MIDIS

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MIDIS: JWST NIRCam and MIRI Unveil the Stellar Population Properties of Lyα Emitters and Lyman-break Galaxies at $z \simeq 3–7$

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Abstract

We study the stellar population properties of 182 spectroscopically confirmed (MUSE/VLT) Lyα emitters (LAEs) and 450 photometrically selected Lyman-break galaxies (LBGs) at $z = 2.8–6.7$ in the Hubble Extreme Deep Field. Leveraging the combined power of Hubble Space Telescope and JWST NIRCam and MIRI observations, we analyze their rest-frame UV-through-near-IR spectral energy distributions, with MIRI playing a crucial role in robustly assessing the LAEs’ stellar masses and ages. Our LAEs are low-mass objects (log$_{10}(M_\odot / M_\odot) \approx 7.5$) with little or no dust extinction ($E(B-V) \approx 0.1$) and a blue UV continuum slope ($\beta \approx -2.2$). While 75% of our LAEs are young ($\approx 100$ Myr), the remaining 25% have significantly older stellar populations ($\gtrsim 100$ Myr). These old LAEs are statistically more massive, less extinct, and have lower specific star formation rate than young LAEs. Besides, they populate the plane of $M_\star$ versus star formation rate along the main sequence of star-forming galaxies, while young LAEs populate the starburst region. The comparison between the LAEs’ properties and those of a stellar-mass-matched sample of LBGs shows no statistical difference between these objects, except for the LBGs’ redder UV continuum slope and marginally larger $E(B-V)$ values. Interestingly, 48% of the LBGs have ages $<10$ Myr and are classified as starbursts, but lack detectable Lyα emission. This is likely due to H1 resonant scattering and/or dust-selective extinction. Overall, we find that JWST observations are crucial in determining the properties of LAEs and shedding light on their comparison with LBGs.

Unified Astronomy Thesaurus concepts: Lyman-alpha galaxies (978); Lyman-break galaxies (979); Galaxy evolution (594); Infrared telescopes (794)

1. Introduction

The Lyα line (Lyman 1906) is the brightest emission line produced by hydrogen electronic transitions, having an energy of 10.2 eV and a wavelength of 1215.67 Å. Given that approximately 74% of the baryonic matter in the Universe is thought to consist of hydrogen atoms (e.g., Croswell 1996; Carroll & Ostlie 2006), this ultraviolet (UV) transition emerges as a highly effective tool for detecting galaxies due to its brightness. This is particularly advantageous at intermediate to high redshifts ($z \gtrsim 2$–3) because the Lyα UV rest-frame wavelength undergoes a cosmological redshift, shifting it into the optical and near-infrared (NIR) regions of the electromagnetic spectrum. This shift enables convenient observations using both ground-based and space-based facilities.
Galaxies detected thanks to their Ly\(\alpha\) emission are generally referred to as Ly\(\alpha\) emitters (LAEs, e.g., Ouchi et al. 2020). The Ly\(\alpha\) detection can be direct, whenever based on spectroscopic data sets (e.g., Herenz et al. 2017, 2019; Claeysens et al. 2022; Bacon et al. 2023), or indirect, when inferred from narrowband photometry (e.g., Ouchi et al. 2008, 2010, 2018; Ota et al. 2010, 2017; Shibuya et al. 2012; Konno et al. 2014; Santos et al. 2016; Zheng et al. 2017; Arrabal Haro et al. 2018). In the last decades, studies have thoroughly investigated the rest-frame UV physical properties of intermediate/high-redshift LAEs, mainly leveraging on the available optical spectroscopy and imaging. This allowed astronomers to find that, in the absence of an active galactic nucleus (AGN), LAEs are low-mass star-forming galaxies (SFGs; stellar mass \(M_\ast \lesssim 10^8 M_\odot\)), with young stellar populations (stellar ages \(\approx 10\) Myr) and star formation rates SFR \(\simeq 1-10 M_\odot\) yr\(^{-1}\) (e.g., Nakajima et al. 2012; Hagen et al. 2014, 2016). Besides, LAEs were found to be dust-poor galaxies with stellar and nebular color extinction values \(E(B-V) \simeq 0-0.2\) (Ono et al. 2010; Kojima et al. 2017) and a subsolar gas-phase metallicity \(Z \lesssim 0.1-0.5 Z_\odot\) (derived from both strong lines and direct electron temperature \(T_e\) methods, e.g., Finkelstein et al. 2011; Nakajima et al. 2012; Trainor et al. 2016; Kojima et al. 2017).

The coarser spatial resolution and sensitivity of the available near- and mid-infrared (MIR) instrumentation at the time (e.g., Spitzer) strongly limited the analysis of the LAEs’ rest-frame optical/NIR properties at \(z \gtrsim 2-3\). Since the rest-frame UV emission of galaxies is known to trace the youngest, brightest, and less obscured stellar populations within a galaxy, our overall general interpretation of the properties of LAEs could be possibly biased. In this regard, a few observational studies highlighted that some LAEs appear to have an underlying stellar population older than what is generally found, with ages significantly above 100 Myr (Lai et al. 2008; Finkelstein et al. 2009; Pentericci et al. 2009; Nilsson et al. 2009; Rosani et al. 2020), thus suggesting the existence of two classes of LAEs already at intermediate/high redshift. Theoretical studies advocate that these two classes of LAEs are the consequence of catching these galaxies in different stages of their evolution (e.g., Shimizu & Umemura 2010): while LAEs hosting a young stellar population (<100 Myr) would be early coeval starbursts due to the contemporary accretion of subhaloes in a young small parent halo (primeval galaxies), LAEs with an underlying old stellar age (>100 Myr) could be delayed starbursts triggered by later subhalo accretion onto evolved haloes (rejuvenation).

Contextually, strong debates took place to understand whether LAEs have or have not different physical properties to SFGs at similar redshifts that do not display Ly\(\alpha\) emission. In the recent literature (e.g., Dayal & Ferrara 2012; Arrabal Haro et al. 2020; de La Vieuville et al. 2020), these galaxies are often referred to as Lyman-break galaxies (LBGs) since they are typically found on the basis of broadband photometry via the Lyman-break technique (Steidel et al. 1996) and spectral energy distribution (SED) fitting methods. On this topic, in the last two decades, both observational and theoretical studies have reached different conclusions. While some works have found no substantial difference between LAEs and LBGs (e.g., Dayal & Ferrara 2012), others found LBGs to have higher stellar mass with less rapid star formation than LAEs (e.g., Gaivalisco 2002; Gawiser et al. 2006).

Today, thanks to the Near-Infrared Camera (NIRCam; Rieke et al. 2005) and Mid-Infrared Instrument (MIRI; Rieke et al. 2015; Wright et al. 2015) on board the James Webb Space Telescope (JWST), we can finally address these open questions by inquiring into the nature of LAEs and LBGs at \(z \gtrsim 3\) and understand their similarities and/or differences. In this sense, the unprecedented spatial resolution and depth reached by MIRI imaging at wavelengths \(\gtrsim 5.6\) \(\mu m\) play a crucial role in the detection of these sources’ optical/near-infrared rest-frame emission (Wright et al. 2023). In particular, between \(z = 2.8\) and 6.7, the imaging at \(5.6\) \(\mu m\) allows for the characterization of the stellar optical emission in the range \(\lambda \approx 0.7-1.5\) \(\mu m\), i.e., reedward of the hydrogen Balmer transition of H\(\alpha\) at 6562.8 Å. Probing a region of the optical spectrum not affected by strong emission lines ensures a much more robust determination of the physical properties of a galaxy (e.g., Papovich et al. 2023).

In this paper, we present our findings on the physical properties of the stellar populations of a sample of 182 LAEs at redshift \(z = 2.8-6.7\) identified in the Hubble Extreme Deep Field (XDF, Illingworth et al. 2013) with the Multi Unit Spectroscopic Explorer (MUSE, Bacon et al. 2010) at the Very Large Telescope (VLT). This analysis takes advantage of the synergy between archival Hubble Space Telescope (HST) and the latest JWST observations to constrain the SED of these sources. In addition, we present a comparison of the properties of our sample of LAEs to those of a sample of 450 photometrically selected LBGs in the same field and redshift range.

Throughout this paper, we consider a flat \(\Lambda\)CDM cosmology with \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\), \(\Omega_M = 0.3\), and \(\Omega_b = 0.7\). All magnitudes are total and refer to the AB system (Oke & Gunn 1983). Finally, we assume a Chabrier (2003) initial mass function (IMF).

2. Data

The XDF \((\alpha_{1200} = 3^h32^m38.5^s, \delta_{1200} = -27^\circ 47'00''\); Illingworth et al. 2013) is a small field of the sky with the deepest HST observations ever taken since this telescope started operations more than 30 years ago. This field has been the main window for studying the early Universe before the advent of JWST, with numerous works scientifically exploiting its unique possibilities. Now, in the JWST era, the HST data in the XDF and surroundings are being enhanced with deep imaging and spectroscopy obtained with JWST/NIRCam and MIRI, extending the wavelength coverage of high-spatial-resolution observations to the near- and mid-infrared. In addition to this rich photometric data set, the XDF has been the target of extended spectroscopic campaigns including the observations with MUSE at VLT. These observations have provided thousands of spectra for sources up to \(z \approx 6.7\). In this section, we briefly describe the data set used for our study, which includes MUSE spectroscopy, and imaging from both HST (Advanced Camera for Surveys (ACS) and WFC3) and JWST (NIRCam and MIRI).\(^{23}\)

\(^{23}\) All the HST and JWST data used in this paper can be found in the Mikulski Archive for Space Telescopes (MAST); the Hubble Legacy Fields Data Release V2.5 (Illingworth 2015), the JWST Advanced Deep Extragalactic Survey (JADES) DR1 (Rieke et al. 2023a), the JWST First Reionization Epoch Spectroscopic Complete (FRESCO) Survey (Oesch & Magee 2023), the JWST Extragalactic Medium-band Survey (JEMS; Williams et al. 2023a), and all of the MIRI HUDF Deep Imaging Survey (MIDIS) 5.6 \(\mu m\) imaging at doi:10.17909/5sxh-pj89.
2.1. VLT/MUSE

The XDF has been extensively studied with VLT/MUSE over the past nine years as part of the MOSAIC and UDF-10 fields (Guaranteed Time Observations (GTO) programs 094.A-0289(B), 095.A-0010(A), 096.A-0045(A), and 096.A-0045(B), PI: R. Bacon), and the most recent MXDF observations (GTO Large Program 1101.A-0127, PI: R. Bacon). For more details about the observations related to the MOSAIC and UDF-10 fields, we refer to Bacon et al. (2017), while we point the reader to Bacon et al. (2023) for a thorough explanation of the MXDF program.

In brief, the three programs covered the XDF area with MUSE observations in wide-field mode (WFM), with each single pointing covering an area of about 1 arcmin², a spectral wavelength range of 4700–9300 Å, and a spectral resolving power $R$ that varies from 1770 (4800 Å) to 3590 (9300 Å). While the UDF-10 and MOSAIC programs were carried out without the ground-layer adaptive optics (GLAO) mode of the VLT Adaptive Optics Facility (AOF) via the GALACSI adaptive optics module (Kolb et al. 2016; Madec et al. 2018), the MXDF program made use of VLT’s AOF and GALACSI. With respect to non-AOF observations, the only change in the MUSE instrumental configuration is the notch filter that blocks the light in the 5800–5966 Å wavelength range, which would otherwise be strongly contaminated by the bright light of the four sodium laser guide stars used by the AOF. In WFM the MUSE spatial sampling is 0.20′′ × 0.20′′, while the spatial resolution varies significantly between programs, going from a median value of $\approx 0.8′′$ (MOSAIC and UDF-10 programs) down to $0.4′′$ in the case of MXDF observations. Within the XDF area, the observations can reach a maximum depth of more than 140 hr but the depth is not homogeneous.

Bacon et al. (2023) provide fully reduced MUSE data cubes for the MOSAIC + UDF-10 and MXDF programs, as well as a catalog of detected sources and corresponding spectroscopic redshifts.24

2.2. JWST/NIRCam

We utilize recent NIRCam images collected as part of the General Observers (GO) program JWST Extragalactic Medium-band Survey (JEMS, PID: 1963; PIs: C. C. Williams, S. Tacchella, M. Maseda) covering the HUDF. These observations were carried out in five medium bands (F182M, F210M, F430M, F460M, and F480M), with 7.8 hr of integration time dedicated to F182M, F210M, and F480M, and 3.8 hr for F430M and F460M (Williams et al. 2023b).

In addition, we use imaging data obtained as part of the GO program The First Reionization Epoch Spectroscopic Complete Survey (FRESCO, PID: 1895; PI: P. Oesch) to complement the JEMS data set. FRESCO provides additional imaging in the F182M and F210M filters as well as at F444W (Oesch et al. 2023).

We process all the NIRCam images from JEMS and FRESCO using a modified version of the official JWST pipeline (version 1.8.25), which includes several procedures to minimize the impact of various image artefacts, such as snowballs, 1/f noise, wisps, and residual cosmic rays (e.g., Pérez-González et al. 2023; Rinaldi et al. 2023). After reducing the images, we drizzle them to a pixel scale of $0.03′′$ pixel$^{-1}$ and align them to the Hubble Legacy Fields (HLF) catalog of Whitaker et al. (2019).

Finally, we complement the JEMS and FRESCO observations with the recently published NIRCam data from the GO program The JWST Advanced Deep Extragalactic Survey (JADES, PIDs: 1180, 1210; PIs: D. Eisenstein, N. Luetzgen-dorf). The JADES data set adds deep imaging in eight JWST/NIRCam bands (F090W, F115W, F150W, F200W, F277W, F335M, F356W, F410M) and significantly increases the depth in the F444W filter (Eisenstein et al. 2023). For our study, we download the fully reduced, publicly released JADES observations26 (Rieke et al. 2023b) from the Mikulski Archive for Space Telescopes (MAST). Although these imaging data underwent a distinct optimization process (developed by the JADES collaboration using the JWST pipeline) compared to our own processing, a visual inspection of the JADES final products in the XDF region did not uncover any artefacts or patterns that might affect the quality of photometric measurements in those bands. Consequently, we consider the quality of the results produced by the two pipelines to be comparable.

After matching their astrometry to the HLF catalog, we resample the JADES images to the same scale as the JEMS and FRESCO NIRCam observations ($0.03′′$ pixel$^{-1}$).

2.3. JWST/MIRI

We complement the NIRCam observations with MIRI 5.6 μm imaging from the JWST GTO program The MIRI HUDF Deep Imaging Survey (MIDIS, PID: 1283; PI: G. Östlin). The MIDIS observations cover an area of about 4.7 arcmin$^2$ of the XDF for about 40 hr of total integration time and were carried out in 2022 December using the broadband filter F560W. This is the deepest 5.6 μm image available to date (e.g., Boogaard et al. 2023; Rinaldi et al. 2023).

Similarly to the NIRCam observations, we use a modified version of the official JWST pipeline (version 1.8.27) to address strong patterns, such as vertical striping and background gradients, that affect the scientific quality of the images (e.g., Iani et al. 2022; Rodighiero et al. 2023). We add extra steps at the end of stages 2 and 3 of the official JWST pipeline to mitigate these issues and reduce the noise in the output image. For more details about the latest MIDIS data collection, we refer the reader to G. Östlin et al. (2024, in preparation).

Finally, we register the astrometry of the final MIRI image to the HLF catalog and drizzle it to the same pixel scale as the NIRCam images.

2.4. HST

We combine our JWST observations with the HST images of the XDF obtained from the Hubble Legacy Field GOODS-S (HLF-GOODS-S)28 Whitaker et al. 2019). The HLF-GOODS-S comprises 13 HST bands, spanning a broad range of wavelengths from 0.2 to 1.6 μm including UV (WFC3/UVIS: F225W, F275W, F336W), optical (ACS/WFC: F435W, F606W, F775W, F814W, F850LP), and near-infrared

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24 The MUSE cubes and catalog of sources can be obtained at https://amuses.univ-lyon1.fr/project/UDF/HUDF/.

25 CRDS context jwst_1018.pmap.

26 The JADES fully reduced images are available at https://archive.stsci.edu/hlsp/jades/#section=28&id=08a-115f-430e-adfe-846ee6b33f3b.

27 CRDS context jwst_1014.pmap.

28 The HST imaging is available at https://archive.stsci.edu/prepds/hlf/.
(WFC3/IR: F098M, F105W, F125W, F140W, F160W) filters. For more detailed information on these observations, we refer the reader to Whitaker et al. (2019).

3. Sample Selection and Multiwavelength Photometry

In this section, we describe the process we follow to select our sample of LAEs and find their UV/optical/near-IR counterparts in the HST and JWST imaging. We also describe how we select a sample of galaxies that are in the same redshift range (\(z \approx 3-7\)) as our sample of LAEs but do not display Ly\(\alpha\) emission (LBGs).

3.1. Ly\(\alpha\) Emitters in XDF

To define our sample of LAEs, we start from the publicly available catalog of Bacon et al. (2023). We select all the LAEs lying within the area covered by the MIRI observations. We discard all sources reported with a quality flag on their spectroscopic redshift confirmation QF = 1 (indicative of a low confidence in the line identification) while keeping, instead, the LAEs with QF = 2.\(^{29}\) We retain the QF = 2 LAEs since they constitute 2/3 of the overall sample (QF = 2, 3) and their removal would introduce significant biases toward brighter LAEs. By doing so, we end up with an initial sample of 480 LAEs.

From a visual inspection, we find that 30 sources are in proximity (\(\leq 1''\)) to bright and extended galaxies at \(z \leq 2.5\). The proximity and brightness of these objects contaminate the photometry of the LAEs' counterparts. Besides, the presence of massive foreground objects can lens and magnify our targets (e.g., Matthee et al. 2017). Hence, we remove these sources from our analysis.

LAEs often host AGNs (e.g., Ouchi et al. 2008). For this reason, we investigate whether AGNs are hidden in our final catalog of LAEs. In fact, due to their peculiar physical properties, the presence of AGNs in our sample could impact and contaminate our final results. We look for AGNs in a twofold way: we cross-match our final catalog with X-ray observations in XDF, and we investigate the presence of high-ionization UV lines in the spectra of our targets. These two methodologies allow us to verify the presence of unobscured (Type I) and obscured (Type II) AGNs, respectively. The publicly available X-ray catalog based on the Chandra observatory (Chandra Source Catalog,\(^{30}\) version 2.0, Evans et al. 2020) does not report any X-ray emitter at our targets' coordinates or in their closest vicinity (\(\leq 1''\)). This is also confirmed by the comparison to the Chandra-based catalog by Luo et al. (2017) and the catalog of AGNs in XDF based on XMM-Newton observations by Ranalli et al. (2013). As for the study of UV lines, the catalog of Bacon et al. (2023) presents the equivalent width (EW) and flux of lines such as He\(\text{II}\) \(\lambda\)1640 (He\text{II}), and the C\text{IV} \(\lambda\lambda1548, 1550\) (C\text{IV}) and C\text{III]} \(\lambda\lambda1907, 1909\) (C\text{III}) doublet. Following Nakajima et al. (2018), we can probe the presence of AGNs via the diagnostic diagrams C\text{IV}/C\text{III]} versus (C\text{III]}+C\text{IV})/He\text{II}, EW(C\text{III}) versus C\text{III}]/He\text{II}, and EW(C\text{IV}) versus C\text{IV}/He\text{II}. According to Bacon et al. (2023), however, only two sources in our sample have a detection of all these lines with a signal-to-noise ratio \(S/N \geq 3\). Both objects lie in the locus of the diagrams populated by star-forming galaxies. Similar results are obtained even when pushing the \(S/N\) down to \(\approx 2\). As an additional check, we extract the MUSE spectra of our sources, bring them to the rest frame, and stack them. The final stacked spectrum does not show the presence of clear UV emission lines except for Ly\(\alpha\). The absence of these lines excludes the possibility that obscured AGNs constitute a significant percentage of our LAEs. Nonetheless, to further investigate the possibility of obscured AGNs, we match our catalog with the one from Lyu et al. (2022), who extended the detection of AGNs in XDF by studying galaxies' rest-frame optical to mid-IR emission. Also in this case, we find no counterparts. Finally, we point out that LAEs hosting an AGN have a Ly\(\alpha\) luminosity \(L(\text{Ly}\alpha) > 10^{45}\text{erg}\text{s}^{-1}\) (e.g., Ouchi et al. 2008). All our sources have \(L(\text{Ly}\alpha) < 10^{44}\text{erg}\text{s}^{-1}\). Based on these results, we safely exclude the presence of AGNs within our sample of 450 LAEs.

We then look for the UV/optical/near-IR counterparts of these objects.

3.2. Photometric Catalogue and SED Fitting

To find the UV/optical/IR counterparts of our sample of LAEs we first construct a source catalog based on HST and JWST images, as follows. We make use of the software SEXTRACTOR (Bertin & Arnouts 1996) to detect and measure photometry for sources in all the 28 available HST and JWST filters that span the wavelength range \(\lambda = 0.2-5.6\mu\text{m}\). We run SEXTRACTOR in dual-image mode, utilizing a superdetection mode, as presented in Galametz et al. (2013), which is well suited to identifying very faint sources.

We combine circular (0.5" diameter) and Kron apertures (Kron 1980) to extract the photometry (i.e., MAG\_APER and MAG\_AUTO, respectively). After applying aperture corrections \(f_\text{aper} \approx f_\text{auto}\) to the MAG\_APER fluxes\(^{31}\) (see Table 1), in each filter we select MAG\_APER over MAG\_AUTO for faint sources (\(\geq 27\text{mag}\)) while, for brighter objects (\(< 27\text{mag}\)), we adopt MAG\_APER (MAG\_AUTO) if MAG\_APER < MAG\_AUTO (MAG\_APER \geq MAG\_AUTO). Following Rinaldi et al. (2023), we set the magnitude threshold at 27 mag after performing various tests with the HST photometry and comparing our fluxes with the HLF photometric catalog.

Due to the typical underestimation of photometric errors by SEXTRACTOR (e.g., Sonnett et al. 2013), we set 0.05 mag as the minimum error for all the HST photometry. We also set 0.05 mag as the minimum error for the JWST photometry to account for possible uncertainties in the NIRCam and MIRI flux measurements.

Finally, we correct all fluxes for Galactic extinction following Schlafly & Finkbeiner (2011). For each filter in our data set, we present the multiplicative correction factors adopted to correct the galaxies' flux for Galactic extinction \(f_\text{ext}\) in Table 1.

\(^{29}\) According to the authors, a confidence level of 2 for LAEs indicates a good confidence. The requirement is to have a Ly\(\alpha\) emitter with \(S/N > 5\) and a width and asymmetry compatible with Ly\(\alpha\) line shapes. A confidence level of 3 indicates high confidence, i.e., if there is no other line than Ly\(\alpha\), they require an \(S/N > 7\) with the expected line shape: a pronounced red asymmetrical line profile and/or a blue bump or double-peaked line profile.

\(^{30}\) The Chandra Source Catalog (CSC) is available at https://cxc.cfa.harvard.edu/csc2/.

\(^{31}\) The HST aperture corrections for the different instruments and filters can be found at https://www.stsci.edu/hst/instrumentation/. For the JWST filters, we estimate the aperture corrections using the WEBPSF software (https://webpsf.readthedocs.io/en/latest/).
We adopt the code LEPHARE (Ilbert et al. 2006) to perform the SED fitting and determine the properties of the detected sources. Our libraries are based on the stellar population synthesis models proposed by Bruzual & Charlot (2003), constructed considering the Chabrier IMF (Chabrier 2003) with a cutoff mass of 100 $M_{\odot}$ (0.1–100 $M_{\odot}$). For the stellar models, we take into account two distinct metallicity values: solar ($Z = 0.02 = Z_{\odot}$) and subsolar ($Z = 0.004 = 0.2 Z_{\odot}$). As for the star formation history (SFH), we adopt two different kinds of model: an instantaneous burst model (i.e., a model with a single stellar population) and exponentially declining SFHs (known as the $\tau$-model, SFR($t$) $\propto e^{-t/\tau}$). In this last case, we adopt values of $\tau$ (the so-called $e$-folding time) equal to 0.001, 0.01, 0.03, 1, 2, 3, 5, 8, 10, and 15 Gyr. We also complement the Bruzual & Charlot (2003) stellar templates with the empirical QSO templates available in LEPHARE from Polletta et al. (2006). To take into account the effects of internal dust extinction, we allow the code to convolve each synthetic spectrum with the attenuation law by Calzetti et al. (2000, hereafter C00) and with the extrapolation proposed by Leitherer et al. (2002) at short wavelengths, leaving the color excess $E(B - V)$ as a free parameter with values ranging between 0 and 1.5 in steps of 0.1. We run LEPHARE in the redshift range $z = 0–20$ in a mode that takes into account the possible presence of nebular emission lines. In this last case, LEPHARE accounts for the contribution of emission lines such as Ly$\alpha$, H$\alpha$, H$\beta$, and [O III] $\lambda$3727, whose contributions to the SED are derived via the SFR–luminosity conversions by Kennicutt (1998). Also the [O III] $\lambda$4959, 5007 doublet is included in the above-listed transitions, considering different ratios with respect to the [O III] line (Ilbert et al. 2006). Finally, emission lines are considered only for galaxies with dust-free color bluer than $|NUV - r| \leq 4$ and their intensity is scaled according to the intrinsic UV luminosity of the galaxy.

For undetected sources in a given filter, after masking all nearby sources, we place 1000 random nonoverlapping circular apertures (0.65 arcsec) on the sky region around each source and within a maximum distance of 15$\sigma$ from its center. After applying a $3\sigma$ clipping, we use the background rms (1$\sigma$) to estimate their flux upper limit. For LEPHARE, we use a $3\sigma$
upper limit for these filters. In all the cases where we have no photometric information (e.g., the MIRI/F560W and NIRCam coverage areas differ), we set the flux value to −99.

After running LEPHARE, we clean our output catalog for Galactic stars by cross-matching it with the Gaia Data Release 3 catalog (Babusiaux et al. 2023) and by excluding all sources that display a high stellarity parameter from SEXTRACTOR (i.e., \textit{CLASS STAR} > 0.8) and lie on the stellar locus of the \((F435W - F125W)\) versus \((F125W - F444W)\) diagram, e.g., Caputi et al. (2011).

To assess the quality of our SED fit, we compare the photometric redshift \(z_{\text{phot}}\) derived with LEPHARE to the catalog of spectroscopic redshifts \(z_{\text{spec}}\) from MUSE (Bacon et al. 2023) and JADES (Bunker et al. 2023). For the MUSE spectroscopic redshifts, we limit our comparison to all those sources having a \(z_{\text{spec}}\) quality flag \(QF = 3\), i.e., the estimates with the highest confidence. We adopt 0\(^{\circ}\)2 as a matching radius between our catalog and the sources from MUSE and JADES. We find that only about 15\% of all the matched sources are catastrophic outliers, i.e., \(|\Delta z|/(1 + z_{\text{spec}}) > 0.15\) with \(\Delta z = z_{\text{phot}} - z_{\text{spec}}\) and the normalized median absolute deviation \(\sigma_{\text{NMAD}} = 0.04\) \((\sigma_{\text{NMAD}} = 1.48 \times \text{median}(|\Delta z - \text{median}(\Delta z)|/(1 + z_{\text{spec}})))\).

3.3. HST/JWST Counterparts for the Ly\(\alpha\) Emitters

To find the HST/JWST counterparts of the LAEs in XDF, we match them with our photometric source catalog (see Section 3.2) within a circular aperture of 0\(^{\prime}\)5 radius. We find that 72 LAEs (about 16\% of the whole sample) do not have a counterpart in our catalog, 250 (about 56\%) match with a single source, and 128 (about 28\%) have multiple sources in their vicinity (up to five possible counterparts). Similar percentages were also reported by Bacon et al. (2023), who found that 15\% of their sample had no HST counterpart, while 68\% were matched to a single object. Upon examining the cutouts of LAEs lacking counterparts in our catalog, we observe that these objects typically exhibit detections solely in the filter corresponding to the Ly\(\alpha\) emission, and in some cases they show no counterparts in any filter. This pattern implies that these objects are likely emitters with low mass, low metallicity, and high equivalent width that are too faint to be detected even in deep imaging \((m_{AB} \gtrsim 30\text{ mag}; \text{e.g., Maseda et al. 2018, 2020, 2023; Mary et al. 2020})\). In scenarios where no detection is observed in any filter, an alternative explanation could be that the counterpart of these LAEs lies at a projected distance exceeding 0\(^{\prime}\)5 from their MUSE detection. In such cases, the separation between the Ly\(\alpha\) emission and the UV/optical counterpart would correspond to an offset greater than 3.9 kpc (2.7 kpc) at \(z = 2.8\) (\(z = 6.7\)). It is worth noting, however, that such offsets would be notably larger than what is typically observed at similar and lower redshifts, as indicated by previous studies (e.g., Hoag et al. 2019; Rasekh et al. 2022; Ribeiro et al. 2020). Furthermore, LAEs with offsets exceeding 3–4 kpc (larger than the typical size of galaxies at those redshifts) constitute a relatively small fraction of all LAEs and are typically associated with UV-bright systems (e.g., Lemaux et al. 2021).

To ensure accurate identification of the LAE counterpart, we rerun the photometric catalog of all matched sources through LEPHARE, this time fixing the redshift of each counterpart candidate to that of the corresponding LAE. In fact, due to the crowding of the field and the depth of the observations, within the matching radius of 0\(^{\prime}\)5 some foreground and background sources could be wrongly associated with the LAE. Besides, the detection of one or more sources close (in the plane of the sky) to the peak position of the Ly\(\alpha\) emission does not necessarily identify the LAE counterpart. Because of this, we decide to only retain the sources with a \(\chi^2_{\text{red}}\) value for the best SED fit (after fixing the redshift to the spectroscopic one) below a given threshold. To determine this threshold, we adopt the value corresponding to the 84th percentile of the \(\chi^2_{\text{red}}\) distribution of LAEs that are matched uniquely to one single counterpart, i.e., \(\chi^2_{\text{red}} = 6.3\).

Since we aim at deriving the physical properties of LAEs from the SED fitting, we limit our study sample to all sources with a secure detection in the MIRI filter \((F560W < 29.5\text{ mag})\). The detection in the MIRI filter allows us to robustly constrain the optical/near-IR emission of our targets \((0.8–1.6\mu m, \text{depending on redshift})\). This requirement ensures a more robust estimate of their stellar mass and the age of their underlying stellar population (for more details see Appendix A).

Finally, we verify that different LAEs are not associated with the same counterpart.

Our final sample consists of 222 LAEs. We show the position of these galaxies in Figure 1. Out of these final 222 objects, 182 LAEs (about 82\%) are associated with a single source, 34 (about 15\%) have two counterparts, and 6 (about 3\%) have three counterparts. We limit our statistical analysis only to the 182 sources with a single counterpart because of their complex interpretation. In fact, the multiple components are easily characterized by different physical properties (e.g., stellar mass, dust extinction, age of the stellar population) both in the case of clumps and in different gravitationally bound/interacting systems. Besides, the association of such multiple components to the Ly\(\alpha\) emission is not trivial, especially when only based on photometric data.

For the LAEs matched to a single counterpart, the median offset \(\delta_{\text{Ly}\alpha}\) between the coordinates of the UV/optical counterpart and the peak of the Ly\(\alpha\) emission is about 0\(^{\prime}\)1. Converting the offset separation for each source from arcseconds into kiloparsecs, we derive a median value of about 0.8 kpc. These estimates are broadly consistent with the typical Ly\(\alpha\)–UV continuum offsets found in previous work targeting LAEs both at lower redshifts (e.g., Rasekh et al. 2022) and at similar ones (e.g., Hoag et al. 2019; Ribeiro et al. 2020; Iani et al. 2021, 2023; Claeyssens et al. 2022). We present the redshift distribution and observed Ly\(\alpha\) luminosity distribution of our final sample of LAEs in Figures 2 and 3.

3.4. Lyman-break Galaxies in XDF

In addition to LAEs at \(z \approx 3–7\) and based on our photometric catalog, we also define a sample of sources in the same redshift range as our LAEs but which do not display any sign of Ly\(\alpha\) emission (at least according to the available MUSE observations). According to recent literature (e.g., Dayal & Ferrara 2012; Arrabal Haro et al. 2020; de La Vieuville et al. 2020), in the following we refer to these objects as LBGs. The comparison of the physical properties of these sources with those of LAEs could determine whether these two classes of objects are well distinguished or show common properties (see Section 5).

To this aim, we select all the sources in our photometric catalog that have the best photometric solution from LEPHARE \((\text{Z\_BEST})\) within the \(z\)-range covered by our sample of LAEs. We additionally discard all the sources with a best-fit \(\chi^2_{\text{red}} > 6.3\) (as for the sample of LAEs) and which have a clear preference \((\Delta \chi^2_{\text{red}} > 4)\) for a stellar or an AGN model. To
further exclude AGNs, we additionally remove all matches (≤1″) between our catalog of LBGs and the catalogs of AGNs from Ranalli et al. (2013), Luo et al. (2017), Evans et al. (2020), and Lyu et al. (2022). We also discard all sources that are matched or close (≤1″) to an LAE reported in Bacon et al. (2023; i.e., QF = 1, 2, 3), and exclude those whose light is contaminated by a nearby source. Lastly, similarly to the

Figure 1. Stacked image of XDF obtained by combining the 28 HST and JWST filters available. We display LAEs in blue and LBGs in green. Circles are 1″ in diameter. We highlight the XDF region covered by the JWST/F560W MIRI image with a lighter background color.

Figure 2. Observed Lyα luminosity vs. redshift of our final sample of LAEs. We highlight with orange and red edges LAEs matched to two and three photometric counterparts, respectively. The top and right panels show the redshift and Lyα luminosity distribution of our sources. The gray shaded region indicates the luminosity corresponding to the 2σ depth of the MUSE observations (Bacon et al. 2023), i.e., 2.1 × 10^{-19} and 4.2 × 10^{-20} erg s^{-1} cm^{-2} at depths of 10 hr and 141 hr, respectively.

Figure 3. Redshift distribution of our sample of LAEs (in blue) and LBGs (in green).
sample of LAEs, we limit our study to objects with detection in the MIRI/F560W filter and a magnitude <29.5 mag. By doing so, we end up with a sample of 450 LBGs. We present the redshift distribution of the selected LBGs in Figure 3.

4. Physical Properties of the LAE Counterparts

In this section, we present and discuss the main physical properties of the LAEs based on the SED analysis of their UV/ optical/near-IR counterparts. In Figure 4, we show a few examples of the LAEs investigated in this work.

4.1. SED Properties of the LAEs

Having identified the right counterpart for each LAE (see Section 3.3), we inspect the properties derived from the SED fitting: the color excess $E(B-V)$, the stellar mass $M_*$, and the age of the stellar population. In Figure 5 we present the distributions of these quantities for our sample of LAEs.

We find that the bulk (∼77%) of our LAEs have $E(B-V) < 0.1$ in agreement with previous studies (e.g., Ouchi et al. 2020, and references therein). Interestingly, however, the $E(B-V)$ distribution presents a tail reaching values up to $E(B-V) = 0.3$, which corresponds to a visual extinction $A_V \approx 1.2$ mag if we assume the C00 attenuation law.

As for the stellar mass, LAEs in our sample have masses spanning the range from a few $10^7$ to a few $10^9$ $M_\odot$ with a median value of about $10^{10.3} M_\odot$. All in all, the LAEs in our sample are all low-mass systems. In Figure 6 we show their stellar mass as a function of redshift (Fynbo et al. 2001; Nakajima et al. 2012; Hagen et al. 2014; Napolitano et al. 2023). While the few most massive galaxies with $M_* \geq 10^9 M_\odot$ in our sample are typically at $z < 4$, galaxies with a stellar mass between $10^8 M_\odot$ and $10^9 M_\odot$ are found up to $z \approx 6$.

The age distribution of our objects is bimodal. While 75% of all the LAEs are best fit by a young stellar population (age <100 Myr), the remaining 25% appear to have significantly older stellar populations, reaching an age of 1 Gyr in a few cases. This is in line with previous findings in the literature (e.g., Lai et al. 2008; Finkelstein et al. 2009; Pentericci et al. 2009; Rosani et al. 2020; Napolitano et al. 2023). Interestingly, we find LAEs with an underlying older stellar population already at $z \approx 6.5$ (see Figure 5), thus suggesting that 800 Myr after the Big Bang there were already galaxies characterized by an old stellar population and undergoing a new phase of star formation (rejuvenation, e.g., Rosani et al. 2020). We discuss the differences between the properties of LAEs with underlying young and old stellar populations further in Section 4.4.

We finally highlight that the majority (71%) of our sample of LAEs tends to prefer subsolar stellar metallicities, while the remainder (29%) have SEDs best fitted with solar metallicity templates. Although metallicities based on SED fitting can be highly uncertain, this result is broadly consistent with previous studies, which found that LAEs are typically metal-poor systems (Finkelstein et al. 2011; Nakajima et al. 2012; Trainor et al. 2016; Kojima et al. 2017).

As a final test, we inquire whether the results reported above could be affected by the best-fit SFH selected by LEPHARE during the SED fitting. However, we do not find any correlation between the SFH and the value of the different parameters retrieved. For more details see Appendix B.

4.2. UV Continuum Slope and Absolute Magnitude

In addition to the above parameters, we investigate the observed slope of the UV continuum $\beta$ and the absolute UV magnitude $M_{(UV)}$ of our sample. To estimate the $\beta$-slope we apply the methodology presented in Castellano et al. (2012), i.e., fitting the observed magnitude covering the rest-frame UV emission of LAEs by means of the equation

$$m_i = -2.5(\beta + 2) \times \log_{10}(\lambda_{\text{eff,}i}) + c$$

where $m_i$ is the observed magnitude of the $i$th filter, $\lambda_{\text{eff,}i}$ its corresponding effective wavelength, and $c$ is a constant representing the intercept for each best-fit observed UV continuum slope. For the estimate of $\beta$, we consider only broadband filters that cover the rest-frame wavelength range between 1300 and 2500 Å. We reject all filters with a transmission curve covering rest-frame wavelength below 1300 Å to avoid any possible contamination from the Ly$\alpha$ in the estimate of the $\beta$-slope. We also discard the medium-band filter HST/F098M since it could be easily affected by the presence of other UV emission lines. Thanks to the extensive data set at our disposal, these conditions allow us to have between four and eight photometric bands (depending on redshift) to perform the UV continuum fit of our sources. On a source-by-source basis, we further discard all filters with an upper limit and perform the fit only for those LAEs that retained at least three photometric bands with a detection (e.g., Bolamperiti et al. 2023). These conditions are met for 148 sources (out of 182) of our sample (about 81%). For each one of these LAEs, we estimate $\beta$ and its associated error by drawing 1000 Monte Carlo realizations of its photometry, perturbing the observed magnitudes according to their errors and following a Gaussian distribution. Then, we assume as $\beta$ the median of the final distribution of all the 1000 Monte Carlo realizations while we adopt the standard deviation of the distribution as its associated error. In Figure 5 we present the distribution of the estimated $\beta$-slopes for all the 148 LAEs. The derived distribution has a median value $\bar{\beta} = -2.21 \pm 0.56$.

We then estimate the LAEs' UV absolute magnitude $M_{(UV)}$ at 1500 Å. For the 148 sources with an estimate of $\beta$, we derive $M_{(UV)}$ by directly extrapolating the absolute magnitude at 1500 Å from the best fit of the UV continuum slope. For the 34 remaining sources, we first find the median value of the photometric bands with a detection within the rest-frame wavelength range 1300–2500 Å, and then we apply the distance modulus.

The derived value, however, corresponds to the absolute magnitude value not at 1500 Å but at approximately the median of the respective effective wavelengths $\lambda$ of the filters adopted for the estimate. In this case, a correction factor has to be applied to the absolute magnitudes thus derived to bring them to the corresponding value at 1500 Å. This correction factor $\delta M$ depends, however, on the slope of the UV continuum according to the relation

$$\delta M = -2.5(\beta + 2) \times \log_{10}\left(\frac{1500}{\lambda \text{ [Å]}}\right).$$

Since we do not have an estimate of $\beta$ for these sources, we adopt the median value $\bar{\beta}$. By doing so, we derive a median magnitude correction of $\delta M = -0.08^{+0.18}_{-0.21}$ mag.
Figure 4. Examples of the imaging and photometric properties of three LAEs in our study: ID 2570 (top), ID 3810 (center), and ID 2958 (bottom). For each LAE, in the top left corner, we present MIRI/F560W cutout images \((2.5'' \times 2.5'')\) with overplotted Ly\(\alpha\) contours (in white) as derived from MUSE. In the bottom left panels, we show the integrated Ly\(\alpha\) spectrum of the galaxies, while in the right panels, we present the LAE’s photometry (in gray with upper limits in blue) along with the LEPHARE best-fit SED (black) and synthetic photometry (red open diamonds).
Finally, we correct the derived $M_{UV}$ for dust extinction assuming the C00 attenuation law and the $E(B-V)$ obtained from LEPHARE. We present the final distribution of UV absolute magnitudes in Figure 5.

4.3. Star Formation Rate

Due to the lack of spectroscopic data targeting any of the Balmer lines of our LAEs (e.g., $H\alpha$, $H\beta$), we estimate their SFR from the conversion of the luminosity of their UV stellar continuum. We highlight, however, that the SFR derived from the $H\alpha$ (SFR($H\alpha$)) and the one inferred from the UV luminosity (SFR($UV$)) are known to describe the star formation of a galaxy on different timescales (e.g., Kennicutt 1998; Leitherer et al. 1999; Kennicutt & Evans 2012; Calzetti 2013): while SFR($H\alpha$) is indicative of the galaxy’s instantaneous star formation activity, i.e., its SFR over a timescale of about 10 Myr after the onset of a burst, SFR($UV$) depicts the SFR, assumed to be continuous and well behaved, over at least 100 Myr.

Following Kennicutt & Evans (2012), we first convert the dust-corrected UV absolute magnitude at 1500 Å into monochromatic luminosity, i.e., $L_{1500}(1500 \text{ Å}) = 10^{-0.4(M_{UV}) - 51.6}$, and then into SFR via the relation

$$ \text{SFR(UV)} \ [M_\odot \text{yr}^{-1}] = C_{UV} \times \frac{L_{1500}(1500 \text{ Å})}{[\text{erg s}^{-1}\text{Hz}^{-1}]} \tag{3} $$

where $C_{UV} = 8.82 \times 10^{-29} \ M_\odot \text{yr}^{-1} \text{erg}^{-1} \text{s Hz}$. We present the distribution of SFR(UV) in Figure 5.
Based on SFR(UV) derived via the above equation, we then compute the specific star formation rate, sSFR = SFR/$M_\ast$. We present the distribution of sSFR in Figure 5. The sSFR clearly shows a bimodal distribution (e.g., Rinaldi et al. 2022), with the majority of our sources having sSFR $> 10^{-7.6}$ yr$^{-1}$.

Based on these results, we investigate which region of the $M_\ast$–sSFR plane our sample of LAEs populate. According to Figure 7, we find that our LAEs display a bimodal distribution. While the representative points of the oldest LAEs ($\geq 100$ Myr) lie along the so-called main sequence (MS) of star-forming galaxies at their redshift (Rinaldi et al. 2022), the youngest objects (the majority of our sample) are located above the MS, above the lower boundary of the starburst galaxies (SBs, Caputi et al. 2017, 2021). The presence, at a given $M_\ast$ value, of LAEs on the MS and in the region of SBs, as well as their separation in age, could be a sign that these objects followed different evolutionary paths, i.e., diverse star formation histories (SFHs), or the consequence of burstiness, i.e., when the star formation is nonsteady and out of equilibrium (e.g., Guo et al. 2016; Faisst et al. 2019; Atek et al. 2022).

4.4. Comparison between Young and Old LAEs

From the SED analysis (see Section 4.1) we found that the distribution of the LAEs’ ages is bimodal, with 28% of the overall sample having an underlying stellar population older than 100 Myr. This result hints at the possible existence of two populations of LAEs with different properties (e.g., Shimizu & Umemura 2010; Arrabal Haro et al. 2020). For this reason, we investigate whether LAEs with an older stellar population display different general properties overall.

In Figure 8 we present the distribution of the physical properties investigated in this paper that separate LAEs with an underlying young stellar population ($\leq 100$ Myr, young LAEs hereafter) and those with an old one ($> 100$ Myr, old LAEs hereafter). The histograms clearly show that old LAEs tend to be more massive and less bright in both their Ly$\alpha$ and UV luminosity than young LAEs. The fainter absolute UV magnitude of young LAEs in turn converts into a systematically lower SFR (especially at fixed stellar mass) and a significantly lower sSFR (≈ 1 dex), see Section 4.3. We report the median values of the properties of LAEs with young and old stellar populations in Table 2.

Our results are in line with those of Arrabal Haro et al. (2020), who studied 404 LAEs at $z = 3–7$ with a clear rest-frame UV/optical detection and found that about 67% of their sample consisted of very young galaxies (median age $\approx 30$ Myr) with stellar masses between $10^8$ and $10^{9.5} M_\odot$, while the remaining 33% showed an overall older stellar population ($\approx 1$ Gyr) and masses above $10^9 M_\odot$.

For a more quantitative estimate of the differences between the two distributions of LAEs, we apply a two-sample Kolmogorov–Smirnov (KS) test. For each physical quantity, we perturb the distribution of its values 200 times according to the errors. Then we run the two-sample KS test for all possible permutations of the randomly generated distributions, i.e., about 40,000 realizations. We assume as the final p-value the median of all measurements and consider its 68% confidence interval. We assume as a threshold a p-value of 0.05 to discern whether the distributions descend from the same parent distribution (i.e., the null hypothesis, $p \geq 0.05$) or not ($p < 0.05$). For the investigated properties, we find that the two-sample KS test return values $p \leq 0.01$ for the color excess, stellar mass, and sSFR, thus implying that young and old LAEs have indeed distinct distributions for these parameters. In contrast, we find that the two classes of objects have similar distributions in UV continuum slope and absolute magnitude, star formation rate, and, marginally, Ly$\alpha$ luminosity. We present the results of the two-sample KS test in Table 3.

The difference between the physical properties of the two classes of LAEs suggests a difference in their SED shapes. In Figure 9 we present the rest-frame average best-fit SED of all the sources with very young ($\leq 10$ Myr) and old ($> 150$ Myr) stellar populations. To obtain the average best-fit SEDs, we first bring every observed best-fit SED to the rest frame. Then, we resample them to a common wavelength range using the PYTHON library SPECTRES (Carnall 2017) and normalize them at 1500 Å. Finally, we derive the median trend and its corresponding 68% confidence interval.
From a visual inspection of the median SEDs thus derived, the separation between the two classes of objects is clear when considering the JWST data set, i.e., photometry at $\lambda > 1.6 \mu m$. The brighter rest-frame optical/near-IR fluxes, as well as the stronger Balmer break (falling for these objects in the bluest JWST bands), determine the higher mass and older age of old LAEs. In contrast, when looking only at the wavelength regime covered by HST, the photometric separation is small and well within the confidence interval of both median SEDs. This result shows the fundamental role played by the JWST near/mid-IR

Table 2

<table>
<thead>
<tr>
<th>Property</th>
<th>Young LAEs</th>
<th>Old LAEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L(\text{Ly}\alpha)$</td>
<td>$(42.14 \pm 0.55)$ M$_\odot s^{-1}$</td>
<td>$(41.87 \pm 0.44)$</td>
</tr>
<tr>
<td>$E(B-V)$</td>
<td>$0.11 \pm 0.09$</td>
<td>$0.09 \pm 0.10$</td>
</tr>
<tr>
<td>$M_*$</td>
<td>$7.31 \pm 0.48$</td>
<td>$6.09 \pm 0.47$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$-2.18 \pm 0.59$</td>
<td>$-2.29 \pm 0.55$</td>
</tr>
<tr>
<td>$M(\text{UV})$</td>
<td>$-18.57 \pm 1.33$</td>
<td>$-18.21 \pm 1.09$</td>
</tr>
<tr>
<td>$\log_{10}(\text{sSFR}(\text{UV})/M_\odot \text{yr}^{-1})$</td>
<td>$-0.01 \pm 0.60$</td>
<td>$-0.16 \pm 0.61$</td>
</tr>
<tr>
<td>$\log_{10}(\text{SFR}(\text{UV})/M_\odot \text{yr}^{-1})$</td>
<td>$-8.09 \pm 0.45$</td>
<td>$-8.24 \pm 0.33$</td>
</tr>
</tbody>
</table>

Note. We report logarithmic values of the Ly$\alpha$ luminosity $L(\text{Ly}\alpha)$, the stellar mass $M_*$, the star formation rate SFR(\text{UV}), and the specific star formation rate sSFR(\text{UV}) and their corresponding 68% scatter. We also present the values of $E(B-V)$, $\beta$, and $M(\text{UV})$ with their 68% uncertainties.

Table 3

<table>
<thead>
<tr>
<th>Property</th>
<th>Young LAEs</th>
<th>Old LAEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>KS Test</td>
<td>$0.04^{+0.07}_{-0.03}$</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>$L(\text{Ly}\alpha)$</td>
<td>$10^{-9}$</td>
<td>$0.34^{+0.24}_{-0.19}$</td>
</tr>
<tr>
<td>$E(B-V)$</td>
<td>$0.43^{+0.27}_{-0.24}$</td>
<td>$0.44^{+0.28}_{-0.24}$</td>
</tr>
<tr>
<td>$M_*$</td>
<td>$0.01^{+0.60}_{-0.55}$</td>
<td>$-0.16^{+0.61}_{-0.44}$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$-8.09^{+0.45}_{-0.33}$</td>
<td>$-8.24^{+0.33}_{-0.26}$</td>
</tr>
<tr>
<td>$M(\text{UV})$</td>
<td>$-18.57^{+1.33}_{-1.50}$</td>
<td>$-18.21^{+1.09}_{-1.26}$</td>
</tr>
<tr>
<td>$\log_{10}(\text{SFR}(\text{UV})/M_\odot \text{yr}^{-1})$</td>
<td>$-0.16^{+0.61}_{-0.44}$</td>
<td>$-8.24^{+0.33}_{-0.26}$</td>
</tr>
<tr>
<td>$\log_{10}(\text{sSFR}(\text{UV})/M_\odot \text{yr}^{-1})$</td>
<td>$-8.09^{+0.45}_{-0.33}$</td>
<td>$-8.24^{+0.33}_{-0.26}$</td>
</tr>
</tbody>
</table>

Note. We report the exact estimate of the $p$-value only for parameters with $p$-value $\geq 0.05$ and for those values with an error bar that comprises $p$-value $= 0.05$. In all the other cases, we only report its magnitude.

Figure 8. Distributions of the physical properties derived via the SED fitting for our final sample of LAEs separated into LAEs showing underlying young ($<100 \text{ Myr}$, in blue) and old ($\geq 100 \text{ Myr}$, in red) stellar populations. The vertical solid lines highlight the median value of the distributions, while the dashed lines are indicative of the 68% confidence interval, i.e., the 16th and 84th percentiles.
Figure 9. Average rest-frame SED (normalized at 1500 Å) of the LEPHARE best fits for young (age ≤ 10 Myr, in blue) and old (≥ 150 Myr, in red) LAEs. The corresponding colored shaded areas represent the 68% confidence interval of the average SEDs, while the background yellow region is indicative of the wavelength range covered by the JWST filters at λ > 1.6 μm assuming z ≈ 4.

Finally, in line with previous studies (e.g., Nilsson et al. 2009; Shimizu & Umemura 2010), we find that the percentage of old LAEs in the overall LAE population $N_{\text{old, LAE}}/N_{\text{tot, LAE}}$ decreases with redshift. In fact, we find that $N_{\text{old, LAE}}/N_{\text{tot, LAE}}$ decreases from 29±3% at $z = 2.8$–4 to 20±4% at $z = 4$–5 and to 17±5% at $z = 5$–6, and finally increases to 75±5% at $z = 6$–7. The decreasing trend we retrieve for the first three redshift bins ($z = 2.8$–6) can be explained by considering that at higher redshifts (i.e., at younger cosmic ages, we expect to find fewer old galaxies. This diminishes the possibility of detecting galaxies going through a rejuvenation process at those redshifts. We interpret the opposite trend at $z > 6$ as a selection effect: young LAEs may be too faint to be detected even in the deep JWST images available. This scenario is clearly shown by the median SED of young LAEs presented in Figure 9, which can differ by more than one magnitude at optical/near-IR wavelengths from that of old LAEs.

5. Comparison between LAEs and LBGs

In this section, we compare the results for our sample of LAEs to the more general population of galaxies at $z ≃ 3$–7 that do not display Lyα emission. By doing so, we want to investigate whether there is any clear separation between these two populations of galaxies based on the physical properties that can be inferred from their photometry.

We have described our LBG sample selection in Section 3.4. To derive the physical properties of LBGs we adopt the same methodology as applied for LAEs; see Section 4. From the SED fitting, we derive the LBG distribution in stellar mass, age, and color excess. We then derive their UV continuum slope, their absolute UV magnitude, and their SFR and sSFR.

As a first step, we investigate the $M_\ast$-SFR and $M_\ast$-sSFR diagrams for LBGs in Figure 10. Similarly to LAEs, the LBGs show a clear bimodal distribution in both diagrams, with the youngest objects mostly confined in the region of SB galaxies (Caputi et al. 2017, 2021) while the galaxies with an older underlying stellar population tend to crowd along the MS (Rinaldi et al. 2022). LBGs and LAEs also populate virtually the same region of the diagrams (see blue contours). This suggests that their star formation histories are possibly similar and the galaxies assembled following analogous paths.

Despite the fact that LBGs and LAEs cover almost the same stellar mass range (see Figure 5), we mass-match the two samples to ensure an unbiased comparison of their physical properties. This means that, in the following, all the statistics that we present for the properties of LBGs will be weighted such that their stellar mass distribution follows that of the LAEs. We present the mass-matched distributions of the physical properties of LBGs in Figure 11. For each measured parameter, we also report the median value and the 68% confidence interval in Table 4.

From a visual inspection of the panels in Figure 11 and according to the values reported in Table 4, LAEs and LBGs appear to follow similar distributions for their properties: the median values of the different parameters for both classes of objects are comparable and fully within the 68% confidence intervals of the distributions (see Table 4). For a more quantitative estimate, we run a two-sample KS test with a similar configuration to the one presented in Section 4.4 and with only the addition of weights due to the mass-matching of the sample of LBGs to that of LAEs. We report the p-value and the corresponding error for each physical quantity in Table 5. Also in this case, we assume as a threshold value $p = 0.05$ for the null hypothesis. According to the two-sample KS test, LAEs and LBGs have very similar properties except for their distributions in $E(B - V)$ and β-slope. We note that a discrepancy between the $E(B - V)$ distributions easily translates into a discrepancy between the β-slopes since the UV continuum is strongly and differentially affected by dust extinction.

The stellar age distribution of LBGs (see top left panel of Figure 11) clearly shows that about 48% of the LBG sample consists of galaxies with a young stellar population ($\leq 10$ Myr). Interestingly, this suggests that even though these systems are young they do not display the presence of the Lyα emission. In Section 5.1, we investigate whether this is simply due to the high dust extinction or whether H I resonant scattering could be playing a role in the absence of a Lyα emission line.

Finally, we highlight that 55% of the whole LBG sample is best fit with a subsolar template. We find a similar percentage (≈49%) even when considering only the population of young LBGs ($< 10$ Myr). These results are broadly comparable to what was found for LAEs, for which the percentage of best-fit subsolar templates is ≈71% for both the overall sample and among the youngest objects.

5.1. Understanding the Lack of Lyα Emission in Young LBGs

The analysis of our sample of LBGs shows that 48% of these galaxies are characterized by a young stellar population ($< 10$ Myr). At the same time, however, they do not display Lyα emission. To understand what could be the reason for the lack of detection of their Lyα, we attempt to estimate their expected observed Lyα flux $F(\text{Ly}_\alpha)_{\text{obs}}$ and compare it with the depth of the MUSE observations available.
On the basis of the SFR–L(Lyα) conversion by Sobral & Matthee (2019), we estimate $F(\text{Ly}\alpha)_{\text{obs}}$ via the equation

$$F(\text{Ly}\alpha)_{\text{obs}} = \frac{8.7 f_{\text{esc}}^{\text{Ly}C} (1 - f_{\text{esc}}^{\text{Ly}C}) \text{SFR}(\text{H}\alpha)}{4\pi d_L^2} \times 10^{-0.4 A_{\text{Ly}\alpha}}$$

(4)

where $f_{\text{esc}}^{\text{Ly}C}$ is the escape fraction of ionizing photons (i.e., the Lyman continuum photons), $C_{\text{H}\alpha}$ is the conversion factor from Kennicutt & Evans (2012; i.e., $C_{\text{R}12} = 5.37 \times 10^{-42} M_\odot \text{yr}^{-1} \text{erg}^{-1} \text{s}$), and $A_{\text{Ly}\alpha} = E(B-V) \times k_{\alpha}(\text{Ly}\alpha)$ with $k_{\alpha}(\text{Ly}\alpha)$ the C00 attenuation law at the Lyα wavelength.

For our sample of LBGs we do not have direct detection of the Hα line. This prevents us from estimating the SFR from the Hα luminosity, as well as the Lyα escape fraction. Therefore, we first assume SFR(Hα) = SFR(UV) and $f_{\text{esc}}^{\text{Ly}C} = 1$. We also set $f_{\text{esc}}^{\text{Ly}C} = 0$. With these conditions, we find that $\approx$97% of the young LBGs should have an observed Lyα flux still detectable (>2σ) by MUSE. This result suggests that, for these sources, the adopted assumptions are not completely valid and other phenomena, e.g., a different SFR estimate, resonant scattering ($f_{\text{esc}}^{\text{Ly}C} < 1$, e.g., Gronke et al. 2016), and/or dust attenuating the Lyα in a different way than the UV and optical continuum (dust-selective extinction, e.g., Neufeld 1991; Finkelstein et al. 2008; Gronke et al. 2016), should be taken into account. Hence, as a first step, we investigate the impact of modifying the SFR adopted. In the absence of direct spectroscopic detection of Hα, we attempt to estimate SFR(Hα) by introducing a correction factor $k$ such as SFR(Hα) = $k$($\text{age, } Z$, SFH) × SFR(UV). The $k$ factor is a function of the age, metallicity, and SFH of the stellar population of each galaxy,
i.e., \( k = k(\text{age}, Z, \text{SFH}) \). We derive \( k \) from the BPASS models (version 2.2.1, Eldridge et al. 2017; Stanway & Eldridge 2018) assuming stellar populations with no binary stars, a Chabrier IMF with a cutoff mass of 100 \( M_\odot \), solar and subsolar \((Z=0.2Z_\odot)\) metallicities, and a set of SFHs as in our SED modeling; see Section 3.2. For each LBG, we apply to its SFR (UV) the corresponding \( k \) correction factor thus derived (see Appendix C). The introduction of \( k \) reduces the proportion of young LBGs with an expected detectable \( F(\text{Ly} \alpha)_{\text{obs}} \) to about 86%; see Figure 12.

Since correcting the SFR estimate lowers the total number of detectable \( \text{Ly} \alpha \) in LBGs by only about 11%, we investigate the impact of the \( \text{Ly} \alpha \) escape fraction on our results. To do so, since we do not have a direct estimate of \( f_{\text{esc}}^{\text{Ly} \alpha} \), for each LBG we assume a typical \( \text{Ly} \alpha \) escape fraction corresponding to the average \( f_{\text{esc}}^{\text{Ly} \alpha} \) value at the galaxy’s redshift. In particular, we follow the \( f_{\text{esc}}^{\text{Ly} \alpha} \) trend with redshift reported by Hayes et al. (2011), i.e., \( f_{\text{esc}}^{\text{Ly} \alpha} = 1.67 \times 10^{-3} \times (1+z)^{2.57} \). By doing so, the total number of LBGs with expected observed \( \text{Ly} \alpha \) flux above the MUSE detection threshold at 2\( \sigma \) is about 43%.

Finally, we investigate how much the introduction of dust-selective extinction could lower the expected observed \( \text{Ly} \alpha \) flux of the young LBGs such that most of the young LBGs would have a \( \text{Ly} \alpha \) flux below the MUSE detection threshold. In this case, following Calzetti et al. (1994), we assume that the dust extinction for the emission lines (nebular component) is given by \( E(B-V)_{\text{neb}} = E(B-V)_{\text{obs}}/0.58 \), valid in the case of the C00 attenuation law (Steidel et al. 2014). This additional condition lowers the number of young LBGs with a detectable \( \text{Ly} \alpha \) in MUSE to only 13%.

This analysis shows the important role that resonant scattering and (potentially) dust-selective extinction play in making the \( \text{Ly} \alpha \) undetectable in LBGs.

All in all, these results indicate that LAEs and LBGs are essentially similar (e.g., Dayal & Ferrara 2012). We also confirm that resonant scattering and/or dust-selective extinction can explain the nondetection of the \( \text{Ly} \alpha \) emission in young LBGs. In contrast to previous studies (e.g., Giavalisco 2002; Gawiser et al. 2006), we do not find any evidence that LBGs

Table 4
Median Values of the Properties of LAEs and Mass-matched LBGs

<table>
<thead>
<tr>
<th></th>
<th>( E(B-V) )</th>
<th>( \log_{10}(M_*/M_\odot) )</th>
<th>( \log_{10}(\text{Age}/\text{yr}) )</th>
<th>( \beta )</th>
<th>( M(\text{UV}) )</th>
<th>( \log_{10}(\text{sSFR(\text{UV})} / M_\odot \text{yr}^{-1}) )</th>
<th>( \log_{10}(\text{SFR(\text{UV})}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAEs</td>
<td>0.09^{+0.11}_{-0.09}</td>
<td>7.50 \pm 0.60</td>
<td>7.17^{+0.03}_{-0.07}</td>
<td>-2.21 \pm 0.56</td>
<td>-18.47^{+1.23}_{-1.35}</td>
<td>-0.05^{+0.54}_{-0.50}</td>
<td>-7.48^{+0.43}_{-0.7}</td>
</tr>
<tr>
<td>LBGs</td>
<td>0.10^{+0.20}_{-0.10}</td>
<td>7.50 \pm 0.51</td>
<td>7.02^{+0.14}_{-0.18}</td>
<td>-1.95^{+0.72}_{-0.54}</td>
<td>-18.27^{+1.43}_{-1.38}</td>
<td>-0.14^{+0.73}_{-0.57}</td>
<td>-7.46^{+0.43}_{-0.94}</td>
</tr>
</tbody>
</table>

Note. We report logarithmic values of the stellar mass \( M_* \), the age, the star formation rate \( \text{SFR(\text{UV})} \), and the specific star formation rate \( \text{sSFR(UV)} \) and the corresponding 68% scatter. We also present the values of \( E(B-V) \), \( \beta \), and \( M(\text{UV}) \) with their 68% uncertainties.

Table 5
Two-sample KS Test between the Properties of LAEs and Mass-matched LBGs

<table>
<thead>
<tr>
<th>KS Test</th>
<th>( E(B-V) )</th>
<th>( M_* )</th>
<th>( \text{Age} )</th>
<th>( \beta )</th>
<th>( M(\text{UV}) )</th>
<th>( \text{SFR(\text{UV})} )</th>
<th>( \text{sSFR(\text{UV})} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p )-value</td>
<td>1e -7</td>
<td>0.70^{+0.23}_{-0.20}</td>
<td>0.22^{+0.23}_{-0.14}</td>
<td>1e - 4</td>
<td>0.08^{+0.10}_{-0.06}</td>
<td>0.09^{+0.11}_{-0.06}</td>
<td>0.10^{+0.18}_{-0.07}</td>
</tr>
</tbody>
</table>

Note. We report the exact estimate of the \( p \)-value only for parameters with \( p \)-value \( \geq 0.05 \) and for those values with an error bar that comprises \( p \)-value = 0.05. In all the other cases, we only report its magnitude.

Figure 12. Comparisons between the distribution of the observed \( \text{Ly} \alpha \) flux of young (\( \lesssim 10 \) Myr) LAEs (in blue) and the expected observed \( \text{Ly} \alpha \) flux of young LBGs (in different colors) as derived from Equation (4) and under different assumptions (reported in the left top corner of each panel). The gray shaded region is indicative of the fluxes below the 2\( \sigma \) depth of the available MUSE observations (Bacon et al. 2023), i.e., \( 2.1 \times 10^{-19} \) and \( 4.2 \times 10^{-19} \) erg s\(^{-1}\) cm\(^{-2}\) at depths of 10 and 141 hr, respectively.
are sources with greater stellar mass and less rapid star formation than LAEs.

6. Conclusions

In this paper we have studied the physical properties of 182 Lyα emitters and 450 stellar-mass-matched Lyman-break galaxies, based on an analysis of their rest-frame UV/optical spectral energy distribution derived from the 28 available filters from HST and JWST in the Hubble XDF. From this rich multiwavelength data set we found that:

1. Out of 450 initial LAEs in the XDF with a secure spectroscopic identification (Bacon et al. 2023), we did not retrieve a UV/optical counterpart in our photometric catalog for 72 LAEs (16%). For the remaining sample, we found that 250 (56%) match with a single source and 128 (28%) have multiple sources in their vicinity (up to five possible counterparts within a radius of 0.′′5). Similar percentages were also reported by Bacon et al. (2023), who found that 15% of their sample had no counterpart while 68% were matched to a single object. The addition of further selection criteria to ensure an accurate identification of the LAE counterpart shrunk the sample to 182 LAEs with a single counterpart.

2. Based on the study of their photometry, the LAEs in our sample are low-mass systems ($M_* = 10^6–10^9 M_\odot$) with no or little dust content ($E(B-V) = 0–0.3$) and have blue UV continuum slopes ($\beta = -2.21 \pm 0.56$). The majority of them ($\approx 71\%$) prefer best-fit stellar templates with a subsolar metallicity. These results are broadly consistent with the past literature (e.g., Ouchi et al. 2020, and references therein).

3. The age distribution of our sample of LAEs is bimodal (e.g., Lai et al. 2008; Finkelstein et al. 2009; Pentericci et al. 2009; Rosani et al. 2020). While 75% of LAEs have an age <100 Myr (young), the remaining 25% are significantly older ($\geq 100$ Myr). A two-sample KS test on the physical properties of the two samples showed that young and old LAEs have different distributions in $E(B-V)$, stellar mass, and sSFR. Specifically, old LAEs are statistically more massive and have lower extinction and sSFR than young LAEs. In contrast, we have not found a statistically significant difference with regard to the overall distributions in Lyα luminosity, UV continuum slope, UV absolute magnitude, and SFR. However, when investigating the regions populated in the $M_*–$sSFR plane by these two subsamples of LAEs, we found that while old LAEs lie along the MS of star-forming galaxies, young LAEs populate the starburst region, displaying a higher SFR at a given stellar mass than old LAEs. This fact hints at the possibility that young and old LAEs are galaxies that followed different evolutionary paths: while young LAEs could be young galaxies undergoing their first burst of star formation, old LAEs could be old systems experiencing a rejuvenation process triggered by a later subhalo accretion. From the analysis of the average SED of these two subsamples, we noticed that JWST observations are crucial to distinguish between these two subclasses of LAEs in the z-range studied. In fact, the rest-frame UV SEDs of young and old (probed by the HST photometry) are virtually identical.

4. From our multiwavelength photometric catalog of sources in XDF, we found 450 galaxies with photometric redshift in the same z-range as our sample of LAEs ($z = 2.8–6.7$) and that do not display Lyα emission. A two-sample KS test between the overall properties of the LAEs and the mass-matched sample of LBGs did not highlight any statistical difference between these two classes of objects except for the $E(B-V)$ and UV continuum slope. Interestingly, we found that 48% of the sample of LBGs consists of objects with a best-fit stellar population age $\leq 10$ Myr. Despite being young, these objects do not display Lyα emission. By looking at their properties, we found that young LBGs typically display a higher dust extinction than young LAEs. However, by inferring the expected observed Lyα flux of these objects from their SFR(UV), we showed that the Lyα emission of these galaxies should be detectable in the available MUSE observations. This suggests that other mechanisms (e.g., resonant scattering and/or dust-selective extinction) are hampering the detection of the Lyα emission. All in all, our results indicate that the overall samples of LAEs and LBGs are essentially similar in the main physical properties investigated in this paper (e.g., Dayal & Ferrara 2012), except for higher dust extinction in LBGs, especially at young ages.

The results obtained by this study highlight the paramount role of JWST NIRCam and MIRI (deep) imaging surveys in allowing the detection of different classes of Lyα emitters, young and old, as well as in unveiling the similarities in the properties of the stellar populations of Lyα emitters and Lyman-break galaxies. The wide wavelength range probed (0.9–5.6 μm) by the available observations, coupled with the high resolution and sensitivity brought by JWST, allows us to tightly constrain the spectral energy distribution of sources at $z \approx 3–7$ up to their rest-frame optical/near-IR emission in an unprecedented way. We expect JWST spectroscopic surveys (e.g., NIRCam Wide Field Slitless Spectroscopy) to extend our knowledge of these sources, enabling us to investigate their physical properties in even greater detail.

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Facilities: VLT:Yepun, HST, JWST.


Appendix A

Impact of the MIRI/F560W Filter

In this Appendix, we investigate the impact that the MIRI/F560W filter has in the determination of the physical properties of our sample of 182 LAEs via the SED fitting performed through LEPHARE. In particular, we probe possible variations in the estimated values of stellar mass $M_*$, age, and color excess $E(B-V)$.

To do so, we run LEPHARE on the photometry of our LAEs, after fixing their redshift to the spectroscopic value (Bacon et al. 2023), both considering and excluding the MIRI/F560W filter. From the comparison of the output best-fit values, we find that 50 (27%) of our LAEs differ in stellar mass larger than 10%. In particular, the lack of the photometric point at 5.6 μm tends to underestimate the stellar mass of our galaxies. Similarly, 62 (34%) LAEs have a difference in stellar age larger than 10%, with the best-fit SED solutions lacking the F560W filter generally underestimating the age of the underlying stellar population of the galaxy. Finally, we find that 22 (12%) LAEs have a variation in their estimated $E(B-V)$ larger than 10%. In this case, the lack of the 5.6 μm photometry prefers higher values for the color excess. The galaxies with a variation of more than 10% in all three properties are 12% (21 objects) of all our sample.

We do not find any evident trend of these discrepancies with redshift nor with the overall Lyα (e.g., flux, luminosity, S/N) and UV properties (observed and intrinsic UV magnitudes) of the sources; see Figure 13.
Figure 13. Redshift, Ly$\alpha$, and UV properties of our sample of LAEs as a function of the variation of their stellar mass, age, and color excess by considering and excluding the MIRI/F560W filter during the SED fitting with LEPHARE. The dashed line represents the identity line, while the dashed–dotted lines are indicative of 10% variation.
Appendix B
Impact of the SFH

In this Appendix, we investigate whether the values of the parameters retrieved from the LEPHARE SED fitting could be partially driven by the SFH of the best fit. As reported in Section 3.2, we allow LEPHARE to choose among an instantaneous burst (i.e., a single stellar population model; SSP) and exponentially declining models ($\tau$-models) with ten different values of the $e$-folding time $\tau = 0.001, 0.01, 0.03, 1, 2, 3, 5, 8, 10, \text{ and } 15$ Gyr. Out of our sample of 182 LAEs, 64 objects (about 35%) have a best fit SFH reproduced by an SSP while the remaining 118 galaxies (about 65%) prefer a $\tau$-model. In Figure 14, we report diagrams showing the values of the main physical parameters retrieved from the SED fitting as a function of the best fit SFH. We do not recover any correlation that could constitute a bias in the values of the parameters investigated in this study. However, we highlight how the stellar mass $\log_{10}(M_*/M_\odot) > 8.5$ and stellar population ages $\log_{10}(\text{Age/yr}) > 8.2$ are only reproduced by $\tau$-models. Interestingly, the youngest objects of our sample of LAEs (i.e., $\log_{10}(\text{Age/yr}) < 6.3$) are derived for a $\tau$-model with an $e$-folding time of 2–3 Gyr.

Figure 14. Best fit SED parameters (stellar mass, age, and color excess) as a function of the best-fit SED star formation history (instantaneous burst, $\tau$-models).
Appendix C
Correction Factors SFR(H\(\alpha\)) – SFR(UV)

In Figure 15, we present the theoretical tracks for the evolution of the SFR(H\(\alpha\))/SFR(UV) ratio (assuming the prescriptions by Kennicutt 1998) as a function of time, in a log–log plane, for solar (left panel) and subsolar (\(Z = 0.2 Z_\odot\), right panel) metallicities. Different tracks correspond to different SFHs. We adopt the same SFH models used during the SED fitting of our sources, i.e., single burst and \(\tau\)-models with \(\tau = 0.001, 0.01, 0.03, 1, 2, 3, 5, 8, 10, \) and 15 Gyr (see Section 3.2). To these models, we also add a constant SFH. The tracks are derived from the BPASS models (Eldridge et al. 2017; Stanway & Eldridge 2018) for a Chabrier IMF with a cutoff mass of 100 \(M_\odot\) and no binary stars.

![Theoretical tracks for the evolution of the SFR(H\(\alpha\))/SFR(UV) ratio as a function of time in the log–log plane for solar (left panel) and subsolar (\(Z = 0.2 Z_\odot\), right panel) metallicities and different SFHs: single burst, constant, and \(\tau\)-models (\(\tau = 0.001, 0.01, 0.03, 1, 2, 3, 5, 8, 10, \) and 15 Gyr). The colored arrow in the bottom right corner of each panel shows the direction of increase of the e-folding time \(\tau\).](image_url)