Scrutiny of a very young, metal-poor star-forming Lyα-emitter at $z \approx 3.7$

E. Iani$^1$, A. Zanella$^2$, J. Vernet$^3$, J. Richard$^4$, M. Gronke$^5$, F. Arrigoni-Battaia$^5$, A. Bolamperti$^6$, K. Caputi$^1$, A. Humphrey$^7$, G. Rodighiero$^6$, P. Rinaldi$^1$, E. Vanzella$^8$

$^1$Kapteyn Astronomical Institute, University of Groningen, 9700AV Groningen, The Netherlands
$^2$Istituto Nazionale di Astrofisica (INAF), Vicolo dell’Osservatorio 5, I-35122 Padova, Italy
$^3$European Southern Observatory, Karl Schwarzschild Straße 2, D-85748 Garching, Germany
$^4$Univ. Lyon, Univ Lyon1, ENS de Lyon, CNRS, Centre de Recherche Astrophysique de Lyon UMR5574, F-69230, Saint-Genis-Laval, France
$^5$Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str 1, D-85748 Garching bei München, Germany
$^6$Dipartimento di Fisica ed Astronomia, Università degli Studi di Padova, Vicolo dell’Osservatorio 3, I-35122 Padova, Italy
$^7$Instituto de Astrofísica e Ciências do Espaço - Centro de Astrofísica da Universidade do Porto, Rua das Estrelas, 4150-762, Porto, Portugal
$^8$Istituto Nazionale di Astrofisica (INAF), Osservatorio di Astrofisica e Scienza dello Spazio, via Gobetti 93/3, 40129 Bologna, Italy

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ABSTRACT

The origin of the Lyman-α (Lyα) emission in galaxies is a long-standing issue: despite several processes known to originate this line (e.g. AGN, star formation, cold accretion, shock heating), it is difficult to discriminate among these phenomena based on observations. Recent studies have suggested that the comparison of the ultraviolet (UV) and optical properties of these sources could solve the riddle. For this reason, we investigate the rest-frame UV and optical properties of A2895b, a strongly lensed Lyα-emitter at redshift $z \sim 3.7$. From this study, we find that our target is a compact ($r_n \sim 1.2$ pkpc) star-forming (star formation rate $\approx 11 M_{\odot}/yr$) galaxy having a young stellar population. Interestingly, we measure a high ratio of the Hβ and the UV continuum monochromatic luminosities ($L(H\beta)/L(UV) \approx 100$). Based on tracks of theoretical stellar models ($\text{STARBURST}99$, $\beta$PASS), we can only partially explain this result by assuming a recent ($\lesssim 10$ Myr), bursty episode of star-formation and considering models characterised by binary stars, a top-heavy initial-mass function (IMF) and sub-solar metallicities ($Z \lesssim 0.01 Z_{\odot}$). These assumptions also explain the observed low (C/O) abundance of our target ($\approx 0.23(C/O)_{\odot}$). By comparing the UV and optical datasets, we find that the Lyα and UV continuum are more extended ($\times 2$) than the Balmer lines, and that the peak of the Lyα is offset ($\approx 0.6$ pkpc). The multi-wavelength results of our analysis suggest that the observed Lyα emission originates from a recent star-formation burst, likely taking place in an off-centre clump.

Key words: galaxies: evolution – galaxies: high-redshift – galaxies: ISM – galaxies: star formation – galaxies: starburst – ultraviolet: galaxies

1 INTRODUCTION

In the hydrogen atom, whenever an electron falls from the first excitation level $2p$ to the ground state $1s$, a photon with an energy of 10.2 eV and a wavelength of 1215.67 Å is emitted. This ultraviolet (UV) transition is the brightest hydrogen emission and it is commonly referred to as Lyman-α (Lyα) line (Lyman 1906). Thanks to its brightness and the fact that hydrogen constitutes about 74 per cent of the baryonic matter in the Universe (e.g. Crosswell 1996; Carroll & Ostlie 2006), the Lyα acts as a beacon for the detection of galaxies at intermediate/high-redshifts ($z \gtrsim 2 - 3$). In fact, its UV rest-frame wavelength is shifted into the optical and near-infrared (NIR) at cosmological distances (cosmological redshift).

Galaxies detected through their Lyα emission (and having a rest-frame Lyα equivalent width $EW_{\alpha} \gtrsim 20$ Å) are generally referred to as Lyα-emitters (LAEs, e.g. Ouchi et al. 2020). In the last decades, studies have revealed that these systems have often compact morphologies with effective radii $r_e \sim 1$ pkpc (e.g. Pascarelle et al. 1996; Matthee et al. 2021; Pucha et al. 2022) and, typically, a disk-like radial surface-brightness (SB) profile with a Sérsic index of $n_s \sim 1$ (e.g. Taniguchi et al. 2009; Gronwall et al. 2011). Whenever in the absence of an active galactic nucleus (AGN), LAEs are found to be low-mass (stellar mass $M_\star \sim 10^7 - 10^9 M_{\odot}$), young (stellar ages $\sim 10$ Myr) star-forming galaxies (SFGs) with star formation rates $SFR \sim 1 - 10 M_{\odot}/yr$ (e.g. Nakajima et al. 2012; Hagen et al. 2014, 2016; Matthee et al. 2021; Pucha et al. 2022). With a specific star formation rate $sSFR \gtrsim 10^{-7} yr^{-1}$ (sSFR = SFR/$M_\star$), Lyα-emitters are generally starbursting systems. As for the properties of their interstellar medium (ISM), LAEs are dust poor galaxies with stellar and nebular colour extinction values $E(B-V) \sim 0.2$ (Ono et al. 2010; Kojima et al. 2017), and a gas-phase metallicity (derived from both strong lines and direct electron temperature $T_e$ methods) $Z \sim 0.1 - 0.5 Z_{\odot}$ (e.g. Finkelstein et al. 2011; Nakajima et al. 2012;...
Trainor et al. 2016; Kojima et al. 2017). Despite all these findings, the origin of their Ly\(\alpha\) emission is still debated.

Up to date, five major phenomena are generally invoked to explain Ly\(\alpha\) emission in and surrounding galaxies (e.g. Ouchi et al. 2020): in-situ and/or ex-situ (i.e. from unresolved faint satellite galaxies, e.g. Mas-Ribas et al. 2017) star formation, AGN, shock heating due to outflows, cold accretion via gravitational cooling, and fluorescence, i.e. when ionising photons can escape their production area and reach and ionise pockets of ISM far from star-forming regions. Despite the fact that each one of these processes can originate the Ly\(\alpha\) line, the emission observed in galaxies is possibly driven by a combination of phenomena, each one dominant on a different scale (see Claeyssens et al. 2022, and references therein). To discriminate between these different phenomena is, therefore, a demanding task.

Notwithstanding its brightness, the Ly\(\alpha\) line is complex to study since it strongly suffers from both dust extinction and resonant scattering. While the main effect of dust is to erode the UV flux and to re-emit it at the infrared (IR) wavelengths, resonant scattering is a diffusive process where Ly\(\alpha\) photons do not escape freely from their production site but undergo a number of absorption and re-emission events due to intervening atoms of neutral hydrogen along the photons propagation line. The amount of scatterings strongly depends on the properties of the medium the Ly\(\alpha\) photons diffuse into, i.e. its neutral hydrogen column density, geometry and kinematics (see, e.g. Dijkstra 2014, and references therein). Besides, each scattering slightly alters the frequency of the Ly\(\alpha\) photons, as well as their direction of propagation (Osterbrock 1962). Hence, the spectral characteristics of the emerging radiation (i.e. the spectral shape of the observed Ly\(\alpha\)) do not only encode the properties of the phenomena driving the emission of the line but also those of the scattering medium along the paths that offered least resistance to the diffusing photons (e.g. Dijkstra et al. 2016; Gronke & Dijkstra 2016). This makes observationally challenging determining what are the actual processes driving the Ly\(\alpha\) emission.

A potential way to tackle this problem is to investigate in depth the properties of the host galaxy and its surrounding medium, and possibly, spatially resolve them. In particular, the joint analysis of the SB profiles and spatial extent of optical hydrogen transitions (i.e. the Balmer lines), Ly\(\alpha\) and UV stellar continuum are believed to be a useful tool to disentangle the different scenarios on the Ly\(\alpha\) origin (e.g. Mas-Ribas et al. 2017). In fact, differently from the several phenomena behind the Ly\(\alpha\) emission, the nebular UV continuum radiation is only produced in the ISM around star-forming regions via recombinations of hydrogen ions, while the Balmer lines arise via both recombinations and fluorescence. Therefore, by comparing Balmer lines and UV continuum SB profiles we can determine the importance of nebular against fluorescent emission, while the comparison between Balmer lines and Ly\(\alpha\) constrains the impact of scattering phenomena. These studies, however, require deep multi-wavelength observations and are hampered by the faintness and small size (both intrinsic and apparent) of distant galaxies.

One possible solution to solve this puzzle is through the study of strongly lensed LAEs (e.g. Swinbank et al. 2007; Karman et al. 2015; Caminha et al. 2016; Patrício et al. 2016; Vanzella et al. 2016; Smit et al. 2017; Claeyssens et al. 2019; Vanzella et al. 2020; Chen et al. 2021; Iani et al. 2021; Claeyssens et al. 2022). In fact, both lensing effects of magnification and stretching can allow to reach faint fluxes and small scales in short observing time, even though robust lensing models have to be developed in order to correctly interpret and compare the results.

In this context, we study a high-redshift (\(z \sim 3.7\)) Ly\(\alpha\)-emitter lensed by the Abell 2895 (hereafter A2895, Abell 1958) galaxy cluster (\(z \approx 0.227\)). Our target (presented in Livermore et al. 2015 as Abell 2895b) has three multiple images (M1, M2 and M3) located at the celestial coordinates (right ascension, declination) of \((1^\text{h}18^\text{m}11.127^\text{s}, -26^\circ57’59.36’’\)), \((1^\text{h}18^\text{m}10.543^\text{s}, -26^\circ58’10.56’’\)) and \((1^\text{h}18^\text{m}10.439^\text{s}, -26^\circ58’14.36’’\)). The multiple images are mirrored with respect to the lensing critical line, i.e. the line of infinite magnification. To investigate the physical properties of our target, we gather a multi-wavelength dataset that covers its rest-frame ultraviolet (UV) and optical emission. We study the galaxy rest-frame UV thanks to VLT/MUSE optical integral-field spectroscopy with adaptive optics (AO). With VLT/SINFONI AO-assisted near-infrared integral-field spectroscopy we probe the rest-frame optical emission of the target. Thanks to the image multiplicity and the high magnification factor (\(\mu = 9 \pm 2\) for the M3 image, Livermore et al. 2015), we are able to probe with unprecedented detail the properties of this source.

This Paper is organised as follows. In Section 2, we present the observations in our hand and on which this paper is based. We also briefly discuss the main steps followed for the data reduction. In Section 3, we summarise the technique adopted to obtain the UV and optical spectrum of our target and their analysis. We also describe the procedure to obtain pseudo-NB images of the main emission lines, as well as the UV continuum. In Section 4, we derive the main properties of our target (e.g. dust extinction, metallicity, star formation rate) based on the analysis of the main spectral features derived from its UV and optical spectra. We also analyse in detail the galaxy Ly\(\alpha\) emission. In Section 5, we summarise and discuss our findings.

In this Paper, we adopt a Flat \(\Lambda\)-CDM cosmology with \(\Omega_\Lambda = 0.7\), \(\Omega_m = 0.3\), and \(H_0 = 70\) km/s/Mpc. All the wavelengths presented in the following (also in the ions nomenclature) are in vacuum.

## 2 OBSERVATIONS AND DATA REDUCTION

In the following, we describe the observations and the steps performed for the data reduction. The properties of the MUSE observations and the description of the lensing model adopted were already presented in Iani et al. (2021). Hence, hereafter we only provide a short description of the MUSE observing programme. We refer the reader to Iani et al. (2021) for further details.

During the analysis of our target, we serendipitously found additional Ly\(\alpha\)-emitters at \(z \approx 4.57, 4.65\) and 4.92. We report their properties in Appendix A.

### 2.1 MUSE data

We observed the central region of the A2895 galaxy cluster with VLT/MUSE (Bacon et al. 2010), in Wide Field Mode (WFM, \(1’ \times 1’\) field-of-view) and with Ground-Layer Adaptive Optics (GLAO) provided by the GALACSI module (Arsenault et al. 2008; Ströbele et al. 2012). The observations were carried out during the 2017 Science Verification of GALACSI (Leibundgut et al. 2017; Programme ID: 60.A-9195(A), PI: A. Zanella), and in August 2019 (Programme ID: 0102.B-0741(A), PI: A. Zanella), for a total exposure time of 5 hours. The MUSE WFM observations cover a wavelength range \(\Delta \lambda = 4750 – 9350\) Å (nominal) with a spectral resolution \(R \approx 3000\). We reduce the data following the standard reduction procedure (i.e. corrections for bias, flat-field, wavelength and flux calibration, atmospheric extinction and astrometric correction) by means of the...
ESO reduction pipeline\textsuperscript{1} (esoREX), version 2.4.1 (Weilbacher et al. 2012, 2014), and the Zurich Atmosphere Purge software (\textsc{zap}\textsuperscript{2} version 2.1, Soto et al. 2016) to properly account for sky residuals. We reconstruct the MUSE PSF via the publicly available algorithm \textsc{rspe}\textsuperscript{3} (Fusco et al. 2020), and find a FWHM of 0.4′′, as requested for the observations.

2.2 SINFONI data
The multiple image M3 of our target was observed with the K-band grating ($\Delta\lambda = 1.95 - 2.45 \mu m$, $R \sim 4000$) of SINFONI (Eisenhauer et al. 2003; Bonnet et al. 2004), between August 29th and September 25th 2011 (Programme ID: 085.B-0848(A), PI: J. Richard), for a total exposure time of 6h with AO (natural guide star mode). The image quality of the observations is $\approx 0.17''$ in K band, as measured from the standard telluric star observed close in time and airmass to the target, and used for flux calibration. We reduce the data with the ESO SINFONI pipeline (esoREX version 3.13.2) following the standard procedure: correction for dark current, bad pixels and distortions, flat field and wavelength calibration. We also correct for telluric features, flux calibrate and stack science exposures within the same OB.

After the reduction of the single OBs, we correct their wavelength calibration for the barycentric velocity, a step that is not automatically performed by the reduction pipeline. We register the astrometry of the final SINFONI datacube to the one of MUSE by minimising the spatial offset between the centroid of the [OIII]5008 emission and that of the target UV continuum. We follow this procedure since no other target falls within the SINFONI FoV and the optical continuum of our source is undetected (see Section 3 and bottom panel of Figure 1). Furthermore, the overlap between UV continuum and optical [OIII]5008 emission ensures the spatial overlap with more energetic transitions of the same ion, i.e. [OIII]λλ1660, 1666.

3 ANALYSIS

In the following Section, we report the procedures adopted to extract the UV and optical spectrum of our target and the methodology applied to derive the main properties of the spectral features presented in Table 1 (e.g. line fluxes, equivalent widths).

3.1 Extraction of the spectra
Following Iani et al. (2021), we extract the UV and optical spectrum of our target considering the spatial extent of the galaxy brightest UV and optical emission lines, i.e. the Ly$\alpha$ and [OIII]λ5008, respectively.

As a first step, we create pseudo-narrow band (NB) images that maximise the signal-to-noise ratio (SNR) of these lines (refer to Iani et al. 2021, for more details).

We create maps of SNR that we use to define the areas where to extract the galaxy optical and UV spectrum. The extraction is performed by summing up the spectra corrected for the lensing magnification factor of all the spaxels where the SNR is $\geq 2.5$. Since the MUSE data cover all the three multiple images (M1, M2, M3) of our target, while SINFONI observed only M3, we repeat this procedure separately for each multiple image, after cleaning the MUSE UV spectrum from the optical stellar continuum of the A2895 BCG (see Iani et al. 2021). Finally, we average the UV spectrum of each multiple image to increase the SNR. In Figure 1 we present the UV (upper panel) and optical (lower panel) spectra of our target.

3.2 Emission and absorption line measurements

The spectra display several UV an optical emission lines as well as a few weak UV absorption features. We fit all the lines (but the Ly$\alpha$) with a Gaussian profile, after modelling their local stellar continuum. We study the Ly$\alpha$ separately because of its resonant nature and asymmetric spectral profile, see Section 4.6.1. To determine the uncertainties on the values derived from the Gaussian fit of each line, we perform 1000 Monte Carlo realisations of the spectra. Each realisation is drawn randomly from a Gaussian distribution with mean and variance corresponding to the observed spectrum flux and variance. We define the uncertainty on the line properties as the half distance between the 16th and 84th percentiles. In Table 1, we present the results of our fit for all the lines with an estimated SNR > 3. As in Iani et al. (2021), we add to the final errors also the flux systematic uncertainties due to absolute flux calibration, equal to 5% and 20% for MUSE\textsuperscript{4} and SINFONI data, respectively.

By averaging the wavelength position of the emission lines (but Ly$\alpha$) we estimate the galaxy systemic redshift $z_{sys} = 3.72096 \pm 0.00012$. For the redshift estimate, we do not consider absorption lines as they are weak spectral features in our UV spectrum and can be blue-shifted whenever the galaxy ISM is characterised by outflows (e.g. Pettini et al. 2000; Dessauges-Zavadsky et al. 2010; Patrício et al. 2016).

Finally, we measure the rest-frame equivalent width (EW$_0$) of each line. We use a definition of EW$_0$ in which negative values indicate emission, while positive values refer to absorption. Since the optical continuum of the galaxy is not detected in the SINFONI data, we report a $3\sigma$ upper-limit\textsuperscript{5} on the line flux and that corresponds to a $3\sigma$ lower limit on the line EW$_0$.

4 GALAXY PROPERTIES

In the following Section, we derive the physical properties (e.g. dust extinction, nebular metallicity, star formation rate) of our target.

4.1 Dust extinction

We estimate the dust extinction in a twofold way: by considering the slope of the UV continuum ($\beta$-slope) and from the ratio of the Balmer lines H$_y$/H$\beta$ (Balmer decrement).

For the UV $\beta$-slope, we define 7 spectral windows in the range 1200-2000 Å (see Table 2) that remove from the fitting procedure all the relevant absorption features of stellar UV spectra, as well as the MUSE Na Notch filter, and fit the observed UV continuum of our target with a power law, i.e. $f(\lambda) \propto \lambda^\beta$ (e.g. Calzetti et al. 1994; Castellano et al. 2012). From the fit we obtain $\beta = -2.6 \pm 0.5$. Such low value of the $\beta$ parameter is typical of stars with steep blue UV slopes, i.e. young and unobscured stellar populations. In fact, we tested the MUSE flux calibration against the HST/ACS F606W observations (the only available HST image in A2895, SNAP program 10881, PI: G. Smith) for a total of 25 sources falling in the MUSE FoV, and found a good agreement (median magnitudes offset $\pm 0.01$ mag).

\textsuperscript{4} We estimate $\sigma$ as the median of the error spectrum in the wavelength range within which the line fit is performed.

\textsuperscript{5} We estimate $\sigma$ as the median of the error spectrum in the wavelength range within which the line fit is performed.

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\textsuperscript{1} https://www.eso.org/sci/software/cpl/esorex.html
\textsuperscript{2} https://zap.readthedocs.io/en/latest/
\textsuperscript{3} https://muse-psfr.readthedocs.io/en/latest/
Figure 1. The rest-frame UV (upper panels) and optical spectrum (bottom panel) of our target galaxy. The grey-shaded regions display the ±1σ error around the spectra, while the vertical light-blue solid lines show the wavelength position of strong telluric lines. In the central panels we present a zoom-in of the UV spectrum around the Lyα line (left panel) and the UV continuum redwards the Lyα and MUSE Notch filter (right panel).
if we convert the measured $\beta$ into the colour excess of the stellar continuum $E(B-V)_{\text{cont}}$ via the relation by Meurer et al. (1999), we obtain $E(B-V)_{\text{cont}} \leq 0.03$. Despite the fact that the $\beta - E(B-V)_{\text{cont}}$ relation depends on metallicity and star formation history (e.g. Kong et al. 2004; Reddy et al. 2010; Schaerer et al. 2013; Zeimann et al. 2015; Reddy et al. 2018), as well as on stellar mass and age (e.g. Buat et al. 2012; Zeimann et al. 2015; Bouwens et al. 2016b), these values are in line with results found for other low-mass galaxies at intermediate/high-redshifts (e.g. Bouwens et al. 2010; Castellano et al. 2015; Reddy et al. 2018), as well as on stellar mass and age (e.g. Bouwens et al. 2010; Castellano et al. 2012; Bouwens et al. 2016a; Vanzella et al. 2018; Iani et al. 2021).

Thanks to the simultaneous detection of H$\gamma$ and H$\beta$, we can estimate the nebular extinction due to dust from the observed ratio H$\gamma$/H$\beta$. For our target, we derive (H$\gamma$/H$\beta$)$_{\text{obs}} = 0.56 \pm 0.11$. Adopting the attenuation law by Calzetti et al. (2000) and an intrinsic Balmer decrement of (H$\gamma$/H$\beta$)$_{\text{int}} = 0.476$ (from case B recombination, e.g. Osterbrock 1989) 6, we obtain a nebular colour excess of $E(B-V)_{\text{neb}} = 0.34^{+0.34}_{-0.34}$.

Despite the tension between the face-value estimates, the wide errorbars make the nebular estimate compatible with the one obtained from the $\beta$-slope.

In the following we always refer to the observed values of the fluxes without taking into account any dust correction (unless differently specified).

### 4.2 Electron temperature and density, nebular metallicity, ionisation parameter and (C/O) abundance

Thanks to the presence of the [OIII] optical lines at 4364, 4959 and 5008Å, we evaluate the electron temperature $T_e$ of the emitting gas following the empirical equation by Proxauff et al. (2014). The electron temperature we derive is of $T_e = (2.2 \pm 0.2) \times 10^4$ K.

In a similar manner, because of the detection of the [CII] doublet at 1908Å, we determine the electron density $n_e$ from the intensity ratio [CIII]19097/[CII]19099. By means of PyNeb and assuming $T_e = (2.2 \pm 0.2) \times 10^4$ K, we derive an upper-limit on the $n_e \leq 3 \times 10^3$ cm$^{-3}$.

The UV emission lines detected in our target spectrum allow us to estimate its nebular metallicity by means of the He$\alpha$ – O3C3 diagnostic diagram by Byler et al. (2020), see Figure 2. The He$\alpha$ – O3C3 diagnostic diagram has been found to robustly determine the ISM metallicity of metal-poor (sub-solar) systems. Specifically, through Equation 8 by Byler et al. (2020), we derive an ISM metallicity of $\log_{10} (O/H) \geq 7.36 \pm 0.02$. Assuming a solar value of $12 + \log_{10} (O/H)_{\odot} = 8.69 \pm 0.05$ (Allende Prieto et al. 2001), the derived estimate corresponds to a sub-solar metallicity of $Z_{\text{neb}} = 0.05 \pm 0.02 Z_{\odot}$, i.e. $Z_{\text{neb}} = (7 \pm 3) \times 10^{-4}$.

In their work, Byler et al. (2020) do not provide any relation to determine the ionisation parameter $U$ (as in the case of the nebular metallicity. However, from the comparison with the model grids, we estimate $\log_{10} (U) \sim -2.5$.

We finally investigate the (C/O) abundance of our target by using Equations 6 and 7 by Pérez-Montero & Amorín (2017). From the equations, we obtain $\log_{10} (C/O) = -0.99 \pm 0.23$. If we compare this estimate to the solar value $(C/O)_{\odot} = 0.44$ (Gutkin et al. 2016), we derive a ratio $(C/O)/(C/O)_{\odot} = 0.23$. The (C/O) estimate is in agreement with the (C/O) – metallicity relation and with the values found in metal-poor high-ionisation dwarf local galaxies and halo stars (e.g. Berg et al. 2016, 2019). Interestingly, because carbon and oxygen are thought to originate primarily from stars of different mass ranges (with O synthesised mostly in massive stars with $M > 10^5 M_{\odot}$, while C is produced in both massive and intermediate mass stars, i.e. $2 M_{\odot} < M < 8 M_{\odot}$), the low (C/O) measured could be interpreted as the consequence of a top-heavy IMF and/or the sign that we are looking at a very recent burst of star formation. In fact, while in the first case an overabundance of massive stars could bring to an enhanced production of O over C, the same effect could be obtained if the stellar population had just recently formed and only type II supernovae (SNe) had time to enrich the ISM ($\leq 40$ Myr, e.g. Veilleux et al. 2005).

### 4.3 The source of the ISM ionisation: AGN, SF, or shocks?

Different mechanisms (e.g. star formation, AGN, shocks) can ionise the ISM of galaxies, thus driving the emission of lines in the UV and optical. To discriminate between the different processes, several tracers can be probed, e.g. the width of emission lines, the presence of...
The Chandra Source Catalog (CSC) is available at https://cxc.harvard.edu/csc2/

Table 1. Properties of the emission and absorption lines with measured SNR > 3. Unless differently stated, the measurements reported refer to the intrinsic values, i.e. corrected for lensing magnification. The wavelengths reported are in vacuum. The flux uncertainties have been increased by 5% (MUSE) and 20% (SINFONI) to take into account errors on the absolute calibration of the datasets. Rest-frame EW of the line (the 1 highlights lines for which the EW0 has been estimated taking into account an upper limit on the stellar continuum flux). We follow the convention for which the EW of emission lines is reported with negative values (see Section 3.2). Estimated redshift of the target according to the wavelength of the best-fit Gaussian peak (only for nebular emission lines, as absorption lines might have blue-shifted spectral profiles due to outflows, see Section 4). Velocity dispersion \( \sigma \) corrected for instrumental broadening (see Iani et al. 2021) and in units of km/s.

| Line   | \( \lambda^a \) | Flux \( b \) [10^{-20} \text{ erg/cm}^2\] | EW \( c \) [\AA] | \( z^d \) | \( \sigma^e \) [km/s] |
|--------|----------------|--------------------------------|----------------|------|-----------------|
| NIII   | 1370.132       | -20.2 ± 5.0                   | 1.7 ± 0.4       | -1   | 104 ± 45        |
| OV     | 1371.292       | -18.7 ± 4.1                   | 1.6 ± 0.3       | -1   | 46 ± 31         |
| SiIV   | 1393.755       | -15.9 ± 3.8                   | 1.4 ± 0.3       | -1   | 176 ± 7         |
| SII    | 1526.707       | -18.4 ± 4.1                   | 2.3 ± 0.5       | -1   | 42 ± 41         |
| SII*   | 1553.431       | 8.0 ± 1.7                     | -1.0 ± 0.2      | 3.72036 ± 0.00001 | 6 ± 1 |
| CIV    | 1548.195       | 29.7 ± 3.4                    | -3.9 ± 0.4      | 3.72072 ± 0.00023 | 72 ± 22 |
| HeII   | 1640.417       | 44.5 ± 3.5                    | -7.8 ± 0.6      | 3.72087 ± 0.00008 | 64 ± 13 |
| OIII   | 1660.809       | 27.4 ± 4.0                    | -4.8 ± 0.7      | 3.72097 ± 0.00019 | 34 ± 14 |
| OIII   | 1666.150       | 79.7 ± 8.4                    | -12.3 ± 1.3     | 3.72095 ± 0.00015 | 51 ± 11 |
| All    | 1670.787       | 9.2 ± 1.4                     | -1.4 ± 0.2      | 3.72041 ± 0.00001 | 47 ± 5 |
| SiIII  | 1892.029       | 25.6 ± 1.3                    | -4.8 ± 0.3      | 3.72110 ± 0.00002 | 47 ± 2 |
| [CII]  | 1906.680       | 96.6 ± 11.6                   | -18.1 ± 2.3     | 3.72095 ± 0.00015 | 44 ± 17 |
| [CIII] | 1908.734       | 72.2 ± 12.0                   | -13.4 ± 2.3     | 3.72119 ± 0.00039 | 58 ± 46 |
| Hy     | 4341.680       | 365.8 ± 99.4                  | \leq -2.3^3     | 3.72151 ± 0.00050 | 14 ± 16 |
| [OIII] | 4364.436       | 178.1 ± 63.1                  | \leq -1.2^3     | 3.72027 ± 0.00084 | 67 ± 53 |
| [O]    | 4652.680       | 652.9 ± 141.2                 | \leq -3.9^3     | 3.72160 ± 0.00024 | 62 ± 28 |
| [OII]  | 4960.295       | 988.6 ± 204.9                 | \leq -5.5^3     | 3.72147 ± 0.00009 | 21 ± 24 |
| [OIII] | 5008.240       | 2090.7 ± 584.3                | \leq -15.5^3    | 3.72147 ± 0.00004 | 50 ± 5 |

Table 2. Rest-frame UV spectral windows employed for the measurement of the stellar continuum \( \beta \)-slope, see Section 4.1.

| Window Number | Wavelength Range [Å] |
|---------------|----------------------|
| 1             | 1268 - 1284          |
| 2             | 1360 - 1371          |
| 3             | 1407 - 1515          |
| 4             | 1562 - 1583          |
| 5             | 1677 - 1725          |
| 6             | 1760 - 1833          |
| 7             | 1930 - 1950          |

4.3.1 Detection, shape and width of UV metal lines

From the UV and optical spectrum, the emission line profiles do not show the presence of blue/red wings nor broad components. All the emission lines are narrow, having a \( \sigma \leq 100 \text{ km/s} \) (see Table 1) and being unresolved or marginally resolved at the spectral resolution of our data. These results disfavour the hypothesis that our target hosts an unobscured (type-I) AGN (e.g. McCarthy 1993; Corbin & Boroson 1996; Humphrey et al. 2008; Matsuoka et al. 2009). This is also supported by the fact that the publicly available X-ray catalogue based on Chandra observations (Chandra Source Catalog, v. 2.0, Evans et al. 2019, 2020)\(^7\) for this cosmological field does not report any X-ray emitter at our target coordinates nor in its closest vicinity.\(^8\)

However, we cannot fully rule out the possible presence of an obscured (type-II) AGN. In fact, the UV spectrum of our target shows several high ionisation potential transitions of He and metals, e.g. CIV\(1550\) and HeII\(1640\), whose presence could be explained by AGN activity. This hypothesis could also be supported by the high EW\(_0\) measured for the HeII line (\( \sim \lambda 8\)). In fact, recent literature has shown that photo-ionisation models fail to reproduce such rest-frame EW with the only contribution of stars (e.g. Berg et al. 2018; Nanayakkara et al. 2019). A line that is generally considered to be the smoking-gun proof of an AGN is NV\(1240\), having an ionisation potential of \( \sim 78 \text{ eV} \), difficult to explain with the typical emission of stellar populations (e.g. Hainline et al. 2011; Laporte et al. 2017; Grazian et al. 2020). Yet, the MUSE Na Notch filter prevents us from detecting this line.

4.3.2 UV spectroscopic diagnostic diagrams

A way possible to better constrain the nature of our target is to consider empirical spectroscopic diagnostic diagrams based on the ratio of UV lines. Similarly to the optical BPT and BPT-like diagrams (Baldwin et al. 1981; Veilleux & Osterbrock 1987; Dopita & Sutherland 1995), the ratio between close-by UV emission lines is effective in discriminating among different mechanisms of ISM ionisation (e.g. Feltre et al. 2016; Nakajima et al. 2018; Hirschmann et al. 2019). Besides, the fact that these diagrams feature the intensity ratio of lines that are close in wavelength makes them rather insensitive to dust extinction.

In our work, we exploit the C4C3-C34, C3-O3 and He2-O3C3 diagrams (e.g. Nakajima et al. 2018; Hirschmann et al. 2019; Byler et al. 2019).
For the C4C3-C34 diagram, we highlight the demarcation lines between AGN and star-forming galaxies presented in Nakajima et al. (2018). In the case of the C3-O3 diagnostic, we resort to those of Hirschmann et al. (2019). We populate the panels with other metal-poor intermediate/high-redshift sources taken from the literature (Fosbury et al. 2003; Stark et al. 2014; Vanzella et al. 2017, 2020; Chen et al. 2021; Lin et al. 2022; Iani et al. 2021), a sample of high-z radio galaxies (HzRG) by Vernet et al. (2001) and Humphrey et al. (2008), a sample of type-II quasars (QS02s) from Silva et al. (2020), as well as from theoretical models9 of both star-forming galaxies (blue stars, Gutkin et al. 2016) and AGNs (red squares, Feltre et al. 2016). We limit both theoretical models to sub-solar gas densities 
\[ \rho \lesssim 10^{4} \mathrm{cm}^{-3} \] and lower metallicity 
\[ Z = [0.0001, 0.0002, 0.0005, 0.001] \] and ionisation parameters 
\[ \log_{10}(U) = [-3, -2.5, -2] \]. As for the stellar models10, we apply an additional cut to 
\[ (C/O)/(C/O)_{\odot} = [0.14, 0.20, 0.27, 0.38] \] and an upper cut-off stellar mass for the IMF 
\[ M_{\text{up}} = 300 M_{\odot} \]. The constraints on the ISM metallicity, ionisation parameter and 
\[ (C/O) \] abundance are based on the estimates that we retrieved in Section 4.2.

On the contrary, we do not limit the stellar and AGN models neither in gas density 
\[ N_{H} = [100, 1000] \mathrm{cm}^{-3} \] nor in dust-to-metal mass ratios 
\[ \xi_{d} = [0.1, 0.3, 0.5] \]. Finally, the AGN models11 have UV spectral slopes 
\[ (f_{\nu} \propto \nu^{\alpha}) \] ranging from 
\[ [-2.1, -1.7, -1.4, -1.2] \].

On one hand, according to the demarcation lines by Nakajima et al. (2018) (grey lines in the C4C3-C34 diagram), our target seems to be a star forming galaxy. On the other hand, based on the redshift-independent separation criteria by Hirschmann et al. (2019), the representative point of our target in the C3-O3 diagram lays at the edge of the composite region, i.e. galaxies that are characterised by both on-going star formation and AGN activity. Depending on the luminosity of the host AGN 
\[ L_{\text{AGN}} \] with respect to star formation 
\[ (f = L_{\text{AGN}}/L_{\text{sf}}) \], the representative points of sources in the composite region can tend more towards the SF 
\[ (f < 0.5) \] or AGN 
\[ (f > 0.5) \] areas. According to the position of our galaxy, the contribution of the AGN luminosity would be less than 0.5 times the one of SF. The composite locus is, however, an area of the diagnostic diagram that is not uniquely determined: theoretical models show that it can also be consistently populated by galaxies whose emission lines originate from shocks (the so-called shock-dominated galaxies, e.g. Hirschmann et al. 2019), as well as pure SF and AGN models (Gutkin et al. 2016; Feltre et al. 2016). Hence, it is difficult to pinpoint the mechanism that originates the observed UV lines. Nonetheless, by comparing the position of our target with the available theoretical models, we observe a higher compatibility of our estimates with the synthetic stellar models by Gutkin et al. (2016). This is also observed in the He2-O3C3 diagram where we do not have separation lines for the different mechanisms. However, we record a net separation between the AGN and star formation models, with the representative point of our galaxy laying in the area populated by the models by Gutkin et al. (2016).

A word of caution has to be spent, however, in interpreting the results presented in these diagnostics. In fact, the diagrams should be constructed considering the ratio of nebular lines only, i.e. lines emitted by the ionised ISM. However, the intensity of CIV can be affected by stellar absorption whereas the HeII emission can come from both stars and the ionised ISM (Brinchmann et al. 2008; Erb et al. 2010). This implies that both the CIV and HeII observed intensities should be corrected for these effects. The corrections would bring to an enhancement of the CIV flux and a decrease of the HeII intensity. In the pure AGN scenario there would be no need of such corrections for HeII (see Nakajima et al. 2018, and references therein). The CIV and HeII intensity used to construct the diagrams presented here have been directly obtained from the fit of the observed spectrum of our target. We are therefore assuming that the HeII flux is only originated by the ionised ISM, while the CIV is not affected by stellar absorption and by the possible presence of a P-Cygni profile originated by stellar winds. With the data at our disposal, we cannot apply any realistic flux correction to CIV and HeII. Besides, the corrections have been found to depend on several stellar population parameters as metallicity and age, as well as if binary stellar evolution is taken into account (Erb et al. 2010; Steidel et al. 2016). For completeness, however, we report with an arrow the general trend of the above-mentioned corrections in the corner of each panel (the length of the arrow along the two axis is not related to the relative strength of the correction). We highlight how, for all diagrams, the introduction of corrections in the CIV and HeII flux would move the representative point of our target even more towards the region of star-forming galaxies. Besides, we observe a net separation between our target and the population of HzRGs from Vernet et al. (2001) and Humphrey et al. (2008), as well as the sample of type-II quasars from Silva et al. (2020). This result reinforces the idea that our target is a star-forming galaxy.

### 4.4 Star formation rate

Assuming that our target is a star forming galaxy, we estimate its integrated star formation rate (SFR) in a two-fold way: from the luminosity of the Hydrogen Balmer lines, and from the luminosity of the stellar UV continuum. In both cases, we start from the recipes by Kennicutt (1998) modified for a Chabrier IMF 12.

For the Balmer lines, the original Kennicutt (1998) prescription is based on the direct conversion of the H\textalpha luminosity into SFR. The estimate that can be derived through this method allows us to probe the so-called instantaneous star formation, i.e. the galaxy star formation activity over its last 10 Myr. However, the H\textalpha line is out of the wavelength coverage of our data. To overcome this problem, we convert the H\textbeta flux into H\textbeta assuming case B recombination (Osterbrock & Ferland 2006)13. We derive a SFR = 10.7 ± 2.3 M\odot/yr.

Similarly, we derive the SFR from the rest-frame UV stellar continuum luminosity. Compared to the H\textalpha – SFR conversion, the UV – SFR relation is based on stronger assumptions, among which a continuous and well-behaved star formation history, ongoing typically for at least 100 Myr. Following Kennicutt (1998), we convert the galaxy rest-frame luminosity at 1500\AA, \[ L_{\nu}(1500\AA) \] to the rest-frame UV continuum with a power-law, see Section 4.1, and obtain \[ L_{\nu}(1500\AA) = (7.63 \pm 0.41) \times 10^{-27} \mathrm{erg} / \mathrm{s} / \mathrm{Hz} \] and a SFR = 0.64 ± 0.03 M\odot/yr. This estimate, however, does not take into account the correction for the contribution of the nebular UV continuum emission. Although typically weaker at the UV wavelengths than in the optical and near-infrared, the nebular continuum

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9 The models are available at http://www.iap.fr/neogal/models.html.
10 The line fluxes presented in the stellar models by Gutkin et al. (2016) are in units of solar bolometric luminosity (i.e. 3.826 \times 10^{33} \text{erg/s}) per unit SFR (in M\odot/yr), and assuming a constant SFR with a Chabrier IMF sustained for 10^9 yr.
11 The line fluxes presented in the AGN models by Feltre et al. (2016) correspond to an accretion luminosity of the central source of 10^{45} \text{erg/s}, and that line luminosities scale linearly with this quantity.
12 To transform from a Salpeter to a Chabrier IMF, we divide by a 1.7 factor.
13 According to case B recombination the intrinsic ratio H\textalpha/H\textbeta is equal to 2.74 for a T_e = 2 \times 10^4 \text{K} and n_e = 10^5 \text{cm}^{-3}.
If we assume \( T \) (Byler et al. 2017). By means of \( P/y.pcN/e.pc/b.pc \), the age of the stellar population emitting the ionising photons (Byler et al. 2018) and a sample of type-II quasars (in magenta, Silva et al. 2020). The blue stars show the area of the diagram populated by the stellar models by Gutkin et al. (2016). In a similar way, we present the ratio of nebular emissions for the AGN models by Feltre et al. (2016) with red squares. For both models, the size and colour of the representative points follow the convention presented in Figure 2. In both panels, the black arrow in the corner highlights the effect of a correction of the H\(\text{HeII}\)1640 and CIV1550 (only in the C4C3-C34 panel) emission. In the C4C3-C34 diagram, the demarcation lines are taken from Nakajima et al. (2018). In the C3-O3 diagram we resort to the separation lines by Hirschmann et al. (2019).

...transitions, and its contribution to the overall continuum emission depends on several physical parameters among which the ionisation parameter \( U \), the temperature of the emitting HII region, the nebular metallicity, the age of the stellar population emitting the ionising photons (Byler et al. 2017). By means of \( P/y.pcN/e.pc/b.pc \), the age of the stellar population emitting the ionising photons (Byler et al. 2018) and a sample of type-II quasars (in magenta, Silva et al. 2020). The blue stars show the area of the diagram populated by the stellar models by Gutkin et al. (2016). In a similar way, we present the ratio of nebular emissions for the AGN models by Feltre et al. (2016) with red squares. For both models, the size and colour of the representative points follow the convention presented in Figure 2. In both panels, the black arrow in the corner highlights the effect of a correction of the H\(\text{HeII}\)1640 and CIV1550 (only in the C4C3-C34 panel) emission. In the C4C3-C34 diagram, the demarcation lines are taken from Nakajima et al. (2018). In the C3-O3 diagram we resort to the separation lines by Hirschmann et al. (2019).

According to our measurements, the SFR(H\(\alpha\)) is about 18 times higher (28\% after correcting for the nebular emission) than the SFR(1500Å). This significant discrepancy is possibly due to the fact that the assumptions behind the conversion of the two tracers are not fully fulfilled. In particular, the conversion factor in the UV – SFR relation is known to be severely underestimated in the case of a young stellar population (\( \leq 10 \) Myr, e.g. Kennicutt 1998; Calzetti 2013). In this regard, the discrepancy between the SFR inferred from the Balmer lines and the UV could favour a bursty on-going star-formation against a steady state process scenario (e.g. Guo et al. 2016; Faisst et al. 2019; Atek et al. 2022). Additionally, deviations on the shape of the IMF and its mass limits, the stellar metallicity and the number of ionising photons produced can play an important role. To estimate the correction factor that should be taken into account when converting the UV luminosity into SFR in the case of a single burst star-formation history, we resort to the bpass1 models (v. 2.2.1 Eldridge et al. 2017; Stanway & Eldridge 2018). If we assume both a Chabrier and top-heavy IMF with an upper cut-off mass of 300 \( M_\odot \) and a sub-solar metallicity \( 10^{-3} \leq Z \leq 10^{-3} \), we obtain a correction factor to the L(UV) – SFR relation by Kennicutt (1998) of about 8 at 2-3 Myr, e.g. Figure 4. The magnitude of the correction decreases rapidly with time and shrinks down to a factor of about 2 at 10 Myr. In particular, the bpass tracks show that both more top-heavy IMFs and lower stellar metallicities increase the magnitude of the correction factor. A similar result is also recovered if we consider spectro-photometric synthetic models derived via the

\[ F_{nuc} = \frac{\gamma}{a_{H\beta} \cdot h_{H\beta}} \cdot F(H\beta) \]

where \( \gamma \) is the nebular continuum emissivity (in erg cm\(^{-3}\) s/Å) as estimated from \( P/y.pcN/e.pc/b.pc \). To estimate the monochromatic flux of the nebular continuum, we apply equation 15 in Fernández et al. (2018):
**4.5 Galaxy mass and stellar population age**

The absence of stellar continuum detection in SINFONI and of additional rest-frame optical and near-infrared (NIR) data prevents us from deriving a robust estimate of the stellar mass $M_\star$ for our target. However, despite being an indirect and uncertain method, we can infer an upper limit on $M_\star$ based on the mass – excitation diagram (ME$\xi$ diagram, Juneau et al. 2011). In fact, assuming that our galaxy is star forming, the ratio between the optical [OIII] doublet and H$\beta$ implies a maximum stellar mass on the order of $10^{9.5} M_\odot$. This puts our target in the typical mass range of LAEs (Ouchi et al. 2020; Pucha et al. 2022) and lensed galaxies at similar redshifts (e.g. Meštrić et al. 2022; Bouwens et al. 2022). Besides, this estimate agrees with the fact that low stellar mass galaxies tend to display larger SFR(Hα)/SFR(UV) ratios (Faisst et al. 2019; Atek et al. 2022).

We estimate the light-weighted age of the stellar population through the ratio between the H$\beta$ and UV continuum luminosity. This ratio is predicted to decrease with increasing stellar age. We derive theoretical tracks from both Starburst99 and BPASS. For our target, the ratio between the observed luminosities is equal to $log_{10}(L(H\beta)/L_\nu(1500Å)) = 1.92 \pm 0.10$, see Figure 4. If we account for the contribution of the nebular continuum, the estimate raises to $2.22 \pm 0.10$. In both cases, the retrieved values are above the Starburst99 and BPASS theoretical predictions. Only if we correct for reddening, our results become compatible with the tracks. Assuming the absolute value of $E(B-V) = 0.75$ (i.e. the upper-limit derived from the Balmer decrement Hγ/Hβ, see Section 4.1), we obtain stellar ages $\leq 10-20$ Myr.

**4.6 The Lyα emission**

In the following section, we present a detailed description of the spectral and spatial properties of the Lyα emission detected in our target.

**4.6.1 Spectral properties of the Lyα**

The spectral shape of the Lyα emission of our target is double peaked. We model each peak through the asymmetric Gaussian profile introduced by Shibuya et al. (2014b). From the best-fit model, we obtain a Lyα observed total flux of $(1.66 \pm 0.03) \times 10^{-17}$ erg/cm$^2$/s, corresponding to a total luminosity of $(2.14 \pm 0.02) \times 10^{42}$ erg/s. The ratio between the blue and red peak is of $\sim 14$ per cent. Since we do not detect any stellar continuum underneath the Lyα, we estimate a Lyα EW$_0 \leq 108$Å. This value is obtained by dividing the Lyα flux by the median value of the 1-$\sigma$ error in the spectral region covered by the Lyα line. The estimate is in agreement with the EW$_0$ of other Lyα emitters at similar redshifts and luminosities (e.g. Runholm et al. 2020b).

Despite the smooth spectral profile, we highlight that contributions from HeII$1215$ and the OV$11214, 1218$ doublet could partially affect the Lyα estimated flux, luminosity and EW$_0$. Theoretical models show that the contribution of the HeII and OV$1$ doublet varies as a function of several physical parameters: the power-law index of the ionising radiation, the nebular metallicity $Z_{ neb}$, the ionisation parameter $U$, and the presence and strength of HI absorptions (Humphrey 2019). According to these models and based on our target estimated nebular metallicity and ionisation parameter, the HeII and OV$1$ lines could contribute from 0.4 (optically thick models) to 8 per cent (optically thin models) to the total Lyα flux. For our object, in the case of an optically thin model, the contaminating flux would be mostly associated to the OV$1$ doublet since the HeII$1215$ flux is negligible ($F(\text{HeII1215}) = (0.28-0.33)\times F(\text{HeII1640}) \approx 6.8\times 10^{-20}$ erg/cm$^2$/s).

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**Figure 4.** Age versus L(H$\beta$)/L(1500Å) (left) and SFR(Hα)/SFR(1500Å) (right) ratios diagram. With dashed lines we present the theoretical tracks from Starburst99 for a Chabrier-like (blue) and top-heavy (red) IMFs. Following the same colour coding, the blue and red shaded areas depict the models from BPASS v. 2.2.1. The horizontal black line shows the observed L(H$\beta$)/L(1500Å) and SFR(Hα)/SFR(1500Å) ratios for our target and the grey shaded region is representative of its associated error. Similarly, in orange, we show the range of values obtained if we correct the observed ratios for nebular continuum emission. The coloured arrows highlight the ratios lower-limits of the aforementioned estimates in the case of dust extinction correction (assuming the upper-limit value $E(B-V) = 0.75$) with the attenuation curve by Calzetti et al. (2000). The horizontal dotted black line is representative of SFR(Hα)/SFR(1500Å) = 1. Finally, with a vertical black dash-dotted line we report the upper-limit on the age of the galaxy youngest stellar population (40 Myr) if we consider the results from the analysis of the (C/O) abundance, see Section 4.2.
erg/s/cm², i.e. 0.4 per cent of the Lyα flux). However, since we do not have direct evidence of the OV doublet in our spectrum and we cannot more robustly constrain its possible flux from the analysis of other lines (e.g. from NV/11240 or [NeV]/1575, Humphrey 2019), in the following we do not consider corrections to the reported Lyα flux, luminosity and EW₀.

The separation between the blue and red peak of the Lyα emission is \( \Delta v_{\text{peak}} \approx 459 \pm 38 \text{ km/s} \), with the red peak offset from the systemic velocity of 320±36 km/s. Following the results by Kakiichi & Gronke (2019), the estimated peak separation suggests a Lyman-continuum escape fraction \( f_{\text{esc}} \) of about 8 per cent. This is in good agreement with the global Lyα escape fraction typically observed at \( z \approx 3-4 \) (e.g. Hayes et al. 2011). Besides, this estimate appears to be consistent with other objects with similar EW₀ (e.g. Erb et al. 2016) and with the \( f_{\text{esc}} \) – EW₀ correlation after having properly taken into account the impact of the target’s ionising efficiency \( \xi_{\text{ion}} \) (\( \xi_{\text{ion}} = 1.3 \times 10^{25} \text{ SFR(H\alpha)/SFR(UV)} \text{ Hz/erg}; \) see Sobral & Matthee 2019, and their Equation 6, for further details). Interestingly, if we hypothesise that the tension between the theoretical and the observed Lyα/EHβ ratios is only due to dust extinction, we would estimate a colour excess \( E(B-V)_{\text{Ly}\alpha} = 0.38 \pm 0.03 \) (adopting the attenuation curve by Calzetti et al. 2000) quite in agreement with the nebular colour excess \( E(B-V)_{\text{HII}} \) that we estimated from the Hγ/Hβ ratio (0.34±0.41, see Section 4.1).

We apply radiative transfer modelling to the Lyα emission to infer the ISM metal and dust content (e.g. Charlot & Fall 1993), HI and HII regions relative geometries, the kinematics of the neutral gas (e.g. Verhamme et al. 2006; Laursen & Sommer-Larsen 2007) directly from the profile of the Lyα line. We applied an updated version of the pipeline introduced by Gronke et al. (2015), implementing 12960 radiative transfer models derived by means of the code tLaC (Gronke & Dijkstra 2014). The radiative transfer models we adopt are "shell-models" (e.g. Ahn & Lee 2002; Verhamme et al. 2006), i.e. they consist of a single point-like source emitting Lyα and continuum radiation and surrounded by a shell of neutral hydrogen, and dust. Because of their simple geometry, only four parameters are needed to fully describe these models: the shells neutral hydrogen column density \( N_{\text{HI}} \), their expansion velocity \( v_{\text{exp}} \) (assuming positive values for outflows, negative in the case of inflows), an (effective) temperature \( T \) that includes the effects of small-scale turbulence, and the dust optical depth \( \tau_d \) to parametrise the dust content. Finally, the emitted Lyα is assumed to have an intrinsic Gaussian emission characterised by an intrinsic Lyα equivalent width \( EW_{\text{int}} \), and its width \( \sigma_{\text{int}} \). We carry out the fitting in wavelength space with a Gaussian prior on the redshift \( z \) and after degrading the synthetic spectrum to the MUSE spectral resolution at the observed Lyα wavelength (derived from equation 8 in Bacon et al. 2017). According to the best-fit model, for the shell we obtain \( \log_{10}(N_{\text{HI}}/(\text{cm}^{-2})) = 16.8 \pm 0.2 \), \( v_{\text{exp}} = 99 \pm 5 \text{ km/s} \), \( \log_{10}(T[\text{K}]) = 5.3 \pm 0.2 \) and \( \tau_d = 0.6 \pm 0.2 \), while the Lyα intrinsic emission has \( EW_{\text{int}} = -415 \pm 12 \text{ Å} \) and \( \sigma_{\text{int}} = 210 \pm 4 \text{ km/s} \). As already pointed out in recent literature (e.g. Orličová et al. 2018), the intrinsic width of Lyα recovered by the radiative transfer model results to be significantly larger than the one of the Balmer lines (for our target a factor ~ 3.4 larger if compared to our estimate of the Hβ line, in line with the results from Orličová et al. 2018). According to Li & Gronke (2022), however, this discrepancy is most likely due to additional radiative transfer effects and, in particular, the possibility that the Lyα propagates within a clumpy gas distribution with velocity dispersions \( \gtrsim 100 \text{ km/s} \).

Since ‘shell-models’ are an oversimplification of the complex structure and kinematics of Lyα-emitters and their surroundings, it is currently debated how much of the radiative transfer is indeed captured by the models and the real meaning and reliability of the involved parameters, especially \( T \) and \( \tau_d \). At the same time, it has been shown that the outflow velocity \( v_{\text{exp}} \) and column density of the ‘shell-model’ \( N_{\text{HI}} \) correlate well with the ones of a more realistic multi-phase medium (Gronke & Dijkstra 2016), thus making the estimate of these two parameters particularly robust. We report the results obtained from the analysis of the Lyα spectral properties in Table 3.

Finally, we investigate the presence of spatial variations and kinematics patterns in the Lyα spectral shape (e.g. Patricio et al. 2016; Smit et al. 2017; Erb et al. 2018; Claeysens et al. 2019; Leclercq et al. 2020). To this aim, we extract the 1st moment map of the Lyα spectral distribution as well as the 0th moment maps created directly from the profile of the Lyα line. From both methods, we find no coherent kinematic pattern. To increase the SNR of the profiles, we decide to compare the integrated Lyα spectrum extracted within a circular aperture (0.4″ radius) centred at the peak position of the Lyα emission with the Lyα profile observed in the outskirts (circular annulus 0.4″ – 0.8″). Also in this case, we do not find any difference in the Lyα profile shape of the two regions and in contrast with results from recent studies of other lensed LAEs (e.g. Claeysens et al. 2019; Chen et al. 2021).

| Parameter | Value |
|-----------|-------|
| \( F(\text{Ly}\alpha) \) [erg/s/cm²] | (1.66 ± 0.03) \times 10^{44} |
| \( L(\text{Ly}\alpha) \) [erg/s] | (2.14 ± 0.02) \times 10^{42} |
| \( f_{\text{blue/peak}}/f_{\text{red/peak}} \) | ~ 14% |
| EW₀ [Å] | ≤ 108 |
| \( \Delta v_{\text{env}} \) [km/s] | 459 ± 38 |
| \( \Delta v_{\text{red/peak}} \) [km/s] | 320 ± 36 |
| \( f_{\text{esc}} \) [Lyα] | 0.08 ± 0.02 |
| \( f_{\text{esc}} \) [CIV] | < 15% |
| \( \log_{10}(N_{\text{HI}}/(\text{cm}^{-2})) \) | 16.8 ± 0.2 |
| \( v_{\text{exp}} \) [km/s] | 99 ± 5 |
| \( \log_{10}(T[\text{K}]) \) | 5.3 ± 0.2 |
| \( \tau_d \) | 0.6 ± 0.2 |
| \( EW_{\text{int}} \) [Å] | –415 ± 12 |
| \( \sigma_{\text{int}} \) [km/s] | 210 ± 4 |

Table 3. Table of the results from the line fitting procedure and tLaC radiative transfer modelling of the target Lyα emission, see Section 4.6.1. The line flux \( F(\text{Ly}\alpha) \) and luminosity \( L(\text{Ly}\alpha) \) are corrected for magnification but not for dust extinction.
4.6.2 Spatial extent of the Ly$\alpha$

Following the procedure described in Section 3.1, we extract the pseudo-NB images of the strongest emission lines of our target, see top panels in Figure 5. We also create a pseudo-NB image of the galaxy UV continuum emission by collapsing the MUSE datacube in the wavelength windows within which we measured the UV $\beta$-slope, see Table 2 Section 4.1, and stacking them together. Similarly, to increase the SNR of the emission line images we stack the intensity maps of the doublets of the optical (OIII). We also stack together the maps of the two Balmer transitions available, i.e. H$\beta$ and H$\gamma$. Because of the different spatial resolution of the MUSE and SINFONI data, we degrade the resolution of the SINFONI pseudo-NB images to match the one of MUSE. To do so, we first convolve the SINFONI images with a Gaussian kernel to match the MUSE PSF, and then we resample them to the MUSE standard spatial sampling, i.e. 0.2″ × 0.2″.

Several statistical studies have shown the existence of an offset between the centroid of the Ly$\alpha$ and UV continuum emission $\delta_{Ly\alpha}$ (e.g. Bunker et al. 2000; Fynbo et al. 2001; Shibuya et al. 2014a; Hoag et al. 2019; Ribeiro et al. 2020; Claeyssens et al. 2022). Theoretical studies based on the 3D modelling of Ly$\alpha$ radiative transfer in disk galaxies (e.g. Laursen & Sommer-Larsen 2007; Verhamme et al. 2012; Zheng & Wallace 2014) ascribe the Ly$\alpha$ UV offset to the easier escape and propagation of Ly$\alpha$ photons perpendicularly to the galaxy disk. In this case, the presence of an offset could be explained as a consequence of the viewing angle under which the observer sees the target. Interestingly, Claeyssens et al. (2022) report how the presence of an offset between the galaxy UV emission and the Ly$\alpha$ could also be linked to the mechanism originating the Ly$\alpha$ emission. In the case of small offsets (whenever the Ly$\alpha$ centroid is within the effective radius of the UV emission), Claeyssens et al. (2022) suggest that the offset likely originates from substructures detectable in the UV, such as an off-center star-forming clump. In the case of larger offsets, other mechanisms could be invoked: gas inflows, scattering effects of the Ly$\alpha$ photons in the CGM, extinction, fluorescence, emission from faint satellites. To investigate this, we resort to the galfit software (Peng et al. 2010). We model the multiple images M2 and M3 of our target simultaneously in both the Ly$\alpha$ and UV continuum map. For each multiple image, we use a single Sérsic profile and obtain smooth residual maps (normalised residuals < 20%). From the galfit best-fit, we estimate an offset between the centroids of the Ly$\alpha$ and UV continuum $\delta_{Ly\alpha} = 0.18 \pm 0.02$ arcsec that corresponds to 1.30 ± 0.17 pkpc. If we correct for magnification, we obtain an intrinsic offset results in 0.43 ± 0.07 pkpc. This estimate is in very good agreement with the recent results presented by Claeyssens et al. (2022) who found a median value for the separation of the Ly$\alpha$ and UV continuum centroids of $\delta_{Ly\alpha} = 0.58 \pm 0.14$ pkpc in the analysis of 603 lensed Ly$\alpha$-emitters in the redshift interval 2.9 < z < 6.7. In addition, our estimate is also in line with the findings by Hoag et al. (2019) and Ribeiro et al. (2020) for Ly$\alpha$-emitters at similar redshifts. Besides, the low $\delta_{Ly\alpha}$ value is in trend with the observed Ly$\alpha$ EW$\alpha$ – $\delta_{Ly\alpha}$ anti-correlation (e.g. Shibuya et al. 2014b; Hoag et al. 2019). Hence, following Claeyssens et al. (2022), the observed offset in our target could be the consequence of an off-centre star-forming clump harboured in our target.

Additionally, we investigate the surface brightness (SB) profiles of UV lines and continuum. From each pseudo-NB image, we extract the radial SB profile within concentric apertures centred at the peak of the UV continuum emission and with increasing radii (in steps of 0.2″) from 0.2″ out to 1.4″ (Figure 5). The UV and optical lines and the UV continuum appear to be all spatially resolved, having a larger spatial extent than the MUSE PSF. In particular, the Ly$\alpha$ and UV continuum are the most spatially extended. By fitting the Ly$\alpha$ SB with an exponential function, i.e. $SB(r) = C_\alpha \exp(-r/r_\alpha)$, we obtain a scale length $r_\alpha$ for the Ly$\alpha$ nebula of $r_\alpha(Ly\alpha) = (0.49 \pm 0.01)$″. If we convert into physical kpc and correct for magnification, we infer $r_\alpha(Ly\alpha) \approx 1.2$ pkpc (not corrected for PSF). This value is in good-agreement with the typical scale length estimates for Ly$\alpha$ halos and with the $r_n = L(Ly\alpha)$ correlation (e.g. figure 13 in Ouchi et al. 2020, and references therein). If we apply the exponential model to the UV continuum and MUSE lines we derive $r_n(UV) = (0.38 \pm 0.02)$″ = 1pkpc and $r_n(H) = (0.25 \pm 0.02)$″ = 0.65pkpc. According to the $r_n$ values and the trend of the SB profiles presented in Figure 5, the Ly$\alpha$ and UV continuum extend more than the Balmer lines.

5 MULTI-WAVELENGTH AND DISCUSSION

The multi-wavelength analysis of our target highlights that A2895b is a lensed Lyman-α emitter at $z \approx 3.721$ with a compact UV morphology ($r_n \approx 1.2$ pkpc) and a Ly$\alpha$ luminosity of $L(\Lyalpha) = 2 \times 10^{42}$ erg/s. In particular, A2895b is a star-forming galaxy with a SFR estimated from the conversion of the H$\beta$ luminosity of 10.7 ± 2.3 M$_\odot$/yr. The MEX diagram (Juneau et al. 2011) suggests that our target has a stellar mass smaller than 10$^{9.5}$ M$_\odot$. If we consider the upper-limit on the stellar mass and the above SFR, A2895b populates a region of the $M_\ast -$ SFR plane above the main-sequence of star-forming galaxies at $2.8 < z < 4$ (Rinaldi et al. 2022), with a lower-limit on its specific SFR of about 3.5 × 10$^{-9}$ yr$^{-1}$. This suggest that our target is likely to be a starbursting system.

From the analysis of the nebular UV line ratios, their shape and width, and the absence of an X-ray counterpart (see Section 4.3), we exclude the presence of an AGN. In this regard, the diagnostic diagrams based on UV line ratios clearly show a net separation between the typical values observed in high-$z$ radio galaxies (e.g. Vernet et al. 2001; Humphrey et al. 2008) and type-II quasars (Silva et al. 2020), as well as from theoretical predictions of AGNs narrow-line regions (Feltre et al. 2016). This result is also in line with the fact that LAEs hosting AGNs are typically characterised by a Ly$\alpha$ luminosity $L(Ly\alpha) \gtrsim 2.5 \times 10^{43}$ erg/s, i.e. one order of magnitude above the diagram of our target (e.g. Konno et al. 2016).

Based on these findings, in-situ star-formation results to be a good candidate for explaining the Ly$\alpha$ emission of our target, whereas we disfavour AGN activity. We also exclude scenarios of both shock heating due to outflows and gravitational cooling. In fact, these processes not only are typically expected to contribute to the Ly$\alpha$ emission at $z \approx 20$ pkpc from the galaxy centre (e.g. Mas-Ribas et al. 2017, and references therein), but also significantly increase the number of collisional excitations of the hydrogen atoms, thus bringing to an increase in the measured Ly$\alpha$/H$\beta$ ratio with respect to what predicted by case B recombination (super case B objects, e.g. Oti-Floranes et al. 2012; Nakajima et al. 2013). Specifically, in the case of a significant contribution to the Ly$\alpha$ emission from inflowing gas accreted onto the central galaxy (i.e. gravitational cooling, e.g. Haiman et al. 2000; Kereš et al. 2005; Dekel & Birnboim 2006; Shull et al. 2009), the Ly$\alpha$/H$\beta$ ratio is expected to exceed the case B value of more than a factor of 10 (e.g. Dijkstra 2014). Nonetheless, for our target we estimate a Ly$\alpha$/H$\beta$ ratio 13 times smaller than the case B value, i.e. 1-2 orders of magnitudes below the predictions for shock heating.
heating and gravitational cooling (see Section 4.6.1). Besides, for the gravitational cooling hypothesis, signatures of Lyα cooling radiation should be found by the analysis of the Lyα EW. In fact, in this case the Lyα intrinsic EW is expected to exceed the maximum predictions for ‘regular’ star-formation activity (i.e. 300 – 400 Å in modulus, e.g. Kashikawa et al. 2012). Also in this regard, we do not need to resort to gravitational cooling to explain our measurements (EW_{\text{int}} = -415 \pm 12 \text{ Å}). We highlight, however, that the details of the Lyα emission via gravitational cooling are still debated and remain uncertain (Yang et al. 2006; Dijkstra & Loeb 2009; Faucher-Giguère et al. 2010; Cantalupo et al. 2012; Lake et al. 2015). Ultimately, we discard the hypothesis of fluorescence due to ex-situ star-formation activity (e.g. from satellite sources), or background sources (QSOs), since we do not find evidence of spectral features of these additional systems in our UV and optical spectra.

The analysis of the spatial extent of the UV continuum, Lyα and Balmer lines (see Section 4.6.2) arises some interesting points. For our target, the UV continuum and Lyα emissions are more extended than the optical hydrogen transitions Hβ+Hγ. While a more extended Lyα SB profile with respect to the Balmer lines could be the consequence of resonant scattering, the fact that the UV continuum is more extended than the Balmer lines is more puzzling and seems to further provide evidence against fluorescence. In fact, while nebular UV continuum emission follows recombination processes in the ISM, Balmer lines arise from both recombination and fluorescence. Hence, we would expect the nebular UV continuum emission to be more compact than the Balmer lines. A possible way to explain this finding is to consider that the extended UV emission observed originates from an unobscured stellar population with age 20 – 100 Myr. The existence of such stellar population seems to be supported by the very blue β-slope of our target (β = −2.6 ± 0.5, see Section 4.1). If so, A2895b would be hosting (at least) two stellar populations: a newly born population of stars (≤ 10 Myr) traced by the Balmer lines, and a more extended, ‘older’ and unobscured stellar population. In this case, the extended Lyα emission could arise from resonant scattering of the Lyα photons produced in the star-forming regions. Interestingly, the presence of two populations could also alleviate the discrepancy of the face value between the dust colour extinction estimated from the UV continuum and Balmer decrement (e.g. dust selective extinction, Calzetti et al. 1994), along with the partial remaining tension between the ratio L(Hβ)/L(UV) and the theoretical stellar models from bpass and starburst99 calculated in the case of top-heavy IMF and sub-solar metallicities, see Section 4.5.

To verify this hypothesis, deeper observations targeting the galaxy rest-frame optical and IR emission are needed. Such follow up could also explain the small Lyα offset (δ_{LYα} ≈ 0.6 pkpc) detected with respect to the UV continuum and Balmer lines. In fact, if δ_{LYα} is a consequence of an off-centre star-forming clump (e.g. Claeyssens et al. 2022), we would expect the Lyα peak to be coincident with the peak of the Balmer lines. However, this discrepancy could be a mere effect of how the astrometry of the SINFONI dataset has been registered to MUSE. As explained in Section 2.2, we registered the SINFONI astrometry to the MUSE one by minimising the spatial offset between the centroid of the optical [OIII] emission and the target UV continuum. By doing so, we also overlapped the centre of the optical and UV [OIII] emissions. We followed this procedure since no other target falls within the SINFONI FoV and the optical continuum of our source is undetected. In this sense, rest-frame optical observations with a more robust astrometry could shed light on this aspect.
6 CONCLUSIONS

In this paper, we presented a detailed study of the integrated UV and optical properties of A2895b, a lensed Ly\(\alpha\)-emitter at \(z \approx 3.721\) in the background of the A2895 galaxy cluster. The analysis was based on the AO-assisted integral field spectroscopy of MUSE and SINFONI. From our study, we inferred that:

(i) our target has a steep blue UV continuum \((\beta = -2.6 \pm 0.5)\). Such blue continuum is possibly the sign of a young, unobscured stellar population.

(ii) the analysis of the shape of spectral lines along with empirical diagnostic diagrams based on UV line ratios (C4C3-C34, C3-O3, He2-03C3) suggests that our target is a star-forming galaxy with a current star-formation rate \(SFR = 10.7 \pm 2.3 \, M_\odot/yr\) (from the H\(\beta\) line luminosity, Kennicutt 1998). We exclude the presence of an AGN harboured in the galaxy centre.

(iii) the galaxy has a sub-solar nebular metallicity \(Z = 0.05 \pm 0.02Z_\odot\) (He2-03C3 diagram Byler et al. 2020) and \((\mathrm{C/O})\) abundance \((\approx 0.23\, (\mathrm{C/O})_\odot)\). While the measured metallicity suggests a short star formation history, the low \((\mathrm{C/O})\) value can be explained by both an over-abundance of massive O-type stars, hence, a top-heavy IMF, and a very recent burst of star-formation \((<< 40 \, \text{Myr})\).

(iv) we find a significant discrepancy between the luminosity of the UV continuum at 1500 \(\AA\) and the H\(\beta\) line. Stellar models (e.g. BPASS, Starburst99) seem to explain this tension only in the case of a young stellar population \((< 10 \, \text{Myr})\) with low-metallicity \((Z \approx 10^{-4})\) and that formed following a top-heavy IMF. To some extent, the introduction of dust extinction tends to alleviate the tension even further.

(v) the Ly\(\alpha\) emission of our target is double-peaked and has a total luminosity (not corrected for extinction) of \(\approx 2 \times 10^{42} \, \text{erg/s}\). The low value of the observed Ly\(\alpha/\text{H}\beta\) ratio \((\text{Ly}\alpha/\text{H}\beta \approx 2.4 \pm 0.5)\) with respect to case B recombination tend to exclude the hypothesis that the galaxy Ly\(\alpha\) emission originates from outflows (shock heating) and gravitational cooling. This is also supported by the Ly\(\alpha\) intrinsic equivalent width \(\approx 130\) \(\AA\) (obtained by modelling the Ly\(\alpha\) emission via radiative transfer ‘shell-models’, e.g. Gronke & Dijkstra 2014) that is in line with the typical values in the case of star-formation (i.e. \(300 - 400 \, \text{Å}\) in modulus).

(vi) The Ly\(\alpha\) is offset \(\delta_1(\text{Ly}\alpha) \approx 0.6 \, \text{pkpc}\) from the UV continuum and Balmer lines. The spatial extent of the Ly\(\alpha\) emission is comparable to the UV continuum while it is more extended than the Balmer emission (a factor about 2). The different extent of the emissions seems to suggest that while the UV emission traces a more extended region inhabited by an older and less extincted stellar population (10-100 Myr), the Balmer lines arise from regions of on-going star-formation \((\leq 10 \, \text{Myr})\). This could happen if phenomenon of fluorescence of H\(\beta\) and H\(\gamma\) can be neglected, i.e. in the case of a low escaping fraction of ionising radiation from the production regions of the Balmer lines. In this scenario, the Ly\(\alpha\) extended emission would be just the consequence of resonant scattering from its region of production, an HII region.

The work presented in this paper shows the power of a multi-wavelength analysis in the characterisation of galaxy properties. In particular, how the combination of rest-frame UV and optical information can help in tackling long-standing issues such as the origin of the Ly\(\alpha\) emission within galaxies. So far, technical limitations (e.g. coarse spatial resolution, depth, limited field-of-view) have significantly limited such studies to small samples of objects (e.g. Nakajima et al. 2013; Erb et al. 2016; Trainor et al. 2019; Runnholm et al. 2020a; Weiss et al. 2021; Matthee et al. 2021; Reddy et al. 2022; Pucha et al. 2022). In this regard, the James Webb Space Telescope (JWST), and in particular the on-board Near Infrared Spectrograph (NIRSpec, Jakobsen et al. 2022), will be able to extend these studies to statistical samples of galaxies at intermediate redshifts, thus possibly providing us some definitive answers.

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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Scrutiny of a young, metal-poor LAE at \(z \approx 3.7\)
During the analysis of the MUSE dataset in our hands, we detected five LAEs in addition to our target and the already known system at $z \approx 3.7$ (e.g. Livermore et al. 2015; Iani et al. 2021). Among the newly discovered sources, we found two multiply-imaged systems (at $z \approx 4.65$ and $z \approx 4.92$), and three single-imaged LAEs (at $z \approx 4.57$ and $z \approx 4.92$). According to the shape of their Ly$\alpha$ emission and their spatial position, we exclude the hypothesis that the single-imaged LAEs at $z \approx 4.92$ are additional images of the multiply-imaged system at the same redshift. In Table A1 we provide the spatial coordinates of these targets and a rough estimate of their redshift. For the nomenclature of these targets, we follow the naming adopted by Livermore et al. (2015). We present MUSE cutouts for the Ly$\alpha$ and UV continuum emission of each new target and related multiple images, as well as a zoomed-in image of their UV spectrum around the Ly$\alpha$ line.
Scrutiny of a young, metal-poor LAE at $z \approx 3.7$
Table A1. Approximate redshift and spatial coordinates of the LAEs serendipitously detected in the MUSE observations of the A2895 galaxy cluster. We also report the possible presence of a possible counterpart in the available HST ACS/WFC F606W image.

| LAE    | $z$     | $\alpha_{J2000,0}$ | $\delta_{J2000,0}$ | $\alpha_{J2000,0}$ | $\delta_{J2000,0}$ | $\alpha_{J2000,0}$ | $\delta_{J2000,0}$ | $HST$-detected |
|--------|---------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|----------------|
| A2895a | 3.395   | 01:18:11.190        | -26:58:04.40        | 01:18:10.890        | -26:58:07.50        | 01:18:10.570        | -26:58:20.50        | y               |
| A2895b | 3.721   | 01:18:11.127        | -26:57:59.36        | 01:18:10.543        | -26:58:10.56        | 01:18:10.439        | -26:58:14.36        | y               |
| A2895c | 4.57    | 01:18:09.151        | -26:57:47.82        | -                     | -                    | -                     | -                    | n               |
| A2895d | 4.65    | 01:18:11.127        | -26:57:59.56        | 01:18:10.304        | -26:58:10.96        | -                     | -                    | n               |
| A2895e | 4.92    | 01:18:10.887        | -26:57:58.56        | 01:18:10.783        | -26:57:58.96        | 01:18:10.319        | -26:58:08.36        | n               |
| A2895f | 4.92    | 01:18:09.465        | -26:57:51.82        | -                     | -                    | -                     | -                    | n               |
| A2895g | 4.92    | 01:18:12.532        | -26:58:38.82        | -                     | -                    | -                     | -                    | n               |