyC escape fractions in five compact star-forming galaxies in low-redshift galaxies. For these same galaxies, Izotov et al. measure Ly \( \alpha \) escape fractions ranging between 22 per cent and 98 per cent. Compared to the \( f_{\text{esc}}(\text{Ly}\alpha) \) from Izotov et al., we measure escape fractions of Ly \( \alpha \) ranging from \( \approx 5 \) per cent to 13 per cent. The low LyC escape fraction we infer is also supported by the relatively low Ly \( \alpha \) escape fractions measured from the individual galaxies. Verhamme et al. (2017) show that a clear correlation between \( f_{\text{esc}}(\text{Ly}\alpha) \) and \( f_{\text{esc}}(\text{LyC}) \) exists. However, LCEs relevant to the cosmic reionization, \( f_{\text{esc}}(\text{LyC}) > 10 \) per cent, exhibit \( f_{\text{esc}}(\text{Ly}\alpha) \) with values \( > 20 \) per cent.

For comparison, we also combine the corrected (redshift, foreground, and intrinsic reddening) VIMOS observations using the same stacking procedure described above. From this optical combined spectrum, we then measure the Ly \( \alpha \) and H \( \alpha \) fluxes and following the recipe described in Section 5 we infer a relative low escape fraction of \( f_{\text{esc}}(\text{Ly}\alpha) = 2.6 \) per cent (also listed in Table 5). Caution is required when comparing this value to the \( f_{\text{esc}}(\text{LyC}) \) limits above as the optical combined spectra includes only six out of the seven objects combined in the UV spectrum.

8 CONCLUSIONS

In this paper, we present the analysis of seven star-forming galaxies observed with HST/COS at redshifts \( z \approx 0.3 \). We aim to study the escape of LyC and Ly \( \alpha \) radiation from these galaxies. Our main findings can be summarized as follows:

(i) We observe Ly \( \alpha \) emission in four out of the seven galaxies studied in detail in this work.

(ii) We find double peak features in the Ly \( \alpha \) profiles from 1084255, 1365128, and 1508056, with corresponding peak separations of 655, 374, and 275 km s\(^{-1}\). The relatively higher peak separation values measured for 1084255 and 1365128 might hint at
an absence of leaking Lyman continuum photons (Verhamme et al. 2015).

(iii) Three out of the four objects with Ly $\alpha$ emission have EW(Ly $\alpha$) > 20 Å. Galaxies with such EW values are classified as Ly $\alpha$ emitters (LAE) in high-$z$ narrow-band surveys.

(iv) We estimate the Ly $\alpha$ escape fraction, $f_{esc}(Ly \alpha)$, and find values up to 13 per cent. We see that our measurements follow the correlation between Ly $\alpha$ EWs and the $f_{esc}(Ly \alpha)$ observed by Yang et al. (2017) in GP galaxies.

(v) After combining the individual galaxy spectra, we conservatively infer upper limits in the absolute escape fraction of the order of $<0.4^{+0.1}_{-0.4}$ per cent, concluding that these galaxies are optically thick to Lyman continuum radiation. This demonstrates the validity of H$\alpha$ as a star formation tracer in these galaxies.

(vi) Comparing several star formation tracers, we find that the inferred SFRs are strongly dependent on the model assumptions.

(vii) We find moderate SFR values for most of the galaxies studied in this work (SFRs $\lesssim 10$ M$_\odot$ yr$^{-1}$).

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APPENDIX A: COS NUV IMAGES

As described in Section 3, HST program 13313 did not perform target acquisitions before observing the objects, instead the program relies on the typical HST pointing accuracy estimated to be $\sim 0.3''$. Although no acquisition was performed, short exposures ($t_{exp} = 120$ s) were taken in imaging mode using the NUV MIRRORA element. Before proceeding with the analysis presented here, we inspect the individual NUV images to confirm the galaxies were indeed in the field of view, on the detector, and inside the COS PSA. In Fig. A1, we show the individual NUV frames. We show the expected location of the COS PSA aperture as solid red circles, and represent the HST pointing accuracy with dashed red circles. We note that the exact location of the PSA on the NUV images is not known; however, with an estimated pointing error of $\sim 0.3''$ as shown in Fig. A1 the targets are still contained inside the COS aperture.

Furthermore, looking at the flux loss due to different pointing offsets (Fig. A2), we find that for an offset of $0.3''$ the typical flux loss is estimated to be around $\lesssim 0.05$ mag. Even for extreme cases where the observations experience offsets of the order of $0.7''$, rare in HST observations, the flux loss is limited to $\sim 0.15$ mag.

APPENDIX B: UPDATES TO CALCOS V2.21D

In Leitherer et al. (2016), we introduced a modified version of CALCOS to perform a 2D background correction available for data taken at lifetime position 1 (LP1). In the modified version of CALCOS, v2.21d, anytime the DARKFILE keyword is found in the primary header of the science exposures the software subtracts the background contribution using a 2D superdark. The user must add manually the DARKFILE keyword and specify the name of the superdark reference file. The dark-subtracted FLT is stored in files with extensions darkcorrflt_a/b.fits.

In CALCOS v2.21d, before performing the spectral extraction we implement a weighting system that assigns low weights to those pixels in the science frames that did not register any counts. After the 2D background correction, these zero-count pixels end up with negative values. Given the low weights assigned to these pixels, the flux extracted from these pixels is close to zero, in the order of $\sim 10^{-21}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$. In order to avoid any biases in the average extracted flux towards higher values, we modify CALCOS v2.21d to remove the weighting system, and instead we now assign a similar weight for all pixels irrespective of positive or negative values. This change is especially critical for those regions on the detector with low sensitivity.

In Fig. B1 we compare the calibrated spectra from CALCOS v2.21d (in red) and from the modified software (in black). We see that the changes made to CALCOS v2.21d decreases the mean flux $<10$ percent between observed wavelengths $1135 \, \text{Å} < \lambda < 1170 \, \text{Å}$. This is mainly due to the fact that by assigning low weights to
zero-count pixels, CALCOS v2.21d avoided negative fluxes and instead provided extremely low flux values. With the new modifications to CALCOS v2.21d we now allow for negative values, as expected from uncertainties in the superdarks. We point out that the floor at negative fluxes seen in the black spectrum in Fig. B1 is caused by the background subtraction and the decreasing instrument sensitivity.

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